Narrow-band extremely low frequency (ELF) wave phenomena observed at South Pole Station

Hyomin Kim,[1] Marc R. Lessard,[1] James LaBelle,[2] and Jay R. Johnson[3]

Received 25 May 2005; revised 2 February 2006; accepted 17 February 2006; published 29 March 2006.

[1] Extremely low frequency (ELF) magnetic pulsations which show a whistler-like spectral structure have been measured at South Pole Station. An initial survey of the first 70 days of data revealed narrow-band ELF pulsations with slowly varying frequency over time. The narrow-band (a few Hz) signatures maintain their bandwidth as their frequencies decrease from 110 to 50 Hz (and their second harmonics) over the course of 40–90 s. Although the narrow-band ELF waves have a signature somewhat similar to very low frequency (VLF) whistlers, their duration and frequency range are much different from those of whistlers; they also show an unusual characteristic where their frequency often increases before it decreases. These events show a peak in their magnetic local time (MLT) occurrence distribution near the pre-midnight region, a result that contrasts sharply with the only three previously published studies of these waves. Two possibilities of generation mechanism are discussed. **Citation:** Kim, H., M. R. Lessard, J. LaBelle, and J. R. Johnson (2006), Narrow-band extremely low frequency (ELF) wave phenomena observed at South Pole Station, *Geophys. Res. Lett.*, *33*, L06109, doi:10.1029/2005GL023638.

1. Introduction

[2] Electromagnetic waves in the range of extremely low frequency (ELF; 3–3,000 Hz) have been associated with a range of magnetosphere-ionosphere coupling phenomena as well as meteorological phenomena. ELF observations include Schumann resonances, sferics, and sprites, which are due to lightning strikes. Besides these atmospheric events, lion roars, ELF noise-bands, and auroral roars have also been observed, which are thought to be associated with the magnetospheric plasma instabilities. In addition to these commonly observed wave activities, narrow-band ELF wave phenomena have been discussed in the literature. *Heacock* [1974] observed the narrow-band ELF waves that have whistler-like characteristics using an induction coil magnetometer at Poker Flat Research Range (65.3°N, geomagnetic). The signals decrease smoothly in the frequencies from 200 to 20 Hz, lasting for ~60 s. They are characterized by a daytime diurnal maximum, a seasonal minimum in winter, and maximum occurrences on magnetically quiet days. Mid-latitude ELF measurements by *Sentman and Ehring* [1994] at Table Mountain, California (40.8°N, geomagnetic) reveal signals with frequencies, the dispersion characteristics, and the local time occurrence distribution very similar to the events detected by *Heacock* [1974], including a narrow-band, decreasing structure in frequency from 120 to 60 Hz over a 40 s duration. Recently, low-latitude observations in Taiwan (16.8°N, geomagnetic) by *Wang et al.* [2005] also showed similar phenomena to the studies of *Heacock* [1974] and *Sentman and Ehring* [1994] but with durations of up to 120 s.

[3] This paper, using the data acquired with a ground-based induction coil magnetometer at South Pole Station (74.1° S, geomagnetic), presents the first very high latitude measurements of narrow-band ELF waves similar to the events reported by the three studies. Although their frequency structure somewhat resembles the typical VLF whistler waves, it should be noted that they are not thought to be whistlers, based on their fundamental frequency, much lower than VLF whistlers, and their durations, much longer than VLF whistlers. Classic atmospheric whistlers are normally detected in the kHz range and are dispersed over only a few seconds. Moreover, the ELF waves in our study show second harmonics with no echoes. The echoes are a signature commonly observed in whistlers that results from the waves bouncing between hemispheres. A unique frequency characteristics (rising and falling tone) shown by *Sentman and Ehring* [1994] and *Wang et al.* [2005] as well as the results in this paper contrasts with the monotonically falling tone structure of typical whistler waves. Those four studies demonstrate diurnal occurrence maximum at different magnetic local time (MLT).

2. Instrumentation and Data Analysis

[4] An induction coil magnetometer having ~0.1–250 Hz frequency response has been used to measure the ELF wave phenomena at South Pole Station. The data analyzed in this paper were acquired during the first 70 days of operation following the installation in January 2004. The ELF system consists of a two-axis induction coil magnetic sensor, a receiver, a data acquisition system, and a GPS receiver. The magnetic sensors are oriented in the geomagnetic north-south and east-west directions (determined by a local compass). The receiver electronics includes a manually selectable 60 Hz notch filter. The gain of the circuit is controlled automatically depending on the strength of input signals using an embedded automatic gain control (AGC) circuit, which provides a variable gain (up to 80 dB) or a dynamic range of 80 dB with a 20 dB/10 s slew rate. The sensitivity of the sensor is up to 0.3 V/nT over the pass band. In addition, a 250 Hz anti-aliasing filter (lowpass filter) is used to allow sampling at 500 Hz. The analog

[1]Space Science Center, University of New Hampshire, Durham, New Hampshire, USA.
[2]Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire, USA.
[3]Plasma Physics Laboratory, Princeton University, Princeton, New Jersey, USA.

Copyright 2006 by the American Geophysical Union.
0094-8276/06/2005GL023638$05.00

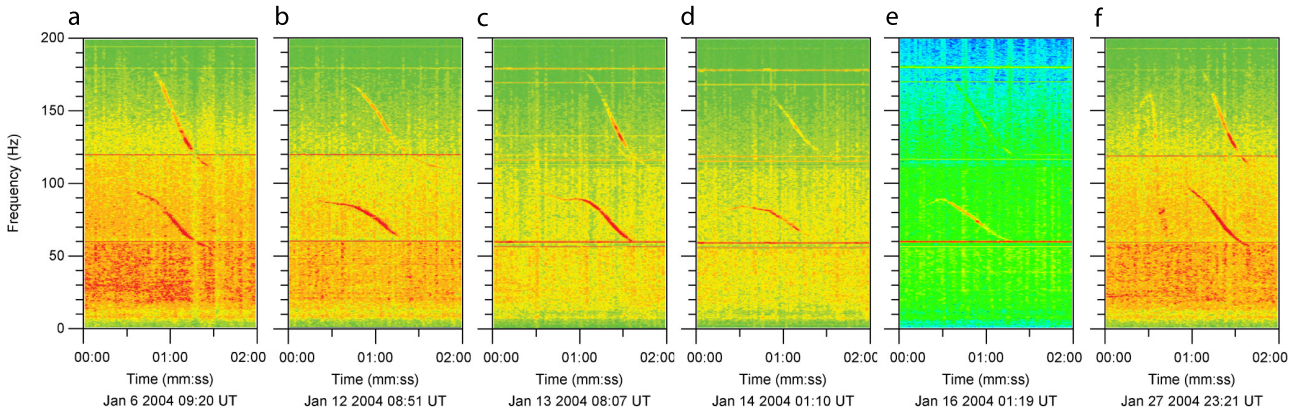

Figure 1. Sample dynamic spectra of narrow-band ELF waves acquired by ELF magnetometer system at South Pole Station. This figure shows the events detected from the y-axis sensor (the east-west direction) since most of the ELF waves are better observed in that direction.

signals are digitized and written every 1 hour by means of a 24-bit A/D converter in association with the GPS receiver for accurate time record.

[5] For initial survey of the data, the acquired data were differentiated to reduce $1/f$ (frequency) noise by flattening the data skewed toward DC frequency component and then Fourier-transformed using 1024-point (0.5 Hz/bin) fast Fourier transform (FFT) with the data overlapped at an interval of 5 s in association with Hanning window. Survey dynamic spectra were produced covering the frequency components (0–250 Hz) over the duration of 1 hour. See *Kim* [2004] for more technical information.

3. Observations

[6] Figure 1 shows the well-defined narrow-band ELF waves measured by the South Pole magnetometer. Each panel displays a frequency structure in the y-axis ranging from 0 to 200 Hz over 120 s of time at each date of event. Color scale is not shown since each dynamic spectrum has an arbitrary scale such that the events can be seen clearly in a few tens of pT range. A 60 Hz power line noise and its harmonics are shown in this figure as straight horizontal lines. The bandwidth of the whistler-like feature is a few Hz and the frequency span ~50–110 Hz, lasting for ~40–90 s. The similarities with the events presented by *Heacock* [1974], *Sentman and Ehring* [1994], and *Wang et al.* [2005] are clear. They have the same approximate frequency range (*Heacock* [1974]: ~40–200 Hz; *Sentman and Ehring* [1994]: ~60–180 Hz; *Wang et al.* [2005]: ~60–100 Hz), duration (typically around ~60 s), narrow-band structure (a few Hz), and the lack of echoes. Second harmonics are shown in almost all of the events in our study. The frequencies of these harmonics are twice the fundamental ones (e.g., in Figure 1a, the lower frequency occurs at 75 Hz and the upper one at 150 Hz at 09:21:00; 55 Hz and 110 Hz at 09:21:30). Some of the events observed by *Heacock* [1974] appear to display harmonics although no discussion is provided in that paper. No harmonics are seen in the events studied by *Sentman and Ehring* [1994] since the sample dynamic spectra span only from 0 to 120 Hz, which lies below the frequency range of the harmonics. Approximately 23% of the total events observed by *Wang et al.* [2005] display such harmonics. The relatively lower occurrences of the harmonics seen by *Wang et al.* [2005] than our study is due to the limitation of the frequency response of the instrument, which lies from 1 to 100 Hz (−3 dB point). There is also a slight difference in that the waves measured at the South Pole show a unique falling tone structure in such a way that they start with slow decrease first (for some waves, sharp increase first), have steep decrease in the middle, and slow decrease again near 50 Hz with a sharp end. Figures 1a and 1b display such a slow decrease at onset. The initial increase that precedes the decrease are shown in Figures 1d and 1e. *Wang et al.* [2005] also show such a varying spectral structure (rising and falling tone in frequency) and identify three different types of frequency structure. Some waves detected by *Sentman and Ehring* [1994] appear to have a similar rising/falling tone structure but it is not clearly shown in their study. The waves found by *Heacock* [1974] mostly display a monotonically falling tone structure in frequency. The typical amplitude of the ELF waves reported by all of the four studies introduced in this paper is roughly a few tens of pT.

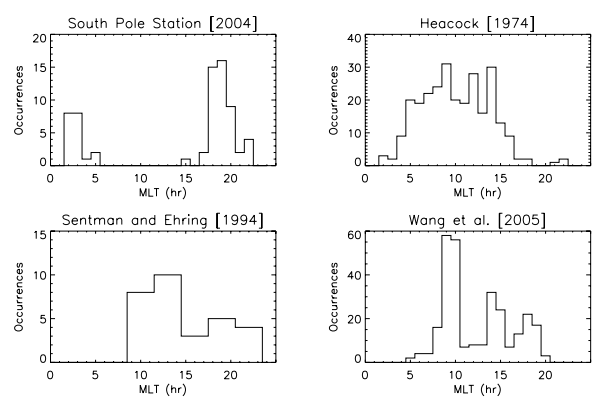

Figure 2. MLT distributions of narrow-band ELF waves observed by the four studies: this study (Jan. 1–Feb. 15, 2004), *Heacock* [1974] (Sep. 1–Dec. 1, 1973), *Sentman and Ehring* [1994] (Sep. 3–Oct. 5, 1985), *Wang et al.* [2005] (Aug. 26, 2003–Jul. 13, 2004). Note that the occurrences are not normalized.

Table 1. Geographic/Corrected Geomagnetic Coordinates and L-Value (R_E) Modelled by IGRF at 0 km in Altitude[a]

Location	Geographic Lat.	Geographic Long.	Corrected Geomagnetic Lat.	Corrected Geomagnetic Long.	L-Value, R_E	MLT Midnight in UT, hh:mm	Inclination, deg	Typical Duration, s
South Pole, Antarctica[b]	−90.0	N/A	−74.1	18.8	13.2	03:51	−72.6	∼60
Fairbanks, AK[c]	64.8	212.3	65.3	264.9	5.6	11:07	76.7	∼60
Table Mt., CA[d]	34.4	242.3	40.8	305.5	1.8	08:22	59.6	∼40
Lulin Observatory, Taiwan[b]	23.5	120.9	16.8	192.8	1.1	16:09	33.6	∼124

[a]Geophysical parameters of the measurement sites and typical durations of the observed ELF waves are also shown.
[b]IGRF 2005.
[c]IGRF 1975.
[d]IGRF 1985.

[7] A total of 59 events have been observed in the data acquired at South Pole Station from January through mid February 2004. For comparison, the histogram of occurrences versus MLT for the waves observed by the four studies are given in Figure 2 and the geographic and geomagnetic coordinates and some geophysical parameters of the four measurement sites are shown in Table 1. The events in our study show a peak in occurrence rate around pre-midnight in MLT and a secondary peak around dawn as shown in Figure 2. There is a gap in the occurrences during daytime. On the contrary, the statistics in the *Heacock* [1974] study showed occurrences broadly distributed around noon, with almost none detected near local magnetic midnight. The *Sentman and Ehring* [1994] study showed both an occurrence peak near noon and a secondary peak (with half the occurrence rate) in pre-midnight region. However, there is a midnight to dawn gap not observed by *Heacock* [1974]. Similar to the results reported by *Heacock* [1974], the occurrence rates observed by *Wang et al.* [2005] also show a broad distribution during daytime with a peak around magnetic local noon also having a midnight to dawn gap.

[8] *Heacock* [1974] found that the comparisons between the daily total occurrences and the daily A_P index show that the events tend to occur in the quieter intervals between geomagnetic storms, and moreover, do not occur during intense substorms ($K_P > 4$), but may precede or follow such substorms. While *Heacock* [1974] suggests the inverse correlation between A_P index and the occurrences, no significant correlations with K_P index and A_P index are observed by *Sentman and Ehring* [1994] or *Wang et al.* [2005]. Since the events in our study were observed in the premidnight region, where substorms are typically observed, fluxgate magnetometer data from the Pole were examined for evidence of substorms (i.e, a negative bay in the north-south component). No significant correlation were noted and, in fact, there appear to be no strong correlations with the K_P or A_P indices.

[9] *Sentman and Ehring* [1994] reported that the waves were predominantly linearly polarized in the east-west direction with most of the events not observed in the north-south direction. Linear polarization in the north-south direction was measured by *Wang et al.* [2005] and no description on polarization is given in the *Heacock* [1974] study. We observed somewhat stronger signals in the east-west direction in many cases but no strong tendency is shown. In addition, no clear signature of circularly polarized waves was found.

[10] Most of the events measured at the South Pole show the durations of ∼60 s, while the average duration of *Wang et al.* [2005] is ∼124 s. Some cases last even for ∼180 s or more, which have not been observed at the South Pole during the same period as that of the *Wang et al.* [2005] study. It appears that the slopes (df/dt) shown in the dynamic spectra lie within a narrow well-defined range for most of the events observed at the South Pole. Interestingly, comparing the four studies, it is observed that the slopes tend to decrease as the latitude of the station becomes lower. In particular, the slopes in our study are typically between 0.75–1 Hz/s while the observations by *Wang et al.* [2005] lie between 0.22–0.67 Hz/s.

4. Discussion

[11] *Heacock* [1974] concluded that the waves in his study are not lightning-generated whistlers but suggested that they may be associated with ELF hiss (broad-band emission) since the observations of hiss by the OGO-5 satellite have the same peak frequency (80–90 Hz) and are observed at the same magnetic latitude and local time (dayside).

[12] *Sentman and Ehring* [1994] illustrate a scenario by which their events enter the cusp waveguide from the magnetosheath and propagate into the Earth-ionosphere cavity through the cusp duct nearly perpendicular to the magnetic field, which results in the relatively long duration of the waves. The inverse correlation between A_P index and the MLT distribution of the occurrences reported by *Heacock* [1974], and the possibility of the observations of the ELF waves at lower altitude have also been explained by this scenario. The physical size of the cusp is known to depend on geomagnetic activity related to A_E index and B_Z

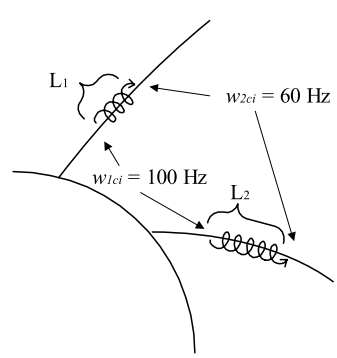

Figure 3. The change of the source region where the local ion cyclotron waves are generated. As the source drifts upward, the ion cyclotron frequency decreases. See text for more details.

component of the interplanetary magnetic field (IMF), which narrows the cusp during periods of enhanced geomagnetic activity and widens it during quiet period [*Carbary and Meng*, 1988; *Newell and Meng*, 1987]. Therefore, under this scenario, observations of the ELF waves on the ground are less likely when the indices indicate enhanced geomagnetic activity.

[13] Although the mechanism proposed by *Sentman and Ehring* [1994] was reasonable based on observations at the time, the new results presented here appear to refute the idea. Specifically, under that mechanism, the waves would be detected simultaneously at stations in different locations. However, the different MLT distributions of the observations of these waves in the four studies do not support this scenario; in particular, the distribution in MLT of the South Pole observations is remarkably different than the three other studies and, moreover, no observations of events at the South Pole coincided with simultaneous observations in Taiwan from January to mid February, 2004.

[14] Since the frequencies in this study appear to be much higher than those of Alfvén waves discussed in the literature and much lower than waves that might be expected to be associated with electron dynamics, it appears that the waves are associated with ion dynamics in some way. Further, the fact that they are observed on the ground implies that they are electromagnetic at higher altitudes, which seems to point to the possibility that they may simply be ion cyclotron waves. For waves with frequencies much less than the local ion cyclotron frequency (ω_{ci}), the classical waves are the Alfvén mode, which is guided along the background field, and the fast mode, which propagates isotropically. Both fast-mode and Alfvén mode waves propagate with negligible frequency-dependent wave dispersion. However, for the case where the wave frequency is near ω_{ci}, the possibility exists for fast-mode waves to propagate parallel to the background field, in which case their parallel group velocity is $|v_g|_{\|} = v_A \frac{(1+\omega/\omega_{ci})^{3/2}}{1+\omega/2\omega_{ci}} \approx v_A(1 + \omega/\omega_{ci})$ [*Dawson*, 1966; *Popecki*, 1991], which can be derived from an equation of Alfvén wave phase velocity near the ion cyclotron frequency given by *Cross* [1988]. Assuming that the frequency dependence on arrival time is due to wave dispersion associated with an abrupt excitation of waves over some frequency band, the group velocity for parallel fast-mode waves is proportional to the wave frequency, which might result in a signature similar to the observations, at least in principle. The logical implication is that fast-mode waves are excited in some localized region, with the higher frequencies arriving on the ground (after mode conversion takes place) before lower frequencies.

[15] If this mechanism is valid, it then becomes straightforward to estimate the altitude of the source region, based simply on the dispersion relation. The altitude can be written as $duration/(1/v_{1g} - 1/v_{2g})$, which has a dependence on ion cyclotron frequency and Alfvén speed. If the simplest case is considered, where the magnetic field and density are constant, however, then the source altitude would have to be the order of tens of R_E. Of course, the actual density and magnetic field would decrease with altitude, so the real altitude of the source would be much greater. Propagation of these waves from such high altitudes is problematic (i.e., the source would have to be in the magnetotail and then would have to propagate to the dayside, etc.) and this scenario is not really considered to be plausible.

[16] Another possibility might be considered where the waves are ducted horizontally in the ionosphere as described by *Greifinger and Greifinger* [1968]. Again, the apparent wave dispersion would reflect the distance from the ground station to the source region. Because the group velocity in this region is so high (typically, ~300–700 km/s), however, waves propagate over several degrees in latitude (or longitude) in just a few seconds, which again is not thought to be plausible, given the coherence of the signal.

[17] Finally, we consider the possibility that the signature is not one of wave dispersion, but instead results from motion of the source. Again assuming that the waves are ion cyclotron waves, the changing frequency over the course of the event would result from a change in the ion cyclotron frequency in the source region, implying that the source is drifting upward, that is, to lower magnetic field strengths. Note that this is not a Doppler effect; rather, the waves are emitted continuously as the source drifts upward. Reasonable numbers can be obtained at any given station to describe this. For example, the observations at the South Pole fit the scenario where the initial wave frequency, 100 Hz, results from protons at ~6,700 km while ~5,000 km is estimated at the same frequency in Taiwan. The observed wave frequency decreases to 60 Hz, which would be associated with protons at ~9,000 km (South Pole) and ~7,000 km (Taiwan). These altitudes are simply estimated since the magnetic field intensity in $\omega_{ci} = qB/m_i$ varies with geomagnetic coordinate and altitude. The specific mechanism that would follow an upward drift remains unknown at this point. Interestingly, the duration of events observed at the Pole are the order of ~60 s while those in Taiwan are ~124 s, a factor of ~2. An important difference between these stations is the dip angle (inclination) of the local field line. If the beginning and ending frequencies of the event are used to infer a beginning and ending source altitude at each station, and if the field line length from beginning to ending altitude is considered, the distance along that field line differs between the Pole (L_1) and Taiwan (L_2) by a factor of ~1.7 (see Figure 3). The field intensities and inclinations are calculated using IGRF (2005). Of course, this may simply be coincidental, but it does seem to be worth noting.

[18] Perhaps the most intriguing aspect of these waves is that they appear to be observed at all latitudes, with the only significant differences being that the duration is longer and the slope is decreased in the equatorial observations. While this result may suggest that they are ducted over large regions, the lack of coincident observations discussed above do not support this notion, at least over the very large distance from the South Pole to Taiwan. This leads to the suggestion that they can be excited over a very wide range in latitudes, with similar occurrence rates in different regions and only a weak dependence on local magnetic field geometry.

[19] For further study, the search for the similar ELF events in other stations relatively close to the Pole and the investigation of the long-term variation would provide some useful information as to whether the waves are localized and whether there are correlations with any other geophysical signatures.

[20] **Acknowledgments.** The authors thank the members of Cusp Lab at South Pole Station for their help with the installation and maintenance of the ELF magnetometer system. The authors would also like to thank Allan Weatherwax for providing the South Pole magnetometer and photomultiplier tube data and Eun-Hwa Kim and Kaiti Wang for useful discussions. Work at University of New Hampshire was conducted under NSF grant ANT-0513990. Work at Princeton University was supported by NASA grant W-19880 and NSF grant ATM-0218847.

References

Carbary, J. F., and C.-I. Meng (1988), Correlation of cusp width with $A_E(12)$ and B_Z, *Planet. Space Sci.*, *36*, 157.

Cross, R. (1988), *An Introduction to Alfvén Waves*, pp. 59–62, Inst. of Phys., Bristol, UK.

Dawson, J. A. (1966), Hydromagnetic wave propagation near 1 c/s in the upper atmosphere and the porperties and interpretation of the Pc1 micropulsations, *Tech. Note 342*, Natl. Inst. of Stand. and Technol., Gaithersburg, Md.

Greifinger, C., and P. S. Greifinger (1968), Theory of hydromagnetic propagation in the ionospheric wavequide, *J. Geophys. Res.*, *73*, 7473.

Heacock, R. R. (1974), Whistler-like pulsation events in the frequency range 20 to 200 Hz, *Geophys. Res. Lett.*, *1*, 77.

Kim, H. (2004), Study of extremely low frequency waves observed at South Pole Station, M.S. thesis, Dartmouth College, Hanover, N. H.

Newell, P. T., and C.-I. Meng (1987), Cusp width and B_Z observations and a conceptual model, *J. Geophys. Res.*, *92*, 13,673.

Popecki, M. A. (1991), A statistical study of narrow bandwidth, high latitude geomagnetic pulsations, Ph.D. thesis, Univ. of N. H., Durham.

Sentman, D. D., and D. A. Ehring (1994), Midlatitude detection of ELF whistlers, *J. Geophys. Res.*, *99*, 2183.

Wang, Y. C., K. Wang, H. T. Su, and R. R. Hsu (2005), Low-latitude ELF-whistlers observed in Taiwan, *Geophys. Res. Lett.*, *32*, L08102, doi:10.1029/2005GL022412.

J. R. Johnson, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08543, USA.

H. Kim and M. R. Lessard, Space Science Center, Morse Hall, University of New Hampshire, Durham, NH 03824, USA. (hyomin.kim@unh.edu)

J. LaBelle, Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755, USA.