LONGITUDINAL VARIATIONS OF VERY-LOW-FREQUENCY CHORUS ACTIVITY IN THE MAGNETOSPHERE: EVIDENCE OF EXCITATION BY ELECTRICAL POWER TRANSMISSION LINES

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Abstract. Very-low-frequency (VLF) chorus activity detected by the Ogo 3 satellite has the highest probability of occurrence in regions threaded by geomagnetic field lines that intersect industrialized areas. Interpretation of these results is based on radiated power line harmonics that leak into the magnetosphere and stimulate the recorded emissions through cyclotron interaction with trapped energetic electrons. These results emphasize the need for a careful evaluation of the effects of man-made VLF noise on the ionosphere and magnetosphere.

Introduction

It is well established that very-low-frequency (VLF) waves originating from lightning and ground-based transmitters can trigger whistler-mode instabilities in the magnetosphere and stimulate emissions of new waves that are much stronger than the input waves. Controlled transmitter experiments at Siple, Antarctica (84°W, $L \approx 4$) showed that the triggered emissions are typically ~30 dB above the input level [Helliwell and Katsufrakis, 1974; Stiles and Helliwell, 1977].

Recently Helliwell et al. [1975] reported another important source of VLF waves that stimulate emissions in the magnetosphere. This source is electrical power transmission lines. Harmonic radiation from power lines leaks into the magnetosphere where it is amplified and stimulates emissions in the manner of transmitter signals. Ground observations showed that under certain conditions, particularly during and immediately following magnetic storms, power line-induced emissions are the strongest VLF waves emerging from the middle magnetosphere in the ~1-10 kHz range [Park, 1976, 1977]. A low altitude (~500 km) satellite survey by Bullough et al. [1976] showed a pronounced peak in VLF wave activity over North America, which the authors attributed in part to the power line effect.

In the present study we examine the distribution of VLF chorus, or discrete emissions, in the high-altitude magnetosphere as detected by the Ogo 3 satellite. This type of chorus occurs predominantly outside the plasmasphere and usually propagates in the unducted mode [Burtis and Helliwell, 1976].

Data

Chorus data used in this study were obtained by a broadband VLF (0.3-12.5 kHz) receiver on Ogo 3 from June 15, 1966 (VLF antenna deployed) to June 14, 1967. A magnetic loop antenna was employed so that only electromagnetic waves would be detected. The initial perigee was less than 500 km altitude. apogee was over 120,000 km, and inclination was 31°. During the next 12 months, the orbit inclination gradually increased to ~50°.

Broadband data from virtually all passes inside $L = 10$ were spectrum analyzed, and the occurrence statistics were compiled by using 1-min samples out of every 5 min of data (occasionally every 10 min when the satellite was at large distances and moving at low speeds). A total of 4,668 samples was thus obtained covering all local times. The same data set was used in an earlier study by Burtis and Helliwell [1976], and a detailed description of the analysis procedure and data coverage can be found in their paper.

In classifying wave activity, any discrete noise appearing on the spectrograms, regardless of its frequency (provided that it is less than the local electron gyrofrequency) was considered to be chorus. The term "discrete" implies structured emissions having amplitude or frequency modulation with durations of order 0.1-1 s. The threshold of chorus detection using spectrograms depends on the background noise level but is typically ~60 dB below 1 γ. Figure 1 shows an example of chorus observed by Ogo 3 at $L = 7.8$, +38° dipole latitude, 1210 local time, and 0° geographic longitude. Chorus may have complex spectral forms, as illustrated here, but is always easy to distinguish from whistlers and unstructured hiss. Chorus is one of the most commonly observed wave phenomena in the outer magnetosphere ($L > 4$).

Results and Interpretations

Of the total 4,668 samples, 1251 or 27% showed chorus activity. In order to examine the spatial distribution of this activity, the data were divided into bins 10°x10° in dipole invariant latitude and longitude. Percent occurrence of chorus was then computed for each bin. The results are summarized in Figure 2, where the bins defined in terms of dipole geomagnetic coordinates are superimposed on a Mercator map of the northern hemisphere. The bins with fewer than 5 data samples are shown as "no data." The number of data samples in shaded bins ranges from 5 to 158. The average is 63. Since the data set was limited to $L \leq 10$ (invariant latitude $\Lambda \leq 71.6°$), those samples that fall between $\Lambda = 70°$ and 71.6° were lumped into the 60°-70° bins. The histogram at the bottom of the figure shows longitudinal variations of percent occurrence including all invariant latitudes. Four prominent peaks from left to right can be associated with Alaska-New Zealand, Eastern United States-Canada, West-

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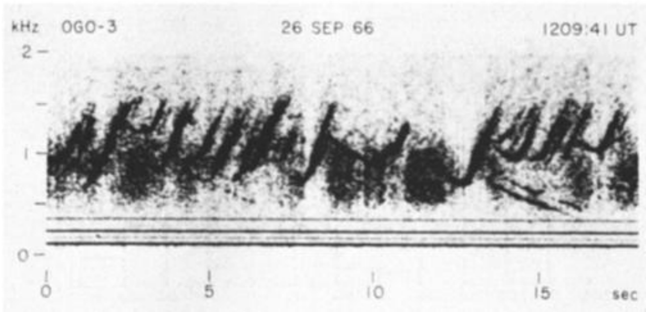

Fig. 1. A spectrogram of chorus activity detected by the Ogo 3 satellite at L = 7.8, 38° dipole latitude, and 1210 local time. The geo magnetic activity was moderate (K_p = 4).

ern Europe, and Western Siberia. These peaks, in the same order, are based on 172, 161-186, 120-124, and 39 samples respectively. They are believed to be significant because six longitude bins have activity above the 46 percent level, which is twice that predicted by a normal distribution of random fluctuations from bin to bin.

Since the occurrence of chorus is known to depend on magnetic substorm activity as well as on local time [Burtis and Helliwell, 1976; Tsurutani and Smith, 1974; Thorne et al., 1974], it is necessary to test whether the peaks in Fig. 2 are simply a result of biased sampling. The mean values of the 3-hr K_p index during satellite observations in the six longitude bins with >46% chorus activity are 2.1, 2.0, 2.1, 1.8, 2.2, and 2.0 respectively, whereas the mean value for all data samples is 1.99 with a standard deviation of 0.46. It is clear that there was no bias in terms of K_p. Similar results are obtained for the maximum K_p during the preceding 24 hours. With regard to local time, the probability of chorus occurrence is ~4.5 times higher on the dayside compared to nightside [Burtis and Helliwell, 1976]. If we divide the samples in each longitude bin into daytime and nighttime passes, the results show that the six bins comprising the four peaks in Fig. 2 were not favored with more daytime passes compared to their neighbors. Since the peaks were not artificially produced by biased sampling, we conclude that they are in fact correlated with geographical areas containing heavy industrial activity or large power distribution networks. We suggest that the enhanced chorus activity is due to radiated harmonics emanating from power lines.

Ariel 3 results by Bullough et al. [1976] has also showed peaks in VLF wave amplitude in the same four longitude sectors of high chorus activity identified in Figure 2. It should be noted, however, that in addition to the differences in orbit altitudes between Ogo 3 and Ariel 3, the data were acquired and analyzed differently. In the Ariel 3 survey, signal intensity in a narrow band channel (3.2 ±0.5 kHz) was used to identify wave events that exceeded a certain threshold. These events presumably include whistlers and hiss as well as chorus. The present survey includes only chorus.

Eastern North America and Western Europe consume large quantities of electrical power. In Eastern Canada, strong harmonics up to several kHz, probably produced by heavy users of dc power, have been associated with magnetospheric line radiation observed there and in the conjugate region in Antarctica [Helliwell et al., 1975]. In the case of the Alaska-New Zealand sector, it is not clear whether the northern or the southern hemisphere source is more important. No information is available to us at present regarding power usage in Siberia.

The amount of VLF power radiated by electrical transmission lines depends on the intensity of harmonic currents carried by these lines and the radiation efficiency. Harmonic currents have not been surveyed systematically, but are likely to vary widely from location to location depending on the type of load. The radiation efficiency is a function of load configuration (i.e., balanced 3-phase system versus single-phase lines using ground return) as well as soil conductivity. For these reasons, we do not expect the intensity of VLF radiation from a given area to be simply related to the amount of power consumed there.

The intensity of power line radiation needed to stimulate the observed chorus activity in the magnetosphere is not known; however, an estimate can be made based on VLF transmitter experiments conducted at Siple, Antarctica. Under favorable conditions, the Siple transmitter is known to stimulate strong magnetospheric emissions with less than 10W radiated power [Helliwell et al., 1975]. However, this figure cannot be applied directly to the present case, because the transmitter-induced emissions were generated within ducts inside the plasmasphere, whereas the chorus activity observed by Ogo 3 occurred predominantly outside the plasmasphere. Since typical growth rates observed outside the plasmasphere (~200-2000 dB/sec) are more than 10 times the typical values inside (~20-200 dB/sec) [Burtis and Helliwell, 1975; Stiles and Helliwell, 1977], the minimum input wave intensity needed to stimulate emissions outside the plasmapause may be significantly less than that required inside. We suggest that power line radiation of only ~1W or less at a given harmonic frequency may be sufficient to stimulate the observed chorus activity and that such power levels can reasonably be expected in industrial areas, or from large distribution networks.

Chorus occurrence in two invariant latitude bands, 50-60° and 60-72°, is shown in Figure 3. Each band is subdivided into two groups, north and south of the dipole equator. Short horizontal bars near the bottom of Figures 3b, c indicate fewer than 10 data samples. Comparing Figures 3a and 3d, we see that chorus activity is more prevalent in the southern hemisphere, the ratio of percent occurrence being 9:5. The trend is reversed in Figures 3b, c. Figure 3d shows the same four peaks as Figure 2, but the pattern is more smeared in Figures 3a, b, and c. The significance of the variations in Figure 3b, however, is questionable because of the relatively small number of data samples.

The pattern in Figure 3 is consistent with the power line hypothesis. If power line radiation originated from industrial areas in the northern hemisphere, magnetospheric emissions triggered by this radiation would start near the equator and propagate southward. Hence, more chorus activity would be expected in the south-

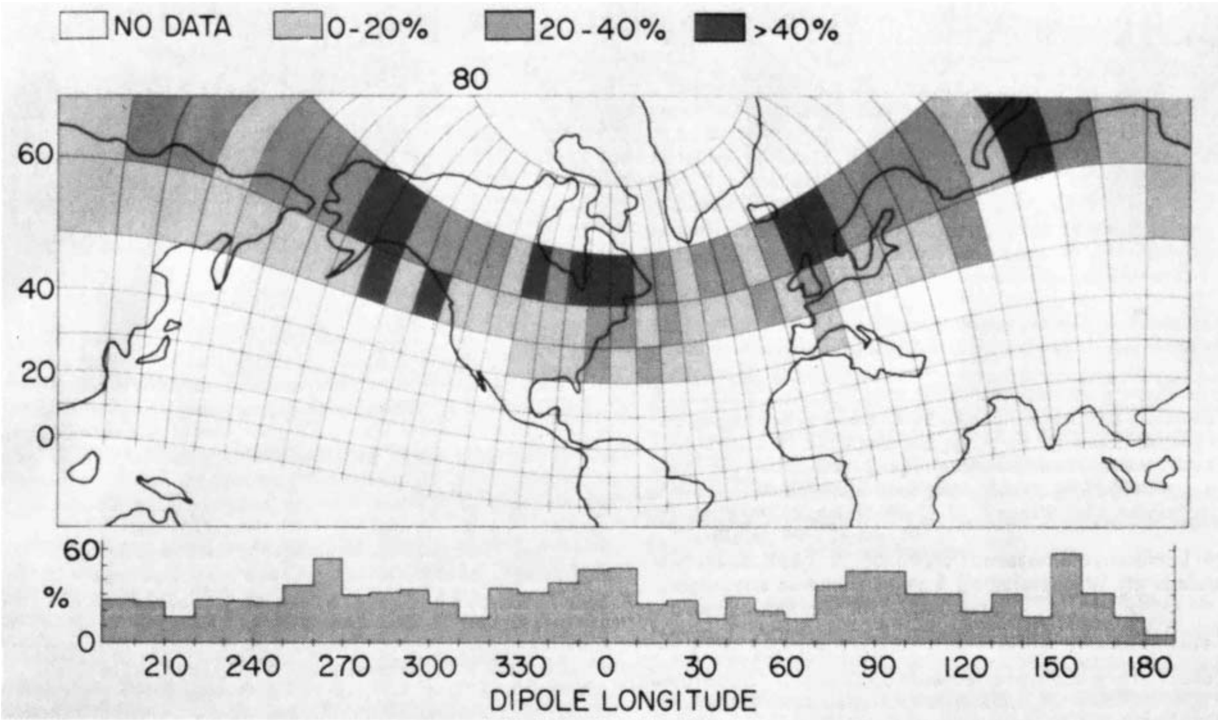

Fig. 2. Chorus occurrence frequency in invariant dipole coordinates. Each bin represents a magnetic flux tube extending from hemisphere to hemisphere with a cross-section of 10°x10° invariant latitude and longitude. The histogram shows longitudinal variations in percent occurrence averaged over invariant latitudes.

ern hemisphere. Unducted emissions would be magnetospherically reflected to the northern hemisphere, but in the process they would tend to spread in both longitude and latitude. They could trigger new emissions that would be observed in the north.

Discussion

Ground-based observations of power-line induced emissions occurring inside the plasmapause frequently show clear evidence of amplified power line harmonics that trigger the emissions [Helliwell et al., 1975; Park and Helliwell, 1977; Park, 1977]. However, chorus in the outer magnetosphere was attributed to spontaneous emissions [Burtis and Helliwell, 1976], because no triggering signals were observed. Our present findings suggest that chorus can be triggered by power line harmonics that are too weak to be clearly discernable on spectrograms. We argue that much weaker signals can trigger emissions outside the plasmapause where growth rates are about 10 times greater compared to inside. One obvious test of the power-line hypothesis is to measure the starting frequencies of chorus emissions to see if they are related to the power line frequencies. This investigation is now in progress, and the preliminary results indicate that chorus starting frequencies are highly correlated with 60 Hz harmonics when the satellite was in the American sector, and with 50 Hz harmonic in the European sector. Correlations have been found with both 50 Hz and 60 Hz harmonics in the Alaska-New Zealand sector.

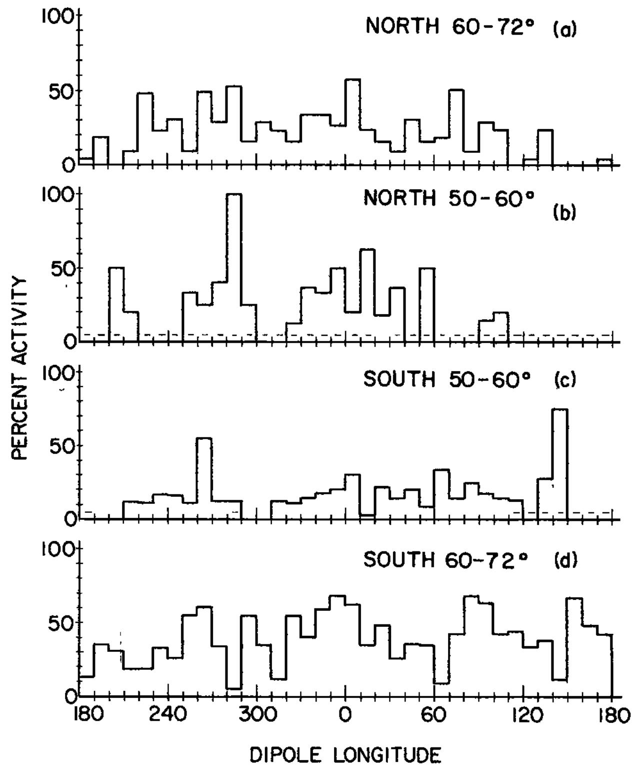

Fig. 3. Chorus occurrence in the 50-60° and 60-72° invariant latitude bands. Short horizontal bars indicate fewer than 10 data samples.

It is well established that whistlers and man-made VLF signals can often trigger emissions in an otherwise quiescent magnetosphere, evidence that the threshold of spontaneous whistler-mode instability is much higher than that for stimulated instability [Storey, 1953; Helliwell, 1965; Helliwell and Katsufrakis, 1974]. Therefore, the continuous leakage of power line radiation may in fact prevent portions of the magnetosphere from reaching the point of spontaneous instability.

Conclusions

VLF chorus activity observed by the Ogo 3 satellite shows significant longitudinal variations, which we interpret as evidence of excitation by power line radiation. If our interpretation is correct, it has important implications since chorus is one of the most commonly observed types of VLF electromagnetic waves in the outer magnetosphere and these waves play an important role in the dynamics of energetic particles. It is apparent that the effects of man-made noise on the magnetosphere require further study.

A general practice is to organize magnetospheric data in local time coordinates, but our results suggest that many types of such data should be re-examined in geographic coordinates to look for possible man-made effects.

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