Ground based VLF observations near $L = 2.5$ during the Halloween 2003 storm

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[1] Ground based recordings at Palmer Station, Antarctica ($L = 2.44$) provide rare observations of VLF waves at low L during and in the aftermath of the Halloween 2003 superstorms. VLF observations in the morning magnetic local time sector for Oct 29 to Nov 5 2003 are compared with daily global average changes in the electron radiation belts near the slot region. Wave activity observed at Palmer was remarkably intense during this period and included discrete chorus emissions, mid-latitude hiss as well as an unusual form of hiss extending up to ~15 kHz suggestive of auroral hiss. While the inner edge of the new radiation belt formed near $L = 2$, analysis of VLF data indicate that chorus was primarily confined outside $L \approx 2.75$.
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1. Introduction

[2] The series of extreme geomagnetic storms of 29 Oct 2003 to 31 Oct 2003, collectively referred to as the Halloween 2003 storms, led to a dramatic reconfiguration of the Earth's electron radiation belts [*Baker et al.*, 2004]. The outer radiation belt was depleted and then re-formed closer to the Earth occupying the slot region. Understanding and isolating the various acceleration processes that occur during this and other large geomagnetic storms remains a central challenge of magnetospheric physics (see reviews by *Li and Temerin* [2001], *Friedel et al.* [2002] and *Horne* [2002]).

[3] Of particular recent interest is the local acceleration of electrons by Doppler shifted cyclotron resonance with whistler-mode chorus emissions [*Horne et al.*, 2005a, and references therein]. Chorus is a discrete ELF/VLF emission typically observed in the low density region outside the plasmapause [*Sazhin and Hayakawa*, 1992, and references therein]. Chorus is generated by anisotropic distributions of electrons (tens to hundred keV) transported into the inner magnetosphere during substorms and periods of enhanced convection. Once generated, chorus can interact with electrons in the hundreds of keV range accelerating them to even higher (MeV) energies. Specifically for the Halloween 2003 storms, *Horne et al.* [2005b] calculated pitch angle and energy diffusion rates and concluded that beginning 1 Nov 2003, the electron flux increases at $L = 2.5$ and 4.5 could be accounted for by wave acceleration within the observed timescale assuming that chorus was present for six hours of local time on the morningside and that the plasmapause was confined to $L < 2.5$ in that local time region. Efficient wave acceleration is limited to the region outside the plasmapause where the plasma- to gyro-frequency ratio is low (<3) [e.g., *Summers et al.*, 1998].

[4] In this letter, we explore the relationship between ground based VLF observations and variations in the electron radiation belts near the slot region during and in the aftermath of the Halloween 2003 storms.

2. Radiation Belt Dynamics

[5] Figure 1 shows an overview of the energetic electron fluxes in the radiation belts from the SAMPEX spacecraft [*Baker et al.*, 1993] and the Provisional Dst index during the days surrounding the Halloween storm. The red, magenta, blue and green lines correspond to daily average electron (2.0–6.0 MeV) flux levels (right axis) at $L = 2.0$, 2.5, 3.0 and 3.5 respectively. These L-shells correspond to the approximate VLF viewing area of the receiver at Palmer station.

[6] At $L = 3$ and 3.5, the daily average flux levels show a decrease throughout the two major Dst drops occurring on Oct 29–31, but by Nov 1, flux levels have again risen. However at the lower L-shells ($L = 2$ and 2.5), the fluxes began to rise as early as Oct 29 and continued throughout the recovery phase.

3. ELF/VLF Observations at Palmer Station

[7] Palmer Station is located on the Antarctic Peninsula (geographic: 64.7°S, 64.0°W, geomagnetic (IGRF): $\lambda = -49.9°$, $L = 2.44$, MLT $\approx$ UT−4 hrs). A broadband ELF/VLF receiver system at Palmer records wave activity incident upon two orthogonal magnetic loop antennas. Each channel is sampled at 100 kHz with 96 dB of dynamic range. The system stores data in both a continuous mode (6 hours per day, typically 03–09 UT) and a synoptic mode. The synoptic mode operates 24 hours per day recording 1 min out of each 15 min starting at 5, 20, 35 and 50 min after the hour.

[8] An overview of the VLF observations at Palmer during the Halloween storm are shown in Figure 2. Although 24 hour recordings are available, we focus our attention on the morning local time sector which is the favored region for chorus occurrence [*Meredith et al.*, 2001]. Chorus was not observed at Palmer Station outside the intervals presented here, with the VLF emissions observed in the afternoon and evening sectors on these days being limited to moderate to weak mid-latitude hiss. In Figure 2a, each row is summary of VLF data from 02:35 to

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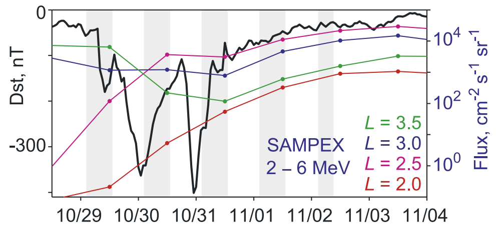

Figure 1. The red, magenta, blue and green lines correspond to daily average electron radiation belt (2.0–6.0 MeV) flux levels determined by SAMPEX (right axis, log scale) at L = 2.0, 2.5, 3.0 and 3.5 respectively. The heavy back line is the Provisional Dst (left axis).

13:05 UT (22.6 to 9.3 MLT) for the day indicated and corresponds to a light gray panel in Figure 1. Within each row, each narrow vertical panel is a 5-sec spectrogram with consecutive panels being 15-mins apart. Thus, the first panel is data from 02:35:00 to 02:35:05 UT, the next is 02:50:00 to 02:50:05 UT, and so on. This display allows us to examine the variation of the VLF intensity over the period of interest while also viewing the spectral characteristics of the emissions. Above ~7 kHz, the spectra are dominated by sferics, the impulsive radio signal emitted by lightning. Daily variations in the sferic activity (e.g. most intense on Oct 31 and Nov 1) depend on global lightning activity and propagation characteristics of the Earth-ionosphere waveguide.

[9] During the Halloween event, sunrise at ionospheric altitudes (100 km) at Palmer occurred at 05:00 UT. According to the IRI model for this day, the total electron content from 100 to 1000 km altitude increased by 25% from 05:00 UT to 09:00 UT as a result of solar illumination. The increase in electron density inhibits the penetration of magnetospherically generated VLF emissions to the ground due to increased absorption losses during trans-ionospheric propagation [*Helliwell*, 1965, p. 61].

3.1. 29 Oct 2003

[10] During the synoptic interval of 06:20 UT on 29 Oct 2003 (Figure 2a), relatively high frequency discrete chorus emissions were observed while Palmer was in the post-midnight sector (~2.5 MLT). The onset of the emissions correspond to the initial arrival of the highly disturbed solar wind to the magnetosphere.

[11] It is typically assumed that chorus emissions observed on the ground are lower-band chorus since only waves below half the equatorial electron gyrofrequency (f_{Heq}) can reach the ground assuming magnetic field-aligned

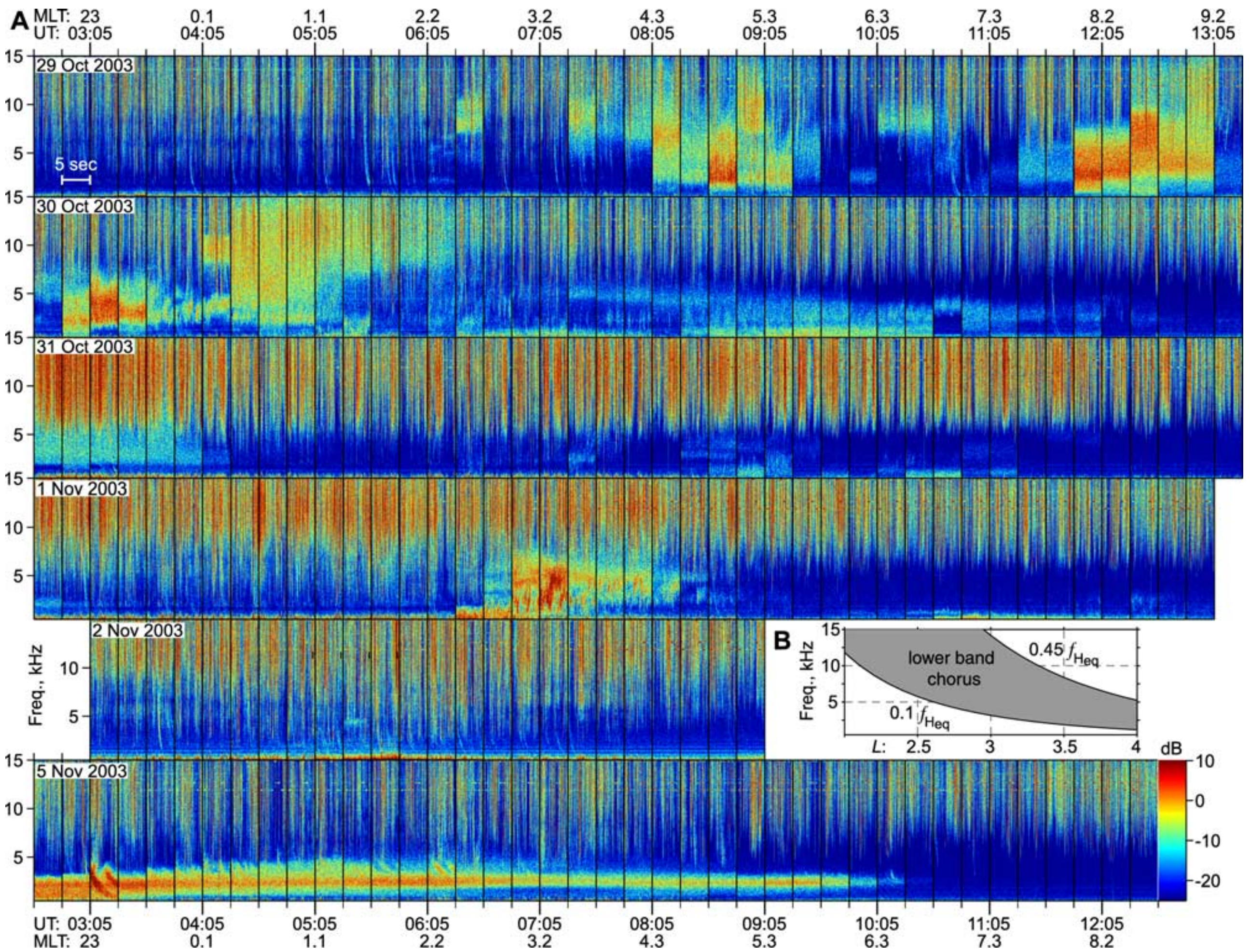

Figure 2. a. Summary of VLF observations at Palmer during the Halloween 2003 storms. See text for details. b. Expected frequency range of lower band chorus from L = 2.0 to 4.0.

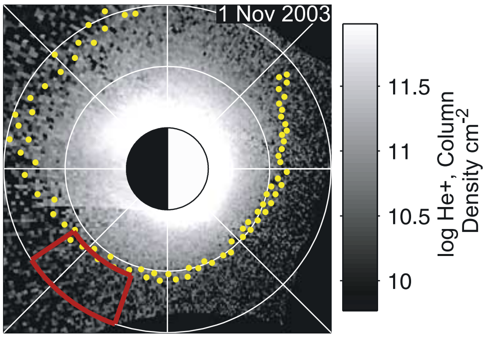

Figure 3. Image of the plasmasphere taken by the IMAGE EUV instrument on Nov 1, 2003 at 06:27 UT and mapped to the magnetic equatorial plane. The intensity corresponds to the line of sight integrated He^+ column density plotted on a log scale. The sun is to the right and the white circles are located at L = 2.5 and 4. The yellow dots are the estimated plasmapause location. The red highlighted section is the estimated generation region of the chorus observed at Palmer from 06:20 to 08:20 UT.

ducting of the waves [*Helliwell*, 1965, p. 43]. As observed on satellites, lower band chorus occurs between about 0.1 and 0.45 of the f_{Heq} [e.g., *Burtis and Helliwell*, 1976]. Figure 2b shows the frequency range of lower-band chorus for the approximate VLF viewing area of Palmer station (L = 2.0–4.0). Thus, the frequency range (~7–11 kHz) at 06:20 UT suggests that waves were generated in the range of L = 2.25 to 3.25.

[12] Chorus activity continued across the morning sector (most intense from about 07:20 to 09:20 UT) with the frequency range varying from several kHz up to nearly 15 kHz. The wide frequency range indicates that the wave generation region likely extended over several L-shells.

[13] By 11:20 UT, the character of the observed emissions changed significantly with intense broadband hiss emissions replacing the chorus emissions. The frequency range of the hiss increased with time and by the synoptic interval at 13:05 UT, the emissions extended from 2 to 17 kHz. By this time, Palmer was in full sunlight, and the observed emissions were extremely intense despite the enhanced ionospheric absorption.

[14] These emissions differ from the type of hiss generally observed at Palmer, that is mid-latitude hiss [*Hayakawa and Sazhin*, 1992]. Mid-latitude hiss tends to be confined to lower frequencies (<4 kHz) and is narrower in bandwidth (2–3 kHz). For example, the bottom panel of Figure 2a shows observations of mid-latitude hiss from 05 Nov 2003 with its typical spectral characteristics (yet atypical in its intensity). The broadband hiss observed on 29 Oct 2003 more closely resembles that observed at much higher latitudes, that is auroral hiss [*Makita*, 1979]. At the time of the hiss observations, Dst exhibited a brief recovery.

3.2. 30 Oct 2003

[15] By the early hours of 30 Oct 2003, Dst began its first major recovery from a minimum of −363 nT. Chorus was observed throughout most of the morning sector (Figure 2a) with the likely generation region between L = 3 to 4 based on the frequency range of the emissions. The most intense chorus was observed when the station was in the midnight local time sector (e.g. 03:05 UT) and near the time of minimum Dst. Starting at 04:05 UT, the low frequency chorus was accompanied by broadband hiss emissions at higher frequencies. At 04:50 UT, the hiss extended to 20 kHz while discrete chorus emissions were confined below 5 kHz. The hiss faded out by 06:35 UT while weaker discrete emissions continued throughout the morning and finally faded after about 12:05 UT likely due to increased ionospheric absorption.

3.3. 31 Oct 2003

[16] At 23:00 UT on 30 Oct 2003, Dst reached its second minimum of −401 nT. By this time the outer radiation belts were depleted (green and blue lines in Figure 1). Also, the plasmasphere was extremely eroded with the plasmapause located near L = 1.5 across the morningside early in the day on 31 Oct [*Baker et al.*, 2004]. However, Palmer observations show only weak VLF activity on this day. Weak mid-latitude hiss was seen when the station was near local midnight (02:35 to 04:20 UT). Later in the morning, weak chorus was observed (e.g. 07:20 UT and 08:05 to 09:05 UT).

[17] Unfortunately, as is typically the case with ground based observations of magnetospheric waves, there is an ambiguity as to whether lack of observations of waves is due to lack of waves generated or the inability of the waves to penetrate through the ionosphere to the ground. Given the prolonged period of enhanced convection and the highly compressed plasmapause, it is possible that during this period the inner magnetosphere was devoid of field-aligned plasma density irregularities (i.e., 'ducts') that allow the waves to propagate along the field lines and efficiently penetrate the ionosphere.

3.4. 1 Nov 2003

[18] By the end of the day of 31 Oct 2003, Dst had sharply recovered from its second minimum and continued steady recovery throughout Nov 1. Intense chorus emissions were observed on Nov 1 beginning near 06:20 UT and fading after 08:20 UT (2.5 to 4.5 MLT). The onset of chorus is associated with a substorm and VLF observations at Halley, Antarctica (L = 4.3) also show an onset of wave activity at this time. The fading of the emissions may have resulted from the source electrons drifting out of the station viewing area or increased ionospheric absorption. The frequency range suggest that the waves were likely generated near $L \approx 2.75$ to 4.

[19] Figure 3 shows an image of the plasmasphere from the IMAGE EUV instrument [*Sandel et al.*, 2003] taken on Nov 1 at 06:27 UT. The plasmapause on the morningside (yellow dots) varied from L = 2.75 pre-dawn to L = 2.5 post-dawn. The red outlined segment is the generation region of the chorus activity observed at Palmer based on the time duration (06:20 to 08:20 UT) and frequency range of the emissions. Chorus appears to be limited to the region just outside the plasmapause. Chorus may have been generated east of this region but may not have penetrated to the ground due to enhanced ionospheric absorption.

3.5. 02–05 Nov 2003

[20] After Nov 1, there were no further observations of chorus at Palmer. Unfortunately on Nov 2, there was a data

dropout after 09:00 UT, but prior to that only weak lightning-generated whistler activity was observed. Observations on Nov 3 and 4 (not shown) are similar to those of Nov 2. However, on Nov 5 (bottom panel of Figure 2a), extremely intense mid-latitude hiss was observed along with long trains of multi-hop whistlers (two of which can be seen in the snapshot from 03:05 UT). This intense hiss was first observed near 01:30 UT and faded out by 10:00 UT.

4. Conclusions

[21] Ground based measurements at Palmer Station, Antarctica provide one of the few observations of VLF waves during and in the aftermath of the Halloween 2003 superstorms. Wave activity was remarkably intense during this period, and the character of the emissions was unusual in a number of ways.

[22] Firstly, intense hiss was observed extending up to exceptionally high frequencies, above 15 kHz, on both Oct 29 and 30. Both periods correspond to Dst recovery intervals although this type of hiss was not seen on Oct 31 during a similar Dst recovery. The emissions are reminiscent of continuous auroral hiss observed at much higher latitudes. Auroral hiss is associated with intense fluxes of precipitating low energy electrons (less than a few keV) [*Gurnett and Frank*, 1972] and is believed to be generated by a Cerenkov process [*Maggs*, 1976].

[23] Chorus, rarely observed at Palmer, was seen on Oct 29, 30 and Nov 1 and weakly on Oct 31. Diffusion calculations by *Horne et al.* [2005b] indicate that the increase in the radiation belt flux levels in the range of L = 2.5 to 4.5 beginning Nov 1 can be attributed to wave acceleration. Our observations of intense chorus in the morning sector on Nov 1 tend to support this conclusion although perhaps not below $L \approx 2.75$ based on the frequency range of the emissions and EUV observations of the plasmapause location. Our observations do not support wave acceleration near L = 2.0 at any time during the storm or recovery. Lower band chorus generated at L = 2 would normally be confined above $\sim$14 kHz. We did not observe discrete emissions extending to such high frequencies during the storm or aftermath although bursts of chorus generated at perhaps as low as L = 2.25 were observed on Oct 29. Also, by Nov 1 the plasmapause had extended past L = 2.5 and thus the region near L = 2.0 was unfavorable for wave acceleration.

[24] Finally, intense mid-latitude hiss was observed on Nov 5 and is likely associated with the drop in the daily average radiation belt flux levels observed by SAMPEX on that day at $L \geq 2.5$ (not shown) [e.g., *Meredith et al.*, 2004].

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References

Baker, D. N., G. M. Mason, O. Figueroa, G. Colon, J. G. Watzin, and R. M. Aleman (1993), An overview of the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) Mission, *IEEE Trans. Geosci. Remote Sens.*, *31*, 531.

Baker, D. N., S. Kanekal, X. Li, S. P. Monk, J. Goldstein, and J. L. Burch (2004), An extreme distortion of the Van Allen belt arising from the 'Halloween' solar storm in 2003, *Nature*, *432*, 878, doi:10.1038/nature03116.

Burtis, W. J., and R. A. Helliwell (1976), Magnetospheric chorus: Occurrence patterns and normalized frequency, *Planet. Space Sci.*, *24*, 1007.

Friedel, R. H. W., G. D. Reeves, and T. Obara (2002), Relativistic electron dynamics in the inner magnetosphere: A review, *J. Atmos. Sol. Terr. Phys.*, *64*, 265.

Gurnett, D. A., and L. A. Frank (1972), VLF hiss and related plasma observations in the polar magnetosphere, *J. Geophys. Res.*, *77*, 172.

Hayakawa, M., and S. S. Sazhin (1992), Mid-latitude and plasmaspheric hiss: A review, *Planet. Space Sci.*, *40*, 1325.

Helliwell, R. A. (1965), *Whistlers and Related Ionospheric Phenomena*, Stanford Univ. Press, Stanford, Calif.

Horne, R. B. (2002), The contribution of wave particle interactions to electron loss and acceleration in the Earth's radiation belts during geomagnetic storms, in *Review of Radio Science 1999–2002*, edited by W. R. Stone, chap. 33, pp. 801–828, John Wiley, Hoboken, N. J.

Horne, R. B., R. M. Thorne, S. A. Glauert, J. M. Albert, N. P. Meredith, and R. R. Anderson (2005a), Timescale for radiation belt electron acceleration by whistler mode chorus waves, *J. Geophys. Res.*, *110*, A03225, doi:10.1029/2004JA010811.

Horne, R. B., et al. (2005b), Wave acceleration of electrons in the Van Allen radiation belts, *Nature*, *437*, 227.

Li, X., and M. A. Temerin (2001), The electron radiation belt, *Space Sci. Rev.*, *95*, 569.

Maggs, J. E. (1976), Coherent generation of VLF hiss, *J. Geophys. Res.*, *81*, 1707.

Makita, K. (1979), VLF-LF hiss emissions associated with the aurora, *Mem. Natl. Inst. Polar Res., Ser. A, Aeronomy*, *16*.

Meredith, N. P., R. B. Horne, and R. R. Anderson (2001), Substorm dependence of chorus amplitudes: Implications for the acceleration of electrons to relativistic energies, *J. Geophys. Res.*, *106*, 13,165.

Meredith, N. P., R. B. Horne, R. M. Thorne, D. Summer, and R. R. Anderson (2004), Substorm dependence of plasmaspheric hiss, *J. Geophys. Res.*, *109*, A06209, doi:10.1029/2004JA010387.

Sandel, B. R., J. Goldstein, D. L. Gallagher, and M. Spasojevíc (2003), Extreme ultraviolet imager observations of the structure and dynamics of the plasmasphere, *Space Sci. Rev.*, *109*, 25.

Sazhin, S. S., and M. Hayakawa (1992), Magnetospheric chorus emissions: A review, *Planet. Space Sci.*, *40*, 681.

Summers, D., R. M. Thorne, and F. Xiao (1998), Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in the magnetosphere, *J. Geophys. Res.*, *103*, 20,487.

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