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Temporal properties of magnetospheric line radiation

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Abstract. Magnetospheric line radiation (MLR) events are relatively narrowband VLF signals that sometimes drift in frequency and have been observed in both ground-based and satellite data sets. We present the results of a survey undertaken on the basis of measurements made of MLR events observed at Halley, Antarctica (75°30'S, 26°54'W, $L \approx 4.3$), in June, July, September, and December 1995, specifically looking at the temporal properties of Halley MLR events. We find that (1) single MLR lines described in previous papers tend to be comprised of up to 3 lines with widths of 5-10 Hz. (2) The multiple lines show highly variable spacings (e.g., < 10 to ~100 Hz). (3) The rate at which MLR lines appears from the noise is ~0.1 to 0.2 dB s^{-1}, considerably smaller than previously reported for other VLF emissions. MLR exhibits slow growth, relative frequency stability, and long lifetimes in comparison with other coherent whistler mode emissions and thus may be generated by a separate mechanism. (4) The diurnal occurrence of MLR observed at Halley is twin-peaked, indicating an association with a combination of chorus and midlatitude hiss. (5) MLR occurrence rates can vary greatly within a given month, but the proportion of MLR present as part of the overall Halley wave activity is roughly constant (10-13%) throughout the year. (6) The occurrence of MLR activity at Halley is weakly linked to geomagnetic activity but only 24-48 hours after very large storms ($Kp > 6$), which affects only 8% of the total MLR events in this study. For smaller storms, there is little effect, although MLR events tend not to occur when the geomagnetic activity has been quiet in the previous 48 hours. (7) There is no dependence of MLR occurrence rates upon the instantaneous levels of geomagnetic activity. (8) The average duration of a typical MLR event at Halley is ~ 30 min, quite similar to previous reports.

1. Introduction

The first report of magnetospheric line radiation (MLR) came from observations made by ground-based receivers at Siple, Antarctica, and Roberval, Quebec [*Helliwell et al.*, 1975]. On frequency spectrograms these lines formed parallel tracks with frequencies in the range 2-5 kHz, widths of ~30 Hz, with some showing separations ~120 Hz. The lines were fairly constant in frequency, but in a number of cases they drifted up or down in frequency together, in one case as fast as 50 Hz min^{-1}. The authors suggested that these lines might be caused by power line harmonic radiation (PLHR), harmonics emitted from long power lines of the Canadian 60-Hz electricity mains transmission system and radiated upward into the ionosphere. It was postulated that PLHR could propagate in the magnetosphere in the whistler mode, where it might be amplified by wave-particle interactions and alter near-Earth geospace. PLHR could act as the "seed" interacting nonlinearly with trapped particles to produce magnetospheric line radiation. Evidence for the power line harmonic generation mechanism of MLR included observations at Roberval of entrainment of transmitter-induced VLF emissions by local induction line harmonics of 60 Hz. The emissions commonly varied freely in frequency by many hundreds of hertz over a few seconds and then on encountering a particular local harmonic were entrained, cut off, or had the slope of their frequency variation reversed [*Helliwell et al.*, 1975].

The association between PLHR and MLR has recently been question by the largest survey to date of MLR line frequency spacing, undertaken using observations from Halley, Antarctica (75°30'S, 26°54'W, $L \approx 4.3$) [*Rodger et al.*, 1999]. In a 2-week period in June 1995, 128 MLR events were observed containing 698 distinct MLR lines. MLR was present in 7.0% of the minute-long VLF recordings. There were a wide range of line spacings which did not preferentially show spacings near harmonics of electrical transmission frequencies, either 50 or 60 Hz. The distribution of MLR line spacings observed had a roughly exponential form, which the authors concluded was suggestive of a different mechanism for MLR than PLHR. Previously, a study making use of ISIS satellite data found that neither the initial frequencies of 42 MLR lines nor the frequency spacings between the lines, were multiples of 50 or 60 Hz [*Rodger et al.*, 1995], although the AUREOL-3 satellite detected 32 MLR distinct lines which were all separated by 50 Hz [*Parrot*, 1994].

MLR and the more general questions and observations associated with PLHR are discussed in detail in the reviews of *Bullough* [1995] and *Parrot and Zaslavski* [1996]. We should

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note that there have been instances where the term PLHR (or sometimes "power line radiation" (PLR)) is used to describe the VLF line radiation which we refer to as MLR. Given that the association between PLHR and MLR is still uncertain, we use PLHR to refer only to the harmonic fields produced by the local electrical supply which is radiated into the Earth-ionosphere waveguide, ionosphere, and magnetosphere. It is uncertain whether PLHR has been observed in the magnetosphere, although "tram line" events characterized by narrow bandwidth and zero frequency drift and with frequencies and spacings that are 50 or 60 Hz harmonics [*Rodger et al.,* 1995] might qualify. Recently, PLHR has been shown to temporarily "capture" or entrain magnetospheric triggered emissions, showing very clearly that PLHR can sometimes directly affect magnetospheric processes [*Nunn et al.*, 1999]. The same data appear to show chorus and periodic emissions which are triggered at PLHR frequencies, as previously reported by some authors [see *Nunn et al.*, 1999 and references therein]. Attempts have also been made to simulate the effects of PLHR in the magnetosphere using a VLF transmitter at Siple. It was found that radiated powers as small as ~0.5 W could produce line radiation at Roberval at the frequencies transmitted from Siple [*Park and Chang*, 1978].

In this paper we report on a survey of MLR activity in the June, July, September, and December 1995, specifically looking at the temporal properties of Halley MLR events. In this case, an MLR event refers to the presence of MLR line activity for some part of a minute-long recording. We analyze VLF recordings made at Halley, Antarctica (75° 30' S, 26° 54' W, $L \approx 4.3$). A limited part of this data set was examined previously to measure the frequency, spacing, drift, and intensity of MLR lines observed at Halley [*Rodger et al.*, 1999].

2. VLF Database and Experimental Procedure

Wideband ELF/VLF (0.05 to ~22 kHz) observations have been made at Halley using two vertical, single-turn 56 m^2 loop antennae which have been amplified by twin low-noise preamplifiers. The aerials and preamplifiers are located sufficiently distant (1.8 km) from Halley station that locally generated electromagnetic noise is negligible over the whole frequency range. Sensitivity (typically ~10^{-31} T^2 Hz^{-1} at 5 kHz) is normally limited by global thunderstorm noise (sferics) rather than receiver system noise. Calibration is achieved by simulating a signal of known intensity, frequency, and arrival direction. Five frequency calibration tones (488, 977, 1953, 3906, and 7813 Hz) are injected into the data once a minute, at the beginning of the minute [*Smith*, 1995]. Recordings are normally made for 1 min every 15 min (05-06, 20-21, 35-36, and 50-51 min past the hour). At times of unusual activity or for special campaigns, alternative schedules of 1 min recording every 5 min, or continuous recording, have been undertaken. Time code (IRIG-B) is simultaneously recorded with the data onto digital audio tapes (DAT). Control of the tape recorders is through the Advanced VLF Data Analysis System (AVDAS) [*Smith et al.*, 1994], which is also used for data analysis.

The search for MLR events in the Halley ELF/VLF data has been undertaken using the AVDAS routine MLRSCAN. This routine is used for digitizing and analyzing MLR events in our recordings. The MLRSCAN routine used in conjunction with AVDAS produces 0-5 kHz spectra with 12.5-Hz frequency resolution averaged every 500 ms. These spectra were examined visually for MLR events. The averaging process tends to emphasize MLR events, drawing them out from the background activity. Examples of MLR events observed in the MLRSCAN data format were shown in Plate 1 of *Rodger et al.* [1999].

In this study we restrict ourselves to the analysis of Halley ELF/VLF data collected in the months of June, July, September, and December 1995, which provide a sufficiently large data-set of MLR observations to examine temporal variation. Inside this time window, there were 15,281 complete min of Halley wideband ELF/VLF data recorded, all of which were examined for MLR activity, producing 863 MLR events. However, as has been reported in previous studies [e.g., *Helliwell et al.*, 1975], MLR tends to be associated with other VLF wave activity (e.g., chorus and hiss). As noted above, at these times a higher recording rate was often used, which could lead to bias in the examination of temporal properties. For this reason we limit ourselves to including only those minutes which were recorded at the 1:15 min schedule, as outlined above. Under this constraint our data set contains 477 MLR events observed in 11,448 min of 1:15 min recordings (thus with an average occurrence rate of ~4.2%). It should be noted that there is no universally agreed definition of what qualifies as an MLR event. As such, MLR detection is subjective, the criteria used for selecting an MLR event are that at least one well-defined line should be visible on the spectrogram and that these lines exhibit characteristics of nonlocal origin (as used by *Rodger et al.* [1999]).

3. Temporal Properties of MLR

3.1. High-Frequency Resolution: Case Studies

In order to better resolve the MLR lines, a frequency translator was used to shift the ~4 kHz MLR lines into the band 0 to 1 kHz. The frequency translated MLR events were examined in greater detail using AVDAS in its mode as a spectral analyzer. Fast Fourier transform (FFT) analysis was undertaken using 1024-point transforms, leading to a 2.5-Hz frequency resolution in the 0-1 kHz range. An example of this is shown in Figure 1, where the spectrogram of a frequency translated MLR event with 2.5-Hz frequency resolution is shown on the right and the 0-5 kHz spectra with 12.5-Hz frequency resolution on the left.

As can be seen from the translated frequency spectra of Figure 1, single lines seen in the 0-5 kHz spectra tend be made up of multiple (2-3) lines with widths of 5-10 Hz with smaller spacings (as small as <10 Hz). It has proved very difficult to clearly show these small spacings in Figure 1 due to changing resolution from screen-display to hardcopy; examples of events with small spacings in these data are lines at ~3660 Hz at ~11:47:00 UT, and those at ~4300 and 4360 around 1147:00 UT. These can be best seen by viewing the figure end on. The multiple lines show highly variable spacings (e.g., <10 to ~100 Hz). It was previously reported that two thirds of MLR events observed in the first 2 weeks of June 1995 were made of between 2 and 6 distinct measurable lines [*Rodger et al.*, 1999]. That study made use of 0-5 kHz spectra with ±7 Hz frequency resolution. The closely spaced lines shown in Figure 1 would be "smeared out" into a single line and would probably be counted as a single MLR line. It is likely that *Rodger et al.* [1999] will have undercounted the number of MLR lines occurring in a typical MLR event. A small number of 0-5 kHz MLR events have been previously reported with a "modulation" in addition to any overall drift [*Rodger et al.*, 1999]. At the higher-frequency resolutions possible with the translated frequency data, variability can be seen in some MLR lines which appeared to be stable in the lower resolution spectra. This is particularly clear in Figure 1 for the MLR lines ~4.3 kHz around 1147 UT. As the Halley data were recorded onto DAT, we

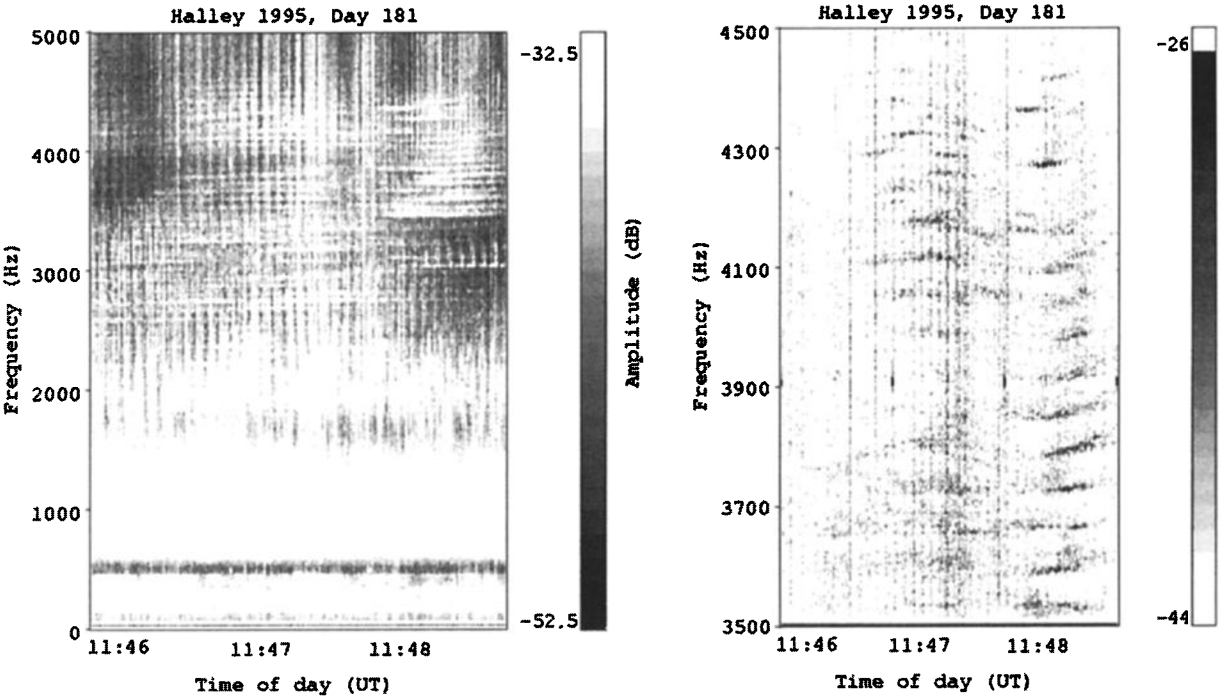

Figure 1. The spectrogram of an MLR event observed beginning at 1146 UT, June 30, 1995. The period taken is ~3 min long, and the beginning of each minute is marked by a calibration tone at 3906 Hz. Amplitudes are given in decibels with respect to the calibration tones. The 0-5 kHz is shown on the left, while the frequency translated spectra is shown on the right. A 50% overlap factor (redundancy) of successive frames was used to produce both spectra, along with 0.64 s (0-5 kHz) and 0.8 s (frequency translated) averaging.

can be confident that this additional modulation is not due to variations in the recording or playback speed.

An area which has not been reported on previously is the "risetime" of MLR lines out of the noise. MLR lines are known to appear quite suddenly, can fade in and out of observations over timescales of less than a minute, and then fade from view. In our complete 15,281 min VLF data set, there are several instances where MLR activity identified using MLRSCAN began well after the start of a period of continuous recording. These have been examined in greater detail to determine the risetime of MLR lines.

The power spectral density of five selected MLR lines in the range 3525 to 3800 Hz from the translated frequency data (Figure 1) are presented in Figure 2. A running mean over a ~7 s window is used to suppress statistical noise and impulsive events (e.g., sferics). The rate at which these lines appear out of the noise is ~0.1 to 0.2 dB s^{-1}, which is typical of other MLR events we have examined. The sensitivity level of our equipment is about –53 dB at this frequency, a level which is dominated by atmospheric noise. This first report of MLR growth rates produces significant constraints on theoretical models of the "growth phase" of newly created MLR lines.

3.2. Diurnal Occurrence of MLR

The diurnal occurrence of MLR activity for all 4 months of data is shown in Figure 3a. Here the occurrence has been normalized to take into account diurnal variations in the number of 1:15 min recordings at Halley. However, this leads to small changes in the shape of the distribution. As can be seen from Figure 3a, the diurnal occurrence of MLR observed at Halley is twin-peaked, with quite well-defined maxima at ~0600 UT and ~1900 UT. Local time (LT) at Halley station is ~2 hours behind universal time (UT), so the peaks lie at ~0400 and ~1700 LT. At Halley magnetic LT (MLT) is ~3 hours behind UT.

The diurnal variation in MLR occurrence at Halley as a proportion of the overall Halley background wave activity is shown in Figure 3b. In Figure 3b, 2-hour bins have been used to

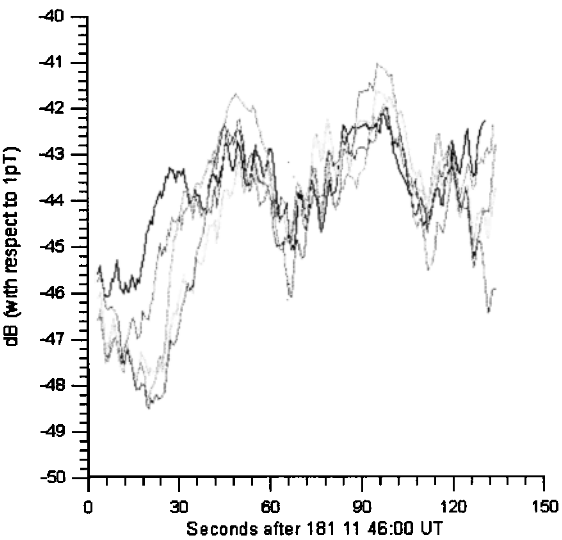

Figure 2. The power spectral density of five selected MLR lines present in the frequency spectra shown in Figure 1. These lines lie in the range 3525 to 3800 Hz, and climb out of the noise at a rate similar to other MLR events we have examined. A seven second running mean is used to suppress statistical noise.

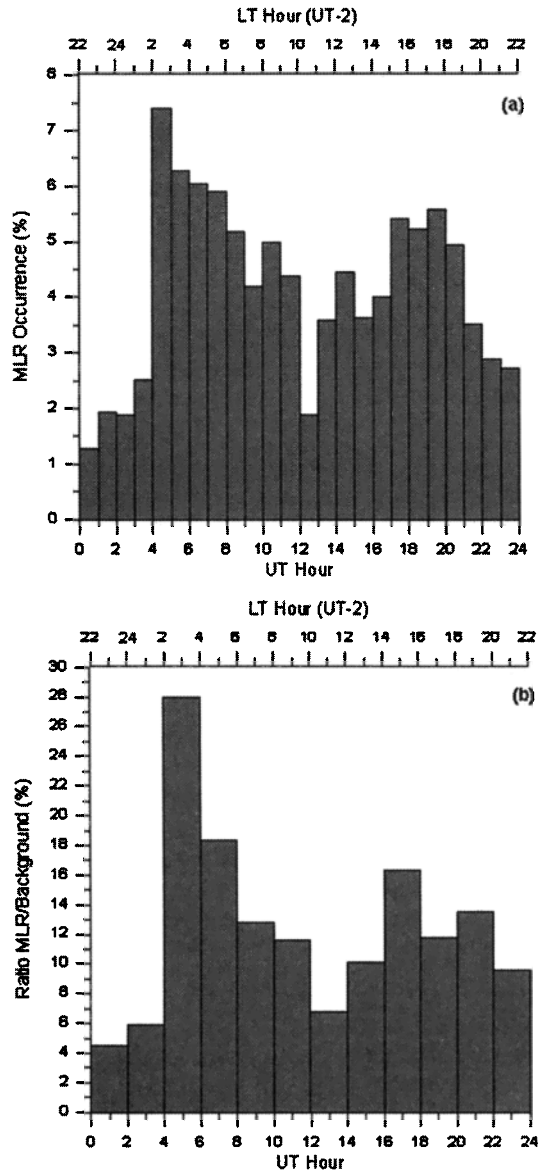

Figure 3. The diurnal variation in MLR occurrence at Halley by UT hour (a) normalized by the number of VLF recordings that were searched for MLR activity. (b) MLR activity present as a proportion of the overall Halley wave activity.

decrease the statistical noise and emphasize the form of the distribution. The background activity level was determined using the MLRSCAN data, examining the first minute of every fifth hour of the four months in question for continuous wave activity (e.g., hiss, chorus) anywhere in the frequency range 1.5 to 5 kHz. This produced 591 samples over the 4-month period with a uniform distribution in LT. Figure 3b shows a similar twin peaked distribution to Figure 3a because of the relatively constant level of background activity present throughout the day.

3.3. Seasonal Variation in MLR Occurrence

An examination of the 4-month data set indicates that the MLR occurrence rate can vary greatly. Figure 4 shows the MLR occurrence rate over the 11,448 min of 1:15 min recordings examined using MLRSCAN. The highest occurrence rate over a third of a month period was ~8% (June), while the lowest is 0.3% (December). It is, interesting to note that MLR occurrence was low in the first two thirds of July, before returning to rates comparable with those of June. As reported previously, MLR cannot be described as "rare" at Halley [*Rodger et al.*, 1999]. Note that the occurrence rates given in Figure 4 represent the minimum for MLR activity at Halley. *Rodger et al.* [1999] found that the MLR lines visible in this data set have amplitudes extending down to the system noise, and thus we have yet to establish the upper bound for occurrence rates.

In order to appreciate the significance of the MLR occurrence rates, we made use of the background activity survey discussed in section 3.2. As expected, background activity levels were found to be highest in June/July and lowest in December, probably because of reduced levels of transionospheric absorption of the waves during periods of darkness [*Helliwell*, 1965]. The form of Figure 4 and the seasonal occurrence of background activity is reasonably similar, confirming that MLR is strongly associated with general wave activity. The proportion of MLR present as part of the overall Halley wave activity is roughly constant throughout the year, as shown in Figure 5. When wave activity is observed at Halley, ~10-13% of the time there will be MLR activity observable in the VLF wideband data.

3.4. Dependence Upon Geomagnetic Activity

The occurrence of MLR activity as a function of the 3-hourly planetary magnetic disturbance index *Kp* is shown in Figure 6 along with MLR occurrence against the maximum value of *Kp* in the preceding 24 hours (Figure 6b) and 48 hours (Figure 6c). As *Kp* is a 3-hourly index the definition of a MLR event has been altered to prevent sampling bias. For comparison with geomagnetic activity an MLR event is defined as MLR being present during at least one of the minute-long observations made over the 3-hour period for which a *Kp* value is given. There are 193 MLR events present over 958 observation periods with a given value of *Kp*. This is the same definition of an MLR event used by *Park and Helliwell* [1978] for the purposes of investigating the dependence on *Kp*. The form of Figures 6a and

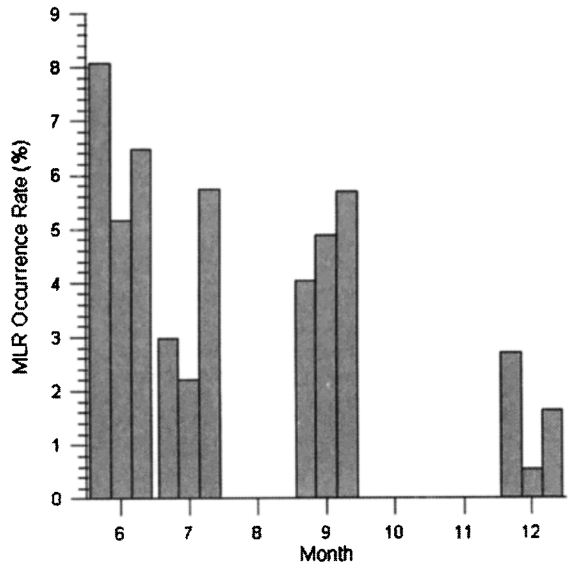

Figure 4. Monthly variation in the MLR occurrence rate. The data for each third of a month have been averaged. No data were analyzed for August, October, and November.

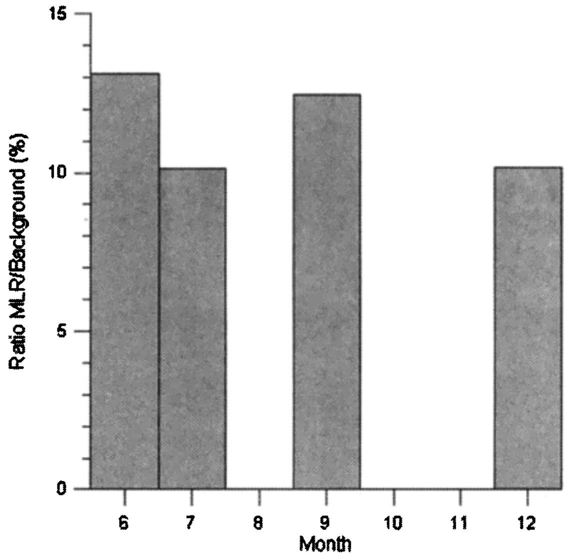

Figure 5. Monthly variation in the occurrence of MLR activity as a proportion of the overall Halley wave activity.

6b is very similar to Figure 5 of *Park and Helliwell* [1978], although our study appears to include nearly 2.5 times more events. These authors concluded that their PLR events tended to occur at geomagnetically quiet times immediately following disturbances and that relatively small substorms (*Kp* of 1 to 2) were as important for PLR occurrence as more severe storms. This appeared to confirm an earlier case study which reported that PLR events (which appears to be generally taken to be MLR activity) were the most intense magnetospheric waves observed at Eights, Antarctica (75°S, 77°W), in the recovery phase from a major magnetic storm [*Park*, 1977].

However, in order to make such conclusions it is necessary to compare the geomagnetic activity at times when MLR is present with the overall activity levels when recordings were made to check if any differences are significant. This normalization process was not undertaken by *Park and Helliwell* [1978]. The variation in MLR occurrence as a function of geomagnetic activity, normalized to the geomagnetic activity distribution of all the observation periods is shown in Figure 7, for the 3-hourly planetary disturbance indices *Kp* (Figure 7a) and also against the maximum value of *Kp* for the preceding 24 hours (Figure 7b) and 48 hours (Figure 7c). In Figure 7 it appears that the normalized MLR occurrence rate for low-moderate *Kp* is essentially constant, while there is a large peak for *Kp* values in the range 6^+ to 7. The form of these plots will be discussed further in section 4.4.

4. Discussion

4.1. High-Frequency Resolution: Case Studies

The MLR lines present in the higher-frequency resolution translated frequency data are quite distinct from the tram-line events of *Rodger et al.* [1995], or induction lines known to be produced by direct pick-up from electrical transmission systems and industry. The multiple-line features seen in Figure 1 are more like a natural, magnetospheric VLF emission than something man-made. One might conclude that the frequency spacing of the MLR lines present in the high-resolution data lends support to the conclusion that MLR lines are not linked to known power transmission frequencies and hence that MLR is probably not produced by PLHR [*Rodger et al.*, 1999]. However, some care must be taken with this interpretation, as the additional line structure might be produced through the generation of sidebands. Sidebands can be generated by nonlinear interactions and have been observed with separations up to 100 Hz and amplitudes sometimes greater than the parent wave [*Park*, 1981]. *Yearby* [1982] noted an example at Halley of sidebands ~15 and 30 Hz above a constant frequency pulse (3750 Hz) transmitted by the Siple VLF transmitter.

In section 3.1, we reported that the rate at which MLR lines appear out of the noise is ~0.1 to 0.2 dB s^{-1}. These growth rates are considerably smaller than those previously reported for other VLF emissions. Artificially stimulated VLF emissions (generally risers and fallers) triggered by pulses from VLF transmitters have been observed to grow exponentially with time at rates ranging from 25 to 250 dB s^{-1}. Their growth rate varied widely from time to time and tended to saturate [*Stiles and Helliwell*, 1977]. The growth rates of satellite-observed spontaneous natural emissions (i.e., not triggered by another signal) outside the plasmasphere can be considerably higher, ranging from 200 to 2000 dB s^{-1} [*Burtis and Helliwell*, 1975]. It is generally accepted [*Omura et al.*, 1991; *Nunn et al.*, 1998] that these VLF emissions are generated through nonlinear electron cyclotron resonance between energetic electrons with energies of ~keV and narrowband or band-limited VLF wave. A review of attempts to simulate such emissions has been given by *Omura et al.* [1991]. MLR exhibits slow growth, relative frequency stability, and long

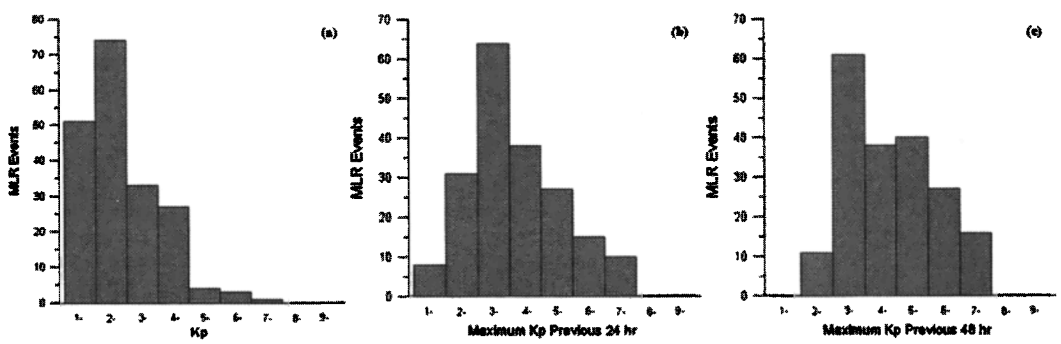

Figure 6. MLR occurrence as a function of geomagnetic activity: (a) the variation in MLR occurrence against the 3-hourly planetary disturbance index *Kp*; (b) the variation in MLR occurrence against the maximum value of *Kp* for the preceding 24 hours; (c) as Figure 6b but for the preceding 48 hours.

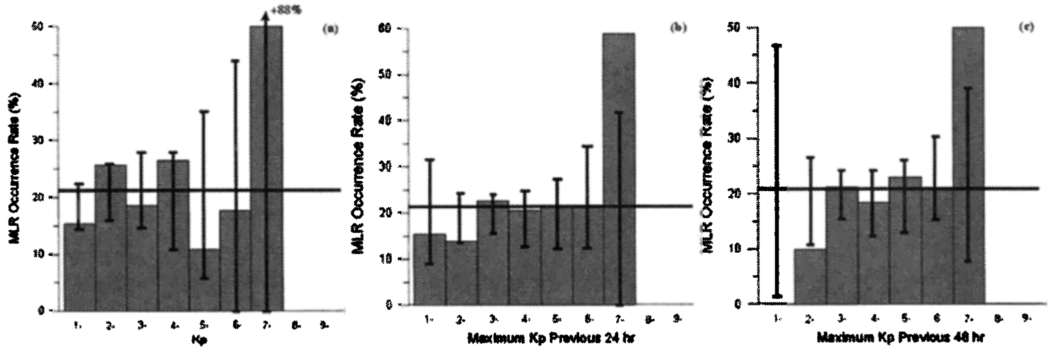

Figure 7. MLR occurrence as a function of geomagnetic activity, normalized to the Kp distribution of all the observation periods. Bars on the figure indicate the 2σ levels (see text): (a) the variation in normalized MLR occurrence against the 3-hourly planetary disturbance indices Kp; (b) the variation in MLR occurrence against the maximum value of Kp for the preceding 24 hours; (c) as Figure 7b but for the preceding 48 hours.

lifetimes in comparison with other coherent whistler-mode emissions [e.g., *Stiles and Helliwell*, 1977, *Smith and Nunn*, 1998], and thus may be generated by a different mechanism. It should be noted that the MLR events for which we have measured risetimes have low frequency drift rates (<20 Hz min^{-1}). It is possible that risetimes for MLR lines which have more significant frequency drifts may be different. The modeling of MLR is worthy of further consideration in light of the findings reported in this paper and by *Rodger et al.* [1999].

4.2. Diurnal Occurrence of MLR

The timing of the twin-peaked distribution of MLR occurrence is consistent with the diurnal variation in maximum VLF emission activity observed at Byrd Station, Antarctica (80°S, 120°W) [*Helliwell*, 1965]. These two peaks were identified as chorus and auroral hiss, respectively. Chorus is aurally perceived as being similar to the "dawn chorus" of birds (see the review by *Sazhin and Hayakawa* [1992]) and is most intense in ground-based observations at ~0600 LT [*Storey*, 1953], while auroral hiss (see the review by *Sazhin et al.* [1992]) is mostly recorded in the evening and night hours [*Harang*, 1968]. However, auroral hiss is likely to be less dominant in our Halley ($L \approx 4.3$) than at the Byrd ($L \approx 7$) and usually does not extend much below 5 kHz. Thus auroral hiss is outside the 0-5 kHz frequency range of our MLRSCAN data. The timing of the double peaks in the MLR occurrence rate probably best correspond to the maxima in the occurrence rate for midlatitude hiss (see the review by *Hayakawa and Sazhin* [1992]), which has its primary maximum at 0500 LT and a secondary peak ~2000 LT [*Hayakawa et al.*, 1975], suggesting that MLR maybe associated with hiss as well as chorus. Ground-based observations indicate that chorus is generally accompanied by hiss emissions [*Helliwell*, 1969], making it difficult to associate one rather than the other (or both) with MLR activity. MLR is least common around local midnight (0200 UT) although background activity is present in similar quantities to daytime, suggesting that MLR may be associated with dayside phenomena.

The diurnal pattern of MLR occurrence rates shown in Figure 3 is rather different from that reported by *Park and Helliwell* [1978]. While these authors reported a sharp increase in MLR activity at 0600 LT, they found no secondary maximum in the evening. *Park and Helliwell* [1978] interpreted the sharp rise in morning MLR as being associated with increased electrical generation and transmission in their generation region, supported by electrical demand data from Hydro Quebec. As the electrical demand remains constant throughout the afternoon and early evening, the authors were forced to speculate that the reason might be associated with the difficulty that energetic electrons (needed for wave-particle interactions) have in gaining access to the afternoon-dusk sector. In this paper, we are not concerned with possible similarities (or otherwise) between the temporal variation of MLR occurrence and electrical load in the industrialised conjugate region (the conjugate of Halley is near Newfoundland, Canada). This will be left for a later work in which we will examine the questions linking MLR with PLHR.

The diurnal MLR occurrence rate shows some seasonal variation, as is shown in Figure 8. As is clear, the ratio of the morning to evening peaks in MLR occurrence changes through the year. In June and July, these two peaks are roughly equal, while in September the evening peak is smaller than the earlier peak in MLR occurrence. By December, only the morning peak is clearly present. The presence of a peak in wave activity in the morning sector due to chorus and hiss, and the lack of any significant wave activity in the afternoon and evening in December is confirmed by summary plots from the VELOX instrument at Halley [*Smith*, 1995]. Thus it is possible that the differences between our study and that of *Park and Helliwell* [1978] might be explainable in terms of the relative weighting of the morning and afternoon-evening peaks in MLR occurrence in summer and winter time. These authors state that the data used in their study is a subset of observations from 1965 (Eights) and from 1973 through 1976 (Siple and Roberval) but do not indicate the distribution of their events throughout the year.

4.3. Seasonal Variation in MLR Occurrence

It has been shown above that the proportion of MLR activity present as part of the overall Halley wave activity is roughly constant (10-13%) throughout the year (section 3.3) and that MLR is associated with chorus and midlatitude hiss (section 4.2). However, section 4.1 has suggested that the growth rates of MLR are quite unlike those of chorus and VLF triggered emissions thought to be generated through gyroresonance wave-particle interactions. These conclusions appear to be contradictory. While a possible answer might be that MLR is only associated with hiss and not chorus, this problem can only be solved by first confirming that the nonlinear and quasi-coherent interactions that are believed to produce chorus and triggered emissions cannot also create MLR under some conditions.

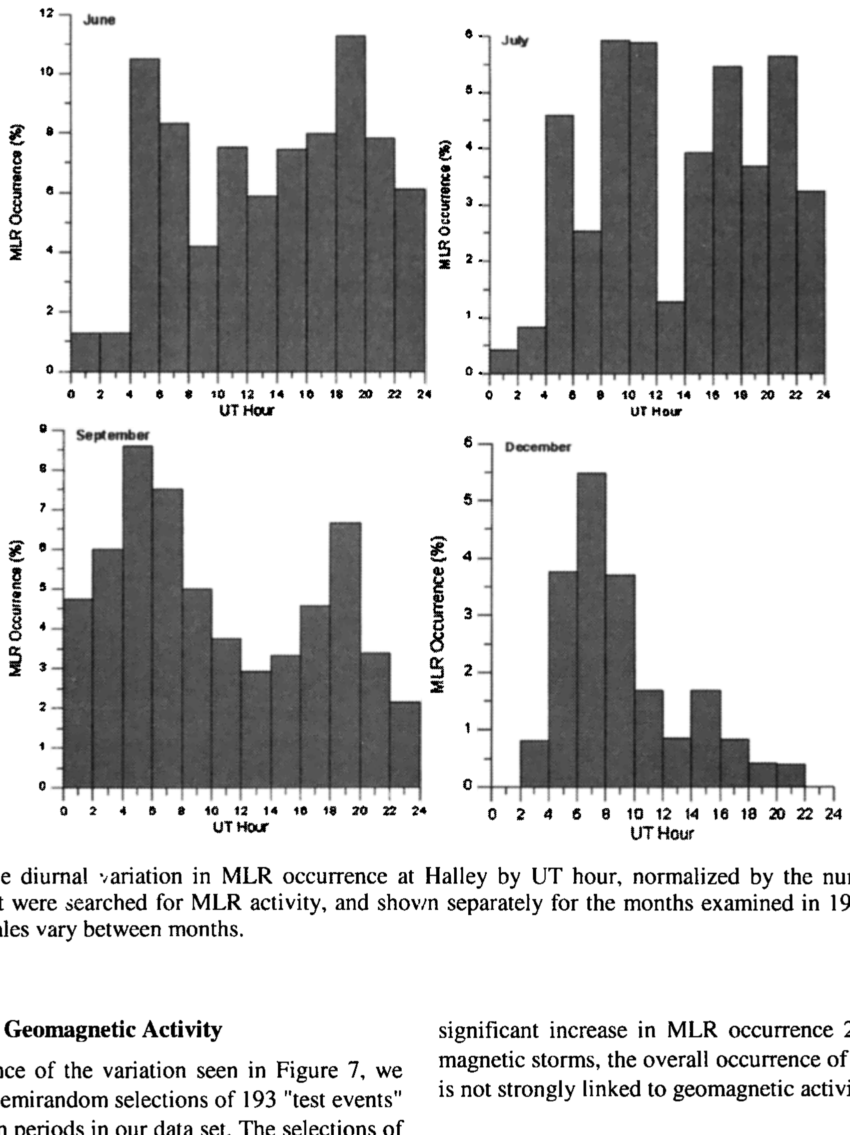

Figure 8. The diurnal variation in MLR occurrence at Halley by UT hour, normalized by the number of VLF recordings that were searched for MLR activity, and shown separately for the months examined in 1995. Note that the vertical scales vary between months.

4.4. Dependence Upon Geomagnetic Activity

To test the significance of the variation seen in Figure 7, we undertook a number of semirandom selections of 193 "test events" from the 958 observation periods in our data set. The selections of test events were biased such that the same number of events were taken from a given month as there were MLR observations. The standard deviation σ and mean of the occurrence rates were then calculated from a comparison set of 2000 semirandom selections of test events. A variation in the normalized MLR occurrence rates was judged significant if it lay more than 2σ from the mean. It was found that none of the differences from the ~20% occurrence level shown in Figure 7a are significant; the large peak around $Kp = 7^-$ is probably due to the high statistical noise produced by the low number of MLR events in this range. While, of course, there could indeed be a peak in the normalized MLR occurrence in these data, it is too small to be observed in our data set. However, the variation in Figures 7b and 7c does appear to be significant. In Figure 7b the normalized MLR occurrence rate around $Kp = 7^-$ is more than 2σ from the mean of the 2000 comparison selections. This is also true for Figure 7c in addition to the rates around $Kp = 1^-$ and $Kp = 2^-$ being smaller than one would expect.

It appears that the occurrence of MLR activity at Halley is linked to geomagnetic activity, but only after very large storms ($Kp > 6$). However, this only affects a small number of the total MLR events in our study (~8%). In addition, MLR events tend not to occur when the geomagnetic activity has been quiet in the previous 48 hours. While there does appear to be a statistically significant increase in MLR occurrence 24-48 hours after large magnetic storms, the overall occurrence of MLR activity at Halley is not strongly linked to geomagnetic activity.

4.5. Typical Duration of MLR Events

Owing to the noncontinuous nature of our observations at Halley, it is difficult to estimate the typical duration of MLR events directly from the data. However, by making use of our 1:15 min and 1:3 hour data sets, we can calculate such an estimate. As noted at the end of section 2, there were 477 MLR events in the data set containing only 1:15 min recordings, and 193 MLR events present when looking for any 1 min worth of MLR activity over any 3-hour period (section 3.4). The ratio of these data sets suggests that the average duration of a typical MLR event is ~30 min. This is reasonably similar to average durations previously reported; this was found to be ~20 min for Halley MLR events in 1978, and ~50 min for Siple in 1977 [*Yearby*, 1982].

5. Conclusions

Observations of MLR activity in data collected from Halley, Antarctica, during June, July, September, and December 1995 lead us to the following conclusions:

1. Case studies of MLR events examined at high-frequency resolution indicate that single lines seen in the 0-5 kHz spectra tend be made up of multiple (2-3) lines with widths of 5-10 Hz with smaller spacings (as small as <10 Hz). The multiple lines

show highly variable spacings (e.g., < 10 to ~100 Hz). At the higher-frequency resolutions possible with the translated frequency data, variability can be seen in some MLR lines which appeared to be stable in the lower resolution spectra. This is not due to variations in the recording or playback speed. These multiple-line features appear to lend support to the conclusion that MLR lines are probably not produced by PLHR [*Rodger et al.*, 1999].

2. The rate at which MLR lines climb out of the noise is ~0.1 to 0.2 dB s^{-1}. These growth rates are considerably smaller than those previously reported for other VLF emissions (which range from 25 to 2000 dB s^{-1}). MLR exhibits slow growth, relative frequency stability, and long lifetimes in comparison with other coherent whistler-mode emissions and thus may be generated by a different mechanism.

3. The diurnal occurrence of MLR observed at Halley is twin-peaked, with maxima at ~0600 UT (0400 LT) and ~1900 UT (1700 LT). The diurnal variation in MLR occurrence as a proportion of the overall background wave active at Halley shows a similar twin-peaked distribution. The morning peak in diurnal occurrence is probably due to an association with a combination of chorus and midlatitude hiss, while the later peak is probably due to midlatitude hiss only. The diurnal MLR occurrence rate shows some seasonal variation. The ratio of the morning to evening peaks in MLR occurrence changes through the year in a manner consistent with the seasonal pattern in overall wave activity.

4. MLR occurrence rates can vary greatly within a given month. The highest occurrence rate over a third of a month period was ~8% (June), while the lowest is 0.3% (December). However, the proportion of MLR present as part of the overall Halley wave activity is roughly constant throughout the year. When wave activity is observed at Halley in the VLF wideband data, there will be MLR activity observable ~10-13% of the time.

5. The occurrence of MLR activity at Halley is linked to geomagnetic activity but predominantly 24-48 hours after very large storms ($Kp > 6$), which affects only 8% of the total MLR events in this study. For smaller storms, there is little effect, although MLR events tend not to occur when the geomagnetic activity has been quiet in the previous 48 hours. There is no dependence of MLR occurrence rates upon the instantaneous levels of geomagnetic activity.

6. The average duration of a typical MLR event at Halley is ~30 min, quite similar to previous reports.

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