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# Sunday Decreases in Magnetospheric VLF Wave Activity

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Magnetospheric wave intensity in the 2- to 4-kHz range was monitored on the ground at Siple, Antarctica, in 1974 and 1975. Sampled broadband spectral data show that the wave activity in the 2- to 4-kHz band is predominantly chorus (discrete narrow band emissions). The measured wave intensity shows a distinct minimum on Sunday in comparison with the rest of the week. The Sunday minimum is confined to the dawn-afternoon local time sector where the chorus intensity has a diurnal maximum. It is suggested that much of the chorus observed at Siple is triggered in the magnetosphere by power line radiation from its conjugate region in eastern Canada and that the Sunday minimum in magnetospheric wave activity is the result of reduced power consumption on Sunday. This interpretation is supported by the results of an independent study based on broadband spectral data from Siple between 1973 and 1975. The results show weekly variations in the occurrence of strong power-line-induced emissions with a pronounced minimum on Sunday. This pattern is similar to the power consumption pattern in Quebec. It appears that power line radiation is an important factor in the overall magnetospheric wave environment. Its role in particle precipitation (through wave-particle interaction) needs to be investigated.

## INTRODUCTION

A number of recent papers have discussed the role of power line radiation (PLR) in triggering very low frequency (VLF) emissions in the magnetosphere. Under favorable conditions, PLR waves are greatly amplified and trigger emissions that may be entrained by the triggering PLR wave or break away from the triggering frequency if the emission becomes sufficiently strong. Amplified PLR and associated emissions often completely dominate the spectrum in a range of a few kilohertz [*Helliwell et al.*, 1975; *Park*, 1977]. The wave growth and triggering are generally thought to take place near the equatorial plane through cyclotron resonance interaction with energetic electrons, but the detailed mechanism is poorly understood at present.

PLR-induced emissions may be divided into two categories. In the first category, amplified PLR and emissions entrained at power line harmonic frequencies are clearly detectable on spectrographic records before free-running emissions develop. Emissions in this category occur when growth rates are relatively small (~100 dB/s or less), as is usually the case inside the plasmapause [*Stiles and Helliwell*, 1977]. Spectral characteristics as well as some limited statistics of these emissions have been reported by *Helliwell et al.* [1975], *Park* [1977], and *Park and Helliwell* [1978].

The second category is associated with large growth rates (~200 dB/s or more) that are typical of the region outside the plasmapause [*Burtis and Helliwell*, 1975]. In this category, free-running emissions develop rapidly, and there is no clear evidence of triggering waves.

Thus the association of these emissions with PLR must be based on indirect evidence. One piece of evidence comes from the work of *Luette et al.* [1977], who showed that VLF chorus observed on the Ogo 3 satellite has maximum probability of occurrence in certain longitude sectors where PLR intensity is expected to be high. Subsequent work showed that about 15% of the chorus emissions observed during selected Ogo 3 passes had well-defined starting frequencies and that the measured starting frequencies were within a few hertz of power line harmonics [*Luette et al.*, 1979]. A low-altitude satellite survey by *Bullough et al.* [1976] revealed a permanent zone of enhanced VLF activity over North America, which the authors attributed in part to PLR-induced emissions. However, it was not possible in this case to distinguish chorus from other forms of wave activity owing to a lack of spectral information.

In this paper we describe some preliminary results of a statistical study aimed at further clarifying the effect of PLR on VLF wave activity in the magnetosphere. A question of particular interest is whether PLR is a significant factor in overall VLF wave activity at middle latitudes. The data used in this study come from Siple, Antarctica (76°S, 84°W; $L \simeq 4$), which is conjugate to a strong PLR source region in Quebec [*Helliwell et al.*, 1975]. The next section gives a detailed description of the data base, followed by statistical analyses and interpretation in subsequent sections.

## DATA BASE

The data used in this study are based on continuous measurements of VLF wave amplitude at Siple. The measurement apparatus consists of a calibrated broadband receiver, a 2- to 4-kHz band-pass filter, and an amplitude detector which has a rise time of ~1 s and a fall time of ~0.1 s. The relatively long rise time of the detector effectively discriminates against sferics and other impulsive events such as individual whistlers and emissions lasting for 1 s or less. The detected signal is recorded continuously on a strip chart recorder. A typical example of the strip chart record is shown at the top of Figure 1.

For the purpose of this study the chart records of VLF amplitude were scaled each UT hour. In scaling the data, visual averaging was done to seek the center of mass of the trace within ±1 min of each hour. The hourly amplitude values thus obtained form the data base for the statistical analysis in the next section. Before discussing the statistical results, however, we will first examine the spectral character of the waves involved.

The three lower panels in Figure 1 show frequency-time spectrograms of broadband data, sampled for 1 min every 5 min. Six selected segments, each 1 min long, are labeled A–F. The arrows in the top panel indicate the starting times of the corresponding sample spectrograms. These six sample spectrograms are shown again in Figure 2 in expanded scales. Panel A shows that the dominant wave energy in the 2- to 4-kHz band is in the form of hiss. Panel B shows mostly hiss but also some echoing whistlers. Note that the hiss in this case shows horizontal striations resembling the PLR-induced emissions discussed in earlier papers (for example, see Figure 5 of *Park* [1977]). In this case, however, the line emissions are not suf-

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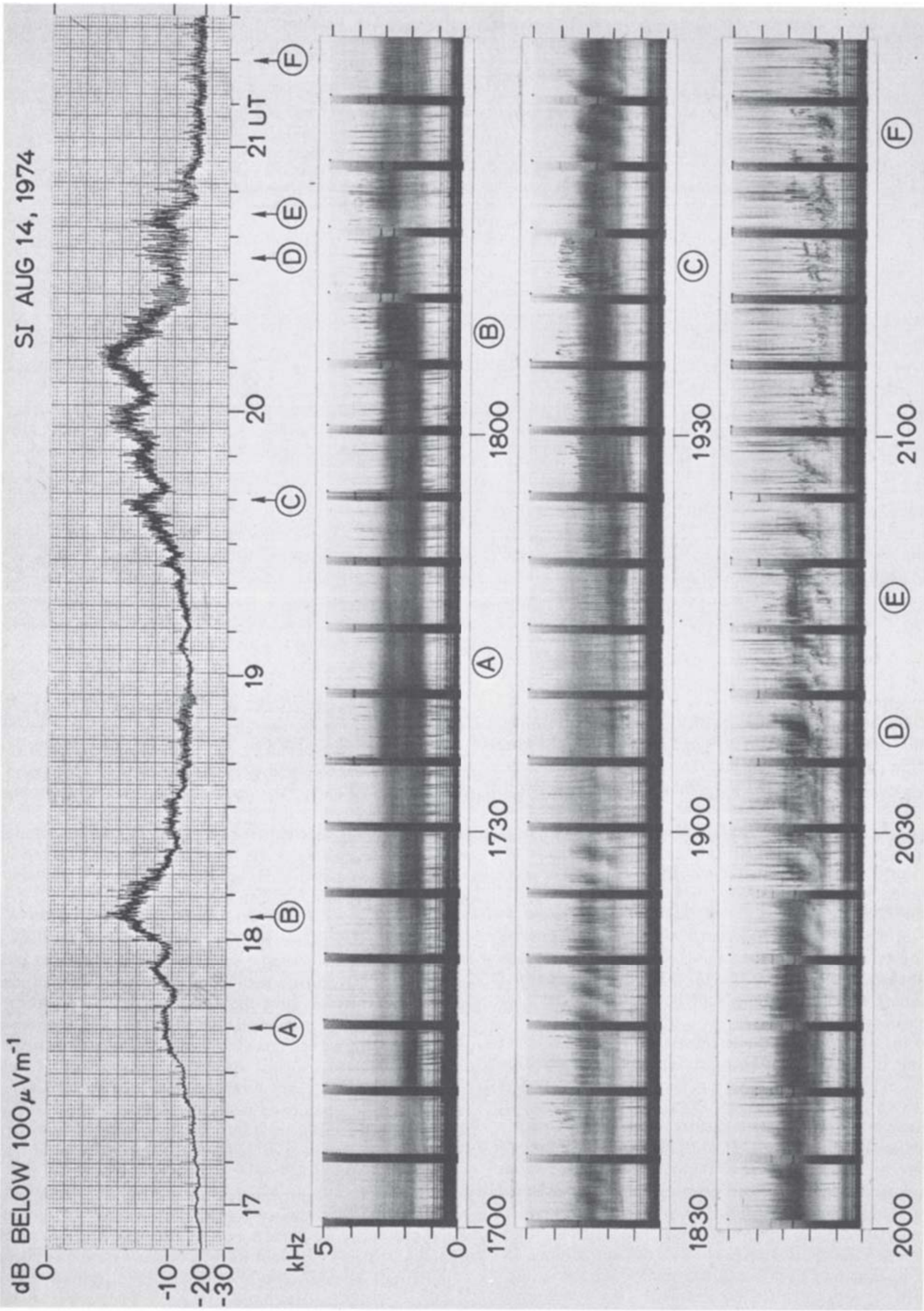

Fig. 1. (Top) A segment of VLF amplitude chart recording for 2- to 4-kHz band. (Bottom) Frequency-time spectrograms of VLF data sampled for 1 min every 5 min.

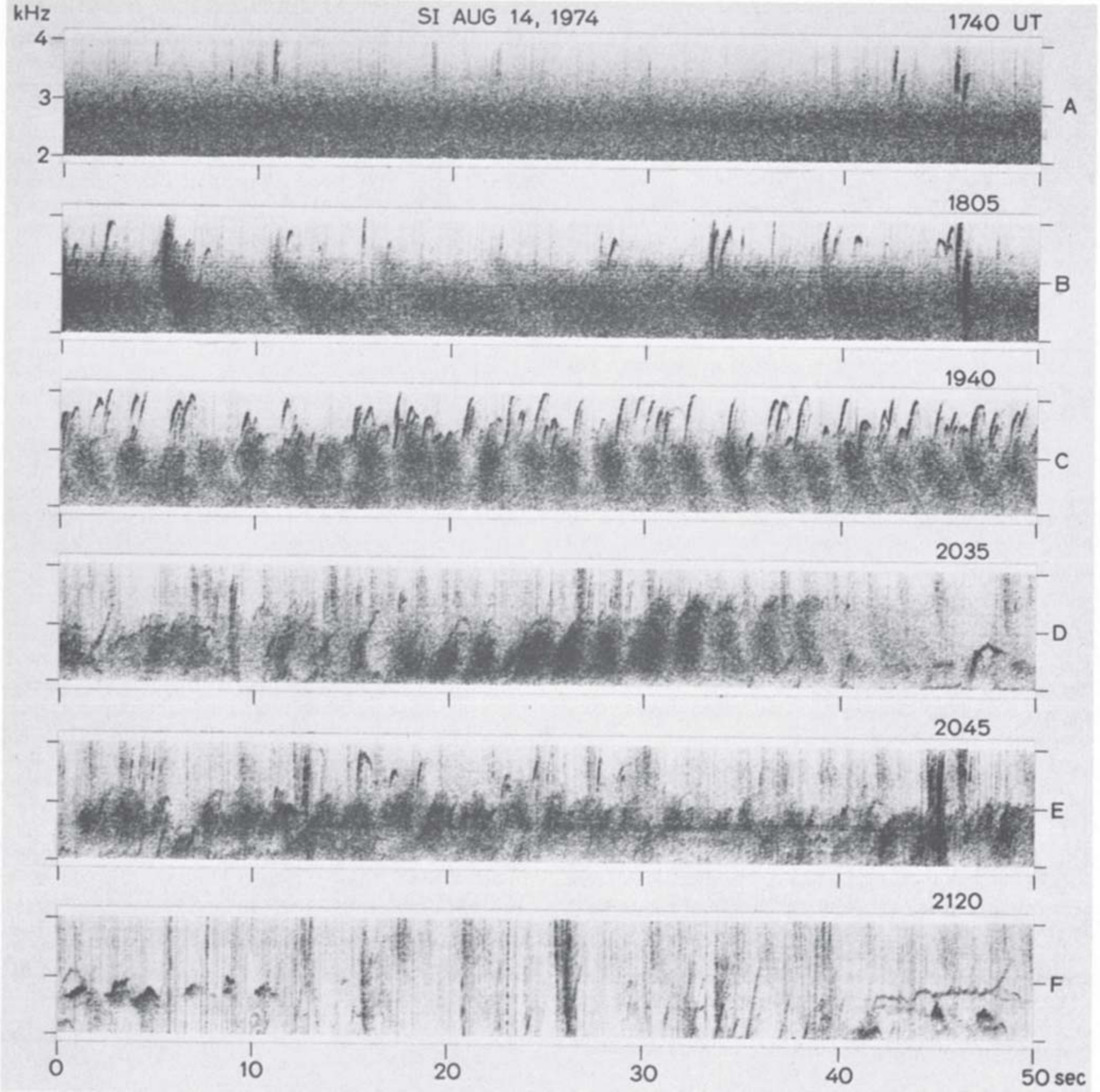

Fig. 2. Selected portions of the spectrograms in Figure 1 in expanded scales.

ficiently well defined to allow accurate measurements of their frequencies.

In panels C–F, chorus clearly dominates the spectra. Panel C shows two distinct types of chorus: discrete rising tone emissions above ~3 kHz and rather diffuse blobs below ~3 kHz. In panel E, two horizontal lines appear with 60-Hz spacing near 30 s. These line emissions could have been stimulated by power line harmonics. For the purpose of this paper, however, we do not attempt to determine whether individual emissions are triggered by power lines.

It is clear in Figures 1 and 2 that most of the amplitude enhancements in the 2- to 4-kHz band are due to chorus: hiss plays only a secondary role. The example shown here is typical of all the data used in our study.

The period of data coverage extends from March 3 to November 18, 1974, and from March 7 to December 3, 1975. Austral summer data are not included in this study because of interference from a noisy generator that was frequently pressed into service to support increased station activity. The data consist of 12,726 hourly values of wave amplitude obtained in the manner described above. Their amplitude distribution is shown in Figure 3 in a normalized form. Approximately 3% of the total data fall beyond the 50 $\mu$V/m limit in the figure. Chorus tends to occur in bursts that typically last for a few hours, and the peak amplitude may reach 100 $\mu$V/m or more on rare occasions.

In the next section we analyze the variations of VLF wave amplitude with the day of the week. We stress that the data collection system operated continuously 7 days a week and introduced no sampling bias in the data set.

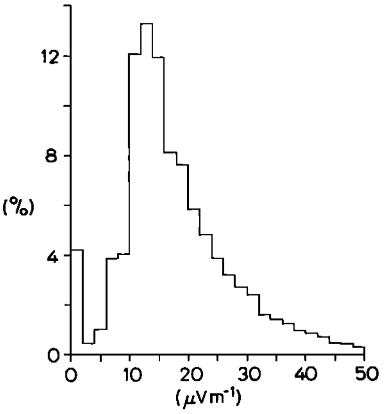

Fig. 3. Histogram of hourly VLF wave amplitude data used in this study.

## THE SUNDAY EFFECT

Figure 4 shows diurnal variations of VLF wave amplitude for Sunday (squares) and for Monday through Saturday. The Monday–Saturday data show large enhancements between 06 and 13 Magnetic Local Time (MLT). The Sunday data also show an increasing trend at 06 MLT, but the amplitude remains ~10–25% below the other days' values until 14 MLT. The statistical significance of this Sunday decrease can be judged qualitatively from the length of the vertical bars, which indicate ±1 standard error of the mean.

For a more quantitative analysis, we apply a standard statistical test of significance using the standardized variable, or $z$ score, given by [e.g., *Spiegel*, 1961]

$$z = \frac{M_1 - M_2}{\sigma} = \frac{M_1 - M_2}{(\sigma_1^2/N_1 + \sigma_1^2/N_2)^{1/2}} \tag{1}$$

$M$, $N$, and $\sigma$ are the mean, number of samples, and standard deviation, respectively, while the subscripts 1 and 2 refer to the two different data sets being compared. The absolute values of the computed $z$ scores are plotted at the top of Figure 4. On the right-hand side are shown 70, 90, and 99% confidence levels with which the difference between the two sets can be accepted as being statistically significant. The confidence level is $\gtrsim$90% between 07 and 14 MLT. The consistency in the trend for many hours, of course, gives us more confidence in its statistical significance than is indicated by individual $z$ scores.

The same analysis that we applied in Figure 4 has also been applied to the other days of the week, and the results are shown in Figure 5. In each plot we use squares and vertical bars to show the means and standard errors, respectively, for the selected day of the week. For comparison we also show the behavior during the rest of the week (ROW). Standard errors associated with the ROW curves are not shown in the plots, but they are generally a factor of ~2–3 smaller than the error bars for individual days. (Compare the Sunday error bars with the ROW error bars in Figure 4.) It appears that with the exception of Sunday the other 6 days of the week are not significantly different from one another. (A question may be raised regarding the significance of enhanced amplitudes on Friday at 13, 14, 16, 17, and 18 UT. The $z$ scores indicate confidence levels of only ~53–88%. On the basis of the $z$ scores as well as the results of further analyses discussed below, we do not believe that the Friday enhancements are significant.)

We now examine the Sunday behavior in more detail by dividing the data set into two subsets according to the 3-hour $Kp$ value and comparing Sunday with ROW within each subset. Figure 6*a* shows the results for the subset with $Kp > 2$ (63% of all data), and Figure 6*b* for the complementary subset with $Kp \leq 2$. The difference between the two subsets is immediately clear. Large amplitude enhancements in the dawn-afternoon hours appear only in the $Kp > 2$ case. This is consistent with earlier results showing enhanced chorus activity in that local time sector during substorms [*Burtis*, 1974; *Thorne et al.*, 1977]. The Sunday effect shows much more clearly when $Kp > 2$. In the $Kp \leq 2$ case the Sunday data are rather noisy and do not show any significant decrease compared to the ROW curve.

In view of the $Kp$ dependence of VLF wave amplitude just discussed, we may ask how $Kp$ varies with the day of the week and if such variations can explain the observed Sunday effect. To answer these questions, we have examined the statistics of $Kp$ during the period of our VLF data coverage and found no significant difference between Sunday and the other days of the week. For example, between 12 and 18 UT, when the Sunday effect in VLF wave amplitude is most pronounced, the difference in the average $Kp$ value between Sunday and the rest of the week is only about 1.3%, and the corresponding $z$ score given by (1) is less than 0.2. The 1.3% decrease on Sunday can be accepted as statistically significant at a confidence level of about 16%. Thus we conclude that the Sunday decrease in VLF amplitude cannot be explained in terms of $Kp$ dependence. We must seek another explanation.

Another interesting feature in Figure 6 is that the average nighttime (21–09 UT) wave amplitude in Figure 6*a* is about 15% less than that in Figure 6*b*. This could be attributed to increased ionospheric absorption during more disturbed times.

In any statistical study of real geophysical data, one cannot rely totally on standard textbook formulas of statistical decision theory. Therefore as a means of further testing the Sunday effect, we have divided the data in Figure 6*a* into still smaller subsets to see if the same trend still persists. In Figure 7 the data have been divided into austral winter (May 1 to August 10) and equinox periods (February 11 to April 31 and August 11 to October 31). Figure 8 shows 1974 and 1975 separately. In each case the Sunday values between 11 and 18 UT tend to be consistently lower than the corresponding ROW values, although the statistics are somewhat noisy as a result of decreased sample sizes. (There are only about 20 Sundays in each

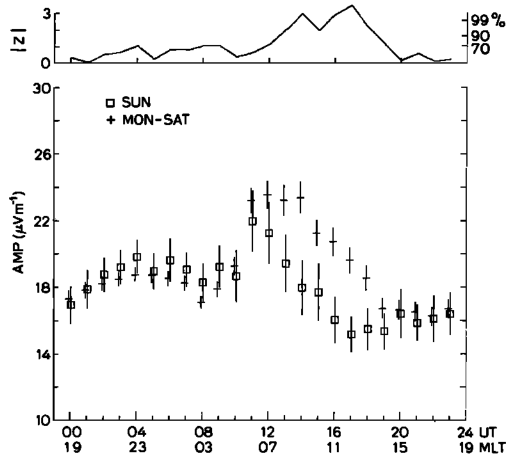

Fig. 4. Daily variations of 2- to 4-kHz wave amplitude showing differences between Sunday and Monday–Saturday. The vertical bars indicate ±1 standard error of the mean. The curve at the top shows the magnitude of the $z$ score, which is related to the confidence level of statistical significance.

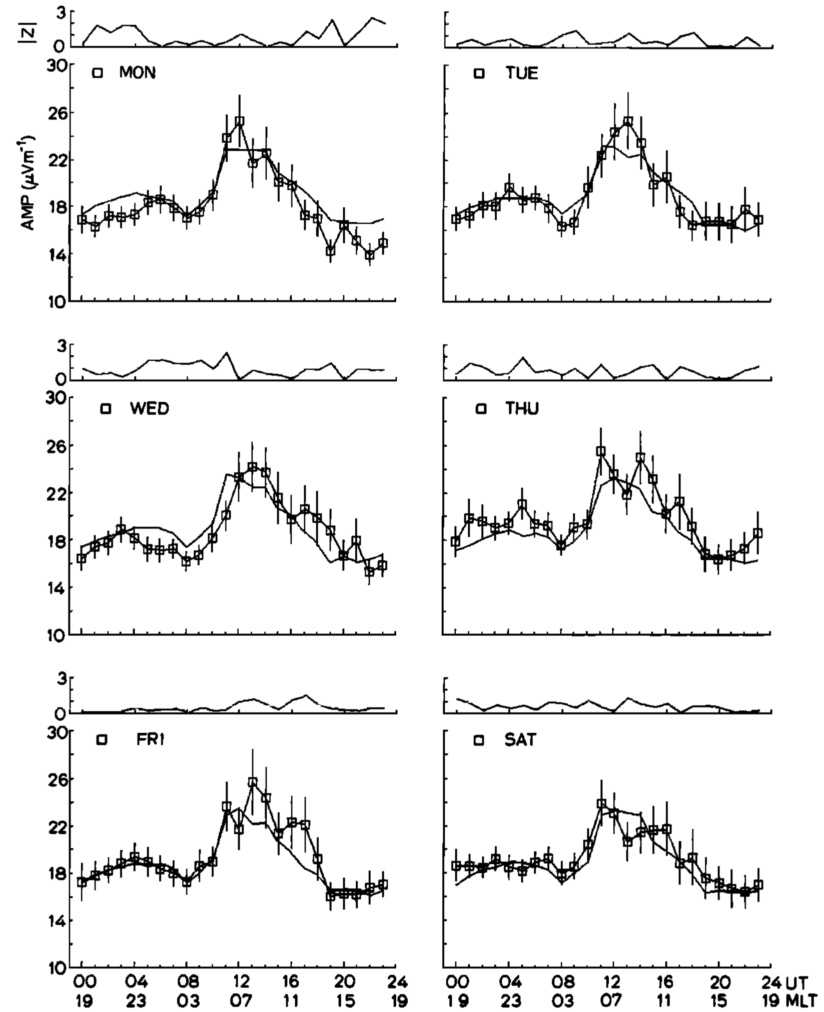

Fig. 5. VLF amplitudes for each day of the week are compared with those for the rest of the week. The format is similar to that of Figure 4.

plot.) Similar results are obtained if the data are divided according to arbitrary criteria such as whether the day number is odd or even. Thus it seems highly unlikely that the Sunday effect is merely due to statistical fluctuations.

A reference was made earlier to the possible significance of the Friday enhancements in Figure 4. If we analyze the Friday data in the same way as the Sunday data, we find that the Friday enhancements do not appear consistently in all subsets of data. In fact, the cause of the Friday enhancements can be traced to intense wave events (up to 100 μV/m) during a few magnetic storms.

As a further comment, it is possible for a few exceptionally intense events to increase significantly the average wave intensity, as was apparently the case for Friday. However, it is clear from the histogram in Figure 3 that a few low values cannot significantly decrease the average amplitude on Sunday.

## RELATIONSHIPS WITH POWER LINE RADIATION

The Sunday effect described above is most likely to be related to human activity. Power line radiation (PLR) appears to be a likely cause, since it is known to trigger strong VLF emissions in the magnetosphere. The ability of PLR to trigger chorus emissions undoubtedly depends on its intensity, although there are other important factors such as the distribution function of energetic electrons that supply the needed

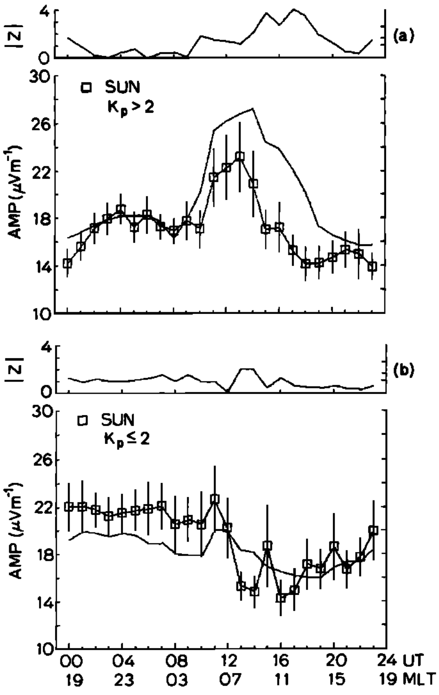

Fig. 6. The data in Figure 4 are divided into two groups according to the *Kp* index: (*a*) $Kp > 2$, and (*b*) $Kp \leq 2$.

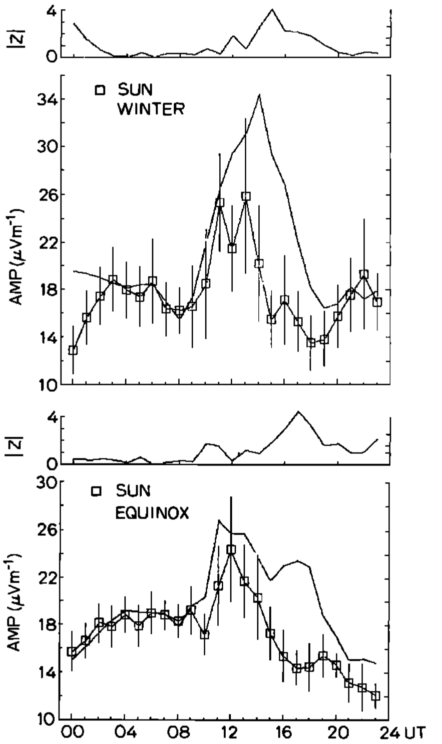

Fig. 7. The data in Figure 6*a* are divided into austral winter and equinox periods.

energy. Thus we propose a hypothesis that the Sunday decrease in magnetospheric wave amplitude is due to reduced electrical power consumption in the PLR source region of eastern Canada. It is clear from Figure 6 that substorm injection of energetic electrons is essential for strong chorus generation. Our hypothesis implies that in addition to these substorm-injected electrons, input waves such as PLR are needed to trigger the emissions. (In the absence of any triggering waves, particle flux could conceivably build up to a level where spontaneous emissions can be generated.) This idea is consistent with experimental evidence that whistlers and transmitter signals can often trigger emissions when no spontaneous emissions are being generated in the magnetosphere [*Storey*, 1953; *Helliwell*, 1965; *Helliwell and Katsufrakis*, 1974].

In order to test the above hypothesis we need to examine the statistics of PLR-induced emissions. Some statistics have been summarized in an earlier article by *Park and Helliwell* [1978]. It was reported that the frequency distribution of PLR emission peaks between 3 and 3.5 kHz, near the center of the 2- to 4-kHz band we are concerned with in this paper. The same article also showed diurnal variations of PLR activity that are similar to the diurnal variations of VLF amplitude shown in the previous section. These similarities would suggest that PLR activity may be an important part of the total VLF wave amplitude in the 2- to 4-kHz range. More will be said about this later. In the meantime, we turn to the question of weekly variation of PLR activity.

We have surveyed spectrograms of tape-recorded data from Siple during the period 1973–1975 to identify PLR-induced emissions. (The tape recorder was programed to record the data during preselected time intervals, typically 1 min every 15 min, irrespective of the day of the week.) It must be stressed at the outset that such identification is necessarily subjective, because in many cases, triggering PLR waves are not sufficiently strong or well defined to allow positive identification. We have already seen two such examples in Figure 2 (panels B and E). For the purpose of this study we adopted fairly conservative criteria so that only exceptionally clear and intense PLR events would be classified as such. Accordingly, the two somewhat questionable examples in Figure 2 were not accepted as PLR-induced emissions. Figure 9 shows two examples we did accept. Other clear examples illustrating different spectral forms of PLR-induced emissions can be found in the work of *Helliwell et al.* [1975] and *Park* [1977].

Out of a total of 255 days surveyed, 44 days showed clear PLR events. Figure 10 (top) shows the distribution of these PLR days as a function of the day of the week. The ordinate is the number of PLR days divided by the number of days surveyed. The weekly cycle from Sunday to Saturday is repeated in order to show the pattern more clearly. For comparison, Figure 10 (bottom) shows the weekly variation of peak load on Hydro-Quebec, the supplier of about 75% of electricity used in the province of Quebec (L. Dubuc, private communication, 1978). Correlation between power consumption and PLR activity is quite clear.

As was noted earlier, it was necessary to establish some arbitrary criteria for judging PLR-like activity on spectrographic records. Nevertheless, we believe that the weekly variations in Figure 10 (top) reflect real variations in PLR activity level, since the same criteria were applied uniformly throughout the entire survey. On the other hand, it is difficult to interpret the absolute value of the normalized occurrence rates. Figure 10 (top) represents only the most intense and clear PLR events. Furthermore, a day was counted as a PLR day if PLR activity was observed sometime during the day regardless of its duration and regardless of what fraction of that day's data was sampled. For these reasons, Figure 10 (top) should not be interpreted in terms of the probability of observing PLR activity at a given time.

The above discussion naturally leads us to the question of what fraction of all chorus is triggered by power lines. This is an important question but also a difficult one to answer. The

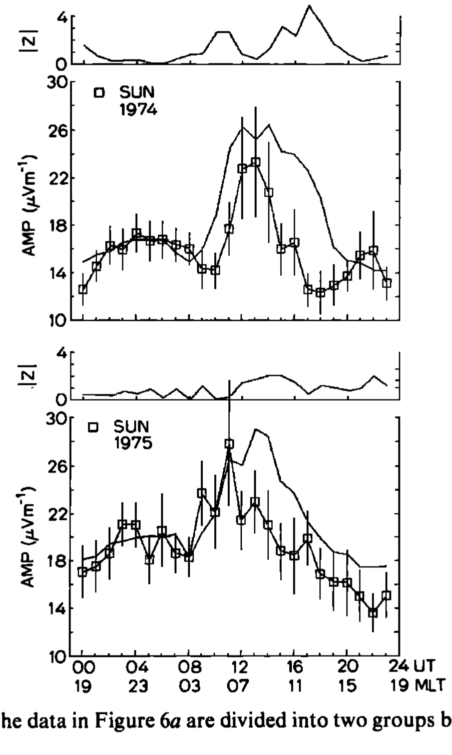

Fig. 8. The data in Figure 6*a* are divided into two groups by the year.

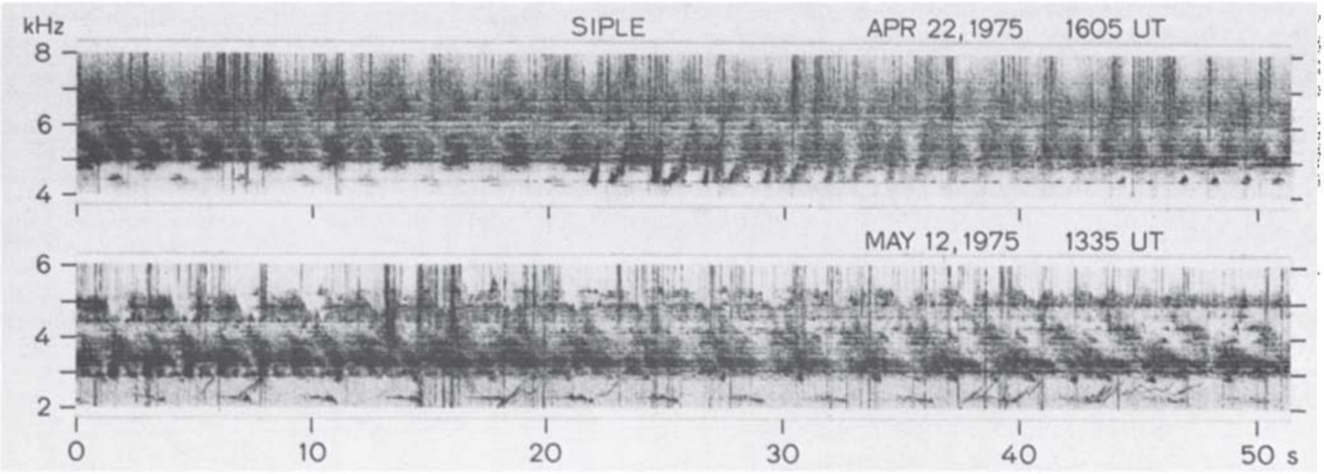

Fig. 9. Examples of magnetospheric emissions stimulated by power line radiation.

difficulty lies in detecting weak triggering signals, which can be 30 dB or more below the triggered chorus intensity. Controlled transmitter experiments at Siple have demonstrated that transmitter signals, too weak to be detected on standard spectrograms, can often trigger strong emissions in an otherwise quiescent magnetosphere [*Helliwell and Katsufrakis*, 1974]. Presumably, weak PLR can do likewise. Thus any study based on visual identification of PLR on spectrograms will underestimate its role in chorus generation. For example, most chorus emissions observed on the Ogo 3 satellite show no evidence of triggering signals and therefore may appear to be spontaneous emissions. However, *Luette et al.* [1977] showed that these emissions tend to occur more frequently in certain longitude sectors where PLR is expected to be strong. This was interpreted as evidence that much of the chorus observed on Ogo 3 was triggered by PLR.

In the previous section it was suggested that the Sunday decrease in VLF amplitude observed as Siple is due to the entry of weaker PLR waves into the magnetosphere on Sundays. If this is true, then the observed magnitude of the Sunday decrease represents a lower limit on the contributions to the total wave amplitude by PLR-triggered chorus. Referring to Figure 4, we see that the minimum PLR contribution inferred this way is about 30% between 07 and 14 MLT. Outside this MLT range such arguments are not useful, since there is no clear Sunday decrease.

An earlier paper by *Park and Helliwell* [1978] discussed local time variations of PLR activity observed at Siple and Eights (185 km and less than 0.3 hour magnetic local time from Siple). Figure 6 of that paper is reproduced here as Figure 11. We note a rather striking resemblance between this curve and the diurnal curve of VLF wave amplitude reported in the previous section (see, for example, the Monday–Saturday curve in Figure 4). This is consistent with our hypothesis that a large fraction of the total VLF wave intensity reported here is stimulated by power lines. *Park and Helliwell* [1978] suggested that the sharp increase in PLR activity at 05 MLT is due to a sudden increase in power usage at that time and that the gradual decrease in PLR activity throughout the afternoon hours is due to limited accessability of the afternoon-evening sector to the energetic electrons that resonate with the PLR waves. The same explanation may apply to the enhanced VLF amplitude in the dawn-afternoon sector reported here.

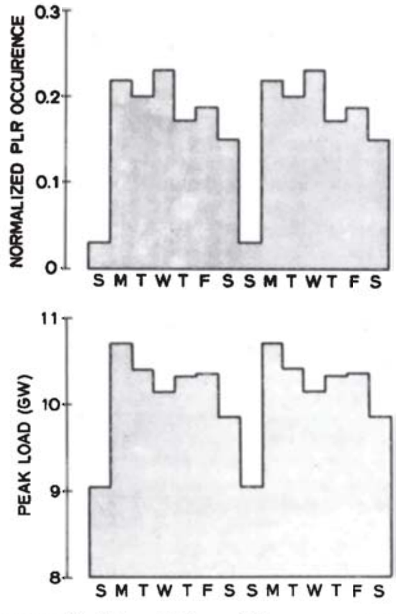

Fig. 10. (Top) Weekly variation of the occurrence of power-line-induced emissions observed at Siple, Antarctica, during 1973–1975. (Bottom) Weekly variations of peak load on Hydro-Quebec in the conjugate area of Siple from November, 1974, to February, 1975 (courtesy of Hydro-Quebec, Montreal, Quebec).

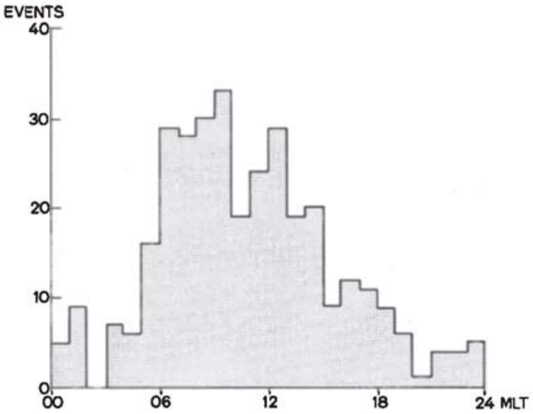

Fig. 11. Magnetic local time variation of power-line-induced emissions observed in Antarctica [from *Park and Helliwell*, 1978].

## DISCUSSION

In Figure 10 it appears that a relatively small percentage decrease in power consumption on Sunday causes a large decrease in PLR intensity. It should be pointed out, however, that PLR intensity at VLF may not be linearly related to the total power consumption. If high-order harmonics in transmission lines are generated primarily by industrial load, then it is likely that harmonic currents at VLF have a much more pronounced minimum on Sunday than is indicated in Figure 10 (bottom). Unfortunately, no information is available at present on the harmonic content of power line currents. In future studies the harmonic content as well as the radiation efficiency of major transmission lines needs to be taken into account.

Since wave-particle interaction is the primary mechanism that causes particle precipitation at subauroral latitudes, the Sunday decrease in VLF wave amplitude reported here is expected to have its counterpart in particle precipitation. (The energy of particles precipitated by 2- to 4-kHz waves at $L = 4$ would range from a few hundred electron volts to a few hundred keV depending on the cold plasma density.) Satellite data on precipitation flux could be used to look for such an effect. Variations in particle precipitation may produce detectable signatures in the ionosphere if the fluxes are large enough to overcome other competing effects, such as solar radiation, (or before sunrise when such competition is absent). If an ionospheric Sunday effect can be found, the magnitude of the effect as a function of altitude would provide useful information on the spectrum of precipitating particles.

The data used in this study came from the longitude sector of eastern Canada and the United States where high PLR levels are expected. It will be interesting to conduct similar studies at other longitudes where power usage is low. Satellite data could also be used to investigate longitudinal variation of the Sunday effect, if sufficiently large data sets are available. Satellite data may also tell us whether there are any fundamental differences between triggering of ducted chorus received on the ground and triggering of nonducted chorus that can be detected only in space.

## CONCLUSION

Magnetospheric wave intensity in the 2- to 4-kHz range monitored at Siple, Antarctica, shows a distinct minimum on Sunday, as does the occurrence of PLR-induced emissions identified in broadband spectral data from Siple. We suggest that both effects are due to reduced power consumption on Sunday in the PLR source region in eastern Canada. This implies that a significant fraction of total VLF wave intensity is due to emissions triggered by PLR, even though triggering PLR waves are only rarely identifiable on conventional frequency-time spectrograms.

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