Low-latitude ELF-whistlers observed in Taiwan

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Received 11 January 2005; revised 19 March 2005; accepted 25 March 2005; published 23 April 2005.

[1] Detections of ELF whistler-like events at a low latitude location are reported. Events with frequencies between 60 and 100 Hz were recorded by the ELF station at the Lulin Observatory in Taiwan from August 26, 2003 to July 13, 2004. The most distinguished feature for these events is the frequency descent in the frequency-time spectrograms, resembling terrestrial whistlers. Other notable features include (a) a long event duration averaging up to two minutes, (b) a daytime diurnal maximum occurring around 10 am, (c) a dominant magnetic field polarization in the north-south direction with strength of a few to tens of pT, and (d) no detection of vertical electric fields. Similar events were only reported twice for the past thirty years: one at an auroral latitude site in Alaska and the other at a mid-latitude site in California. Possible source mechanisms including magnetosheath lion roars and lightning-generated whistlers are discussed. Citation: 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.

1. Introduction

[2] Observations of lightning-generated whistlers by satellites and ground stations showed that the detected frequency for terrestrial whistlers ranges from about 2 kHz to 10 kHz, with peak occurrence around 5 kHz [Helliwell, 1965]. Based on the data acquired in this type of studies, Heacock [1974] and Sentman and Ehring [1994] reported detections of whistler-like events at much lower frequencies between 60 to 200 Hz in the ELF band. Heacock’s measurements were made in Alaska (65°N, 256°E, geomagnetic) at high latitude. These events were detected to possess a frequency range similar to lion roars observed in the magnetosheath [Smith et al., 1967, 1969], but their spectral forms are quite different [Heacock, 1974]. Sentman and Ehring’s measurements were made in California (34.4°N, 117.7°W) at mid-latitude. They called these events ELF-whistlers and remarked that the most probable interpretation would be whistler-mode waves of magnetosheath lion roars entering into the ionosphere. Both studies ruled out lightning-generated whistlers as a source because the observed dispersions cannot be accounted for under normal plasma environmental conditions.

[3] In this paper, we report the first low-latitude observations of ELF-whistler events at Lulin Observatory in Taiwan. These events are similar to those observed previously at high and middle latitudes by Heacock [1974] and Sentman and Ehring [1994].

2. Instruments and Observations

[4] In this study, both electric and magnetic ELF antennas were used. The ELF magnetic field antenna (EMI-BF4) was located at Lulin Observatory (23.47°N, 120.87°E; 2862 m) in the Yu-Shan National Park, Taiwan. This site was built far away from residential and industrial regions to reduce background noises. The antenna is in operation since August, 2003. The range of receiving frequency is from 1 Hz to 200 Hz and notch-filtered at both 60 Hz and 120 Hz. The response of the receiver drops below 10% for signals with frequencies higher than 100 Hz. The signals were sampled by a 16-bit A/D converter at a rate of 400 Hz. Both north-south (H) and east-west (D) components of magnetic fields on the horizontal plane were measured.

[5] The 60-meter long wire ELF electric field antenna was constructed at National Cheng Kung University (23.00°N, 120.22°E, 32 m) about 100 km south of Lulin. The preamplifier has a gain of 100 and 50 dB notch filters at 60 and 120 Hz. The system receives electric fields at the same frequency range as the magnetic ELF system by using the same signal condition and notch filtering module. The electric ELF antenna only measured fields in the local vertical direction, same as that of Sentman and Ehring [1994].

[6] Whistler-like events were recorded between 26 August 2003 and 13 July 2004. Figure 1 shows examples of events in the frequency-time (f-t) spectrograms that were assembled from the recorded signals. The H and D components of magnetic fields are plotted on the top and the bottom panels, respectively. The color bar on the right represents the scale of intensity in dB. On these spectrograms, two background features should be noted: periodically-occurring horizontal signals with stronger intensities at lower frequencies (<40 Hz) are from Schumann resonances; vertical fine, enhanced signals covering almost all frequencies often come from global lightning. In Figures 1a
and 1b, the brightest-colored event traces resemble conventional lightning-generated “whistlers” patterns: descendent frequencies with increasing time. In addition to the classical or the type-I ELF “whistlers”, other types of patterns were also found. Figures 1c and 1d demonstrate the type-II ELF-whistlers, which basically are “type-I whistlers” but with a short curvy trace at onset. This type of events were also appeared in the spectrograms of Heacock [1974] and Sentman and Ehring [1994] but were not specifically indicated therein. Figures 1e and 1f illustrate the type-III ELF whistlers with signal traces like the silhouettes of “mountains”, with an ascending trace, a crest, and a descending trace. There are cases of these three types of events but containing two or more signal traces as shown in Figures 1b, 1d and 1f. In all, 296 such events around 60 to 100 Hz were detected during the observation period. Among them, 135 events are classified as “type-I” ELF-whistlers, 125 are “type-II”, and 36 are “type-III”.

3. Data Analysis

[8] In our ELF events, the average lower cutoff frequency is 62 Hz, and the upper cutoff frequency is 94 Hz. Whereas for Heacock [1974] and Sentman and Ehring [1994], their observed frequencies reached up to 200 Hz. Since our instruments are less responsive above 100 Hz, the existence of signals with frequencies extending up to 200 Hz cannot be excluded. A comparison chart for the key results from Heacock [1974], Sentman and Ehring [1994], and this paper can be found in Table 1.

[9] Time durations for these detected events range from 40 seconds to 5 minutes. The average duration is 124 seconds, longer than those in previous studies which were around 40 s to 1.5 minutes. For comparison, the duration of whistlers observed on Earth typically lasts a few seconds. All dispersions shown in these signals exhibit no echoes, same as previous two reports. There are 69 events exhibiting multi-trace, approximately 23% of the total events. These multi-trace events can also be found in the work by Heacock [1974].

Table 1. Comparisons of ELF-Whistlers Observations at Different Locations

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic Location</td>
<td>auroral latitude 65°N</td>
<td>midlatitude 34°N</td>
<td>low latitude 23.5°N (ßm = 18°N)</td>
</tr>
<tr>
<td>Frequency</td>
<td>40 – 200 Hz</td>
<td>60 – 180 Hz</td>
<td>60 – 100 Hz</td>
</tr>
<tr>
<td>Duration</td>
<td>40 s – 1.5 mins</td>
<td>40 s – 1.5 mins</td>
<td>40 s – 5 mins</td>
</tr>
<tr>
<td>Dispersion</td>
<td>no echoes</td>
<td>no echoes</td>
<td>no echoes</td>
</tr>
<tr>
<td>Local Time</td>
<td>daytime maximum</td>
<td>daytime maximum</td>
<td>daytime maximum</td>
</tr>
<tr>
<td>Amplitude</td>
<td>a few pT</td>
<td>1 – 20 pT Hz$^{-1/2}$</td>
<td>a few pT to 70 pT</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>E-W</td>
<td>E-W</td>
<td>N-S</td>
</tr>
<tr>
<td>Vertical Electric Field</td>
<td>No measurement</td>
<td>Null</td>
<td>Null</td>
</tr>
<tr>
<td>Correlation with Ap</td>
<td>anticorrelated</td>
<td>insufficient samples</td>
<td>not obvious</td>
</tr>
</tbody>
</table>

Figure 1. (a) A type-I ELF-whistler, (b) a type-I ELF-whistler containing two traces of signals between 60–100 Hz and 150–180 Hz, (c) a type-II ELF-whistler, (d) a multi-trace type-II ELF-whistler, (e) a type-III ELF-whistler, and (f) a multi-trace type-II ELF-whistler. A short curvy trace at onset distinguishes the type-II ELF-whistler from the type-I. There are no discernible signals in the magnetic east-west direction (ELF_D) for the events depicted in Figures 1a, 1b, 1e and 1f.
All 296 events possess the H component of magnetic fields, and 137 events also possess a weak D component. Therefore, the observed signals have linear polarizations dominated by north-south directions. Previous observations in Alaska and California showed linear polarization in E-W direction, probably due to variations of local geomagnetic field directions. As to electric fields, no distinguishable signals in the local vertical direction were detected for these events. This is similar to features observed by Sentman and Ehring [1994] in which the vertical electric fields weren’t detected either.

Figures 2, 3, and 4 show the statistical graphs for these events. The relation between event occurrences time vs. local time is plotted in Figure 2. Please note that all events occurred between 6 am to 8 pm. The peak occurrence happened at around 9 to 10 am, about 3 hours earlier than previous observations. There is also a very clear night to dawn gap, the same as that of Heacock [1974] and Sentman and Ehring [1994]. There are also another two distinguished peaks occurring at local time around 2–3 pm and 6–7 pm, which were not reported in previous studies.

Figure 3 shows the relation between occurrence and $A_p$ index. Sentman and Ehring [1994] mentioned that there was no strong correlation on the base of fewer observations. However, Heacock [1974] showed anti-correlations between $A_p$ index and occurrences. Most events occurred at quiet ($A_p < 29$) and minor storm times ($29 < A_p < 50$). Only one event occurred at major storm time with $A_p = 70$, but it has the same features as signals detected at other times. Figure 4 shows event durations vs. $A_p$ index. The upper limit of event durations tends to decrease at greater value of $A_p$, which is a feature not reported in previous studies.

Please note that even though we categorize these events into three patterns, their statistical characteristics such as frequency range, occurrence time, correlation with $A_p$ index, durations are fundamentally similar. There is no unique or distinctive feature can be found for any of these patterns.

4. Discussions

Striking similarities between our observed ELF events and those recorded in previous studies on frequency ranges, daytime occurrences, wave field strengths, linear polarizations, long durations, and signal patterns on f-t spectrograms have suggested that they should have been generated from the same source mechanism. Whistler-mode waves were believed to be the most possible wave modes. Two probable source mechanisms, magnetosheath lion roars and lightning-generated whistlers, are discussed.

Magnetosheath lion roars were found to have frequencies below 120 Hz, field strengths of ~0.1 nT and signal duration of ~1s [Smith et al., 1967, 1969; Smith and Tsurutani, 1976; Tsurutani et al., 1982; Zhang et al., 1998; Baumjohann et al., 1999]. Basing on frequency ranges and dayside occurrence of the observed ELF-whistlers, Sentman and Ehring [1994] suggested they were induced by lion roars that entered the Earth-ionosphere waveguide.

However, the lion roar emission is incoherent and contains a band of frequencies, whereas the ELF-whistlers observed on the ground are very narrow-banded and coherent. It is unclear that how magnetosheath lion roars could be converted into the ELF-whistlers. Furthermore Smith and Tsurutani [1976] had shown that the percentage of occurrences for lion roars increases as storm index Kp increases. In our data, the correlation between occurrence percentages of ELF-whistlers and Kp are not as evident as that in the lion roars studied. All these imply that if lion roars are indeed the source, some unknown processes may need to be considered.

Previous studies had questioned how lightning-generated whistlers could generate ELF events with such a long durations and dispersions. The average dispersion $D$ of Lulin events is 5500 sec Hz$^{1/2}$, whereas the dispersion for lightning whistlers observed on Earth ranges from 12 to 400 sec Hz$^{1/2}$ [Helliwell, 1965]. To metamorphose the
lightning-generated whistlers into the observed ELF-whistlers, a long propagation path is required for the dispersion to accumulate. Here we examine a mechanism which was suggested to generate the very-long-dispersion whistlers \((D > 26000 \, \text{sec Hz}^{1/2})\) observed near Neptune by Voyager 2 [Gurnett et al., 1990]. The constraint of total path \(l\) needed to produce the ELF-whistlers can be estimated basing on field-aligned propagation [Gurnett et al., 1990]:

\[
l = 2c \frac{f_1^{1/2}}{f_p} D.
\]

Where \(f_e\) is electron cyclotron frequency, \(f_p\) is plasma frequency, and \(c\) is the light speed. They are all assumed to be constant.

The magnetic \(L\)-shell for our station is 1.09 derived from IGRF field model with Earth radius \((R_e)\) 6371 km. The geomagnetic latitude and longitude are 16.76° and 192.73°, respectively. The field line length \(S\) corresponds to \(L = 1.09\) can be estimated from \(S = R_e (2.76L - 2)\) [Volland, 1984] to be 1.0084\(R_e\). The field line completely sinks in the ionosphere so that the electron density is assumed to be \(10^5/\text{cm}^3\). Using \(f_e\) derived from the weakest field strength of 0.300 Gauss to the strongest field strength of 0.446 Gauss at this field line, \(l\) is deduced to range from 166 \(R_e\) to 202 \(R_e\), corresponding to 83 to 101 times of the back-and-forth bounce motion along the field line. However in this propagation pathway, highly-dispersed ELF-whister echoes are expected in \(f\)-t spectrograms. The observed ELF events at Lulin, contain no echoes, and hence are not likely to be formed from whistlers bouncing along the same field line.

Alternatively, the ELF-whistlers may be generated from non-ducted whistlers propagated from other longitudes with azimuthal crossing as suggested by Gurnett et al. [1990]. The whistlers propagate in a zigzag fashion reaching required path length \(l\), accumulating dispersion via repetitively-integrated electron densities. However, besides needing to perform a large numbers of hops in the plasmasphere that was never observed, it is not clear how these whistlers could re-enter the Earth-ionosphere waveguide; because they are very oblique and cannot be easily trapped in a duct. Hence, for the lightning-generated whistlers to undergo the mode conversion into the observed ELF-whistlers, some exotic processes may be needed for them to happen.

Heacock [1974] indicated a reason that these events were only detected in Alaska probably was due to low latitudes of other sites. Nevertheless, this type of events was detected at a lower latitude site in California, and now was observed in Taiwan as well. Recently, similar ELF emissions were also detected at Antarctica during January of 2004 [Kim et al., 2004]. Therefore, the low frequency and long dispersed ELF-whistlers maybe widely distribute across the globe. As for the source mechanisms, magnetosheath lion roars, field line bouncing and non-ducted whistlers all have great deficits and likely are not the sources of the ELF-whistlers. Further study has been taken to elucidate the multi-ion effects of the ionosphere on the whistlers, and the potential role of the multi-ion plasma in converting lightning-generated whistlers into the observed ELF-whistlers. We hope that the work reported here could invoke the interest of other ELF researchers and contribute their effort in resolving the mysterious ELF-whistlers, after thirty years since their first detection.

Acknowledgments. Yun-Ching Wang and Kaiti Wang contributed equally to this work. The authors thank Drs. D. D. Sentman, L. C. Lee, W. S. Kurth, H. C. Yeh, C. H. Lin, Y. H. Yang, and R. M. Thorne for the valuable discussions. We thank the Lulin Observatory, National Central University for hosting our ELF station and for logistic supports. Assistance from S. C. Wang, H. F. Rong, Y. H. Lin, P. J. Yang, J. Y. Lee, and R. I. Oyang are gratefully acknowledged. This work was supported in part by research grants NSC93-2111-M-159-001, 93-NSPOB-ISUAL-FA09-001, NSC93-2112-M-006-007, and NSC93-2111-M-006-001.

References


