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Radiation from electrical power transmission lines disturbs the magnetosphere, out to many earth radii.

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Summary. Radiation from electrical power lines leaks into the magnetosphere and stimulates strong very-low-frequency wave activity out to many earth radii. Observations in Antarctica show that wave activity induced by power lines tends to occur during the daytime when power consumption is high in the source region in eastern Canada. The wave frequency ranges from 1 to 8 kilohertz. This man-made wave activity may have significant effects on energetic electrons trapped in the earth's radiation belts.

It was recently discovered that very-low-frequency (VLF) radio waves radiated by electrical power transmission lines leak into the magnetosphere and strongly interact with energetic electrons (corpuscular radiation) trapped in the earth's magnetic field (*1*). As a result of this wave-particle interaction, the wave power may grow by a factor of 1000 or more during one passage through the interaction region (*2*). The orbits of the interacting electrons are altered in such a way that electrons are precipitated into the upper atmosphere where their energy is dissipated by collisions with ambient gas; this process produces enhanced ionization, heat, optical emissions, and x-rays. These processes are illustrated schematically in Fig. 1.

Power lines on the earth's surface produce detectable effects in the remotest parts of the earth's space environment (*1, 3, 4*). This process is obviously a matter of serious concern, but much more research is needed before we can estimate how much impact this phenomenon has on the upper atmosphere and what effects, if any, filter down to the lower atmosphere.

Earlier studies based on VLF data from Antarctica showed that VLF activity induced by power lines increases immediately after geomagnetic disturbances (*3*). This increase is presumably due to an enhanced flux of energetic electrons in the magnetosphere during such times, but it also implies that power lines play an important role in the decay of storm-produced energetic electrons. Satellite surveys have revealed permanent zones of enhanced wave activity that could be traced to large power distribution systems on the ground (*4*). Thus it appears that power lines have significant long-term effects as well as more pronounced effects that are observed immediately after magnetic storms. In this article we present some statistical results on power line radiation (PLR) effects observed on the ground over a period of several years.

Most of the world's power systems operate at 60 or 50 hertz, but nonlinear loads such as rectifiers and imperfect machinery introduce higher frequency components at harmonics of the fundamental frequency, extending up to many kilohertz. Transmission lines carrying these harmonic currents radiate radio waves over wide frequency ranges. These waves penetrate the ionosphere and are guided by the earth's magnetic field to the region where waves and particles interact in the equatorial magnetosphere. There the waves may be greatly amplified and under certain conditions may also trigger emissions of new waves that are much stronger than the input waves. In this sense, the magnetosphere is analogous to a marginally stable amplifier that is occasionally stimulated to act as an oscillator. The output wave form is usually quite complex and generally shows large amplitude fluctuations with time scales of the order of a second. Two examples of power line–induced emissions are given below.

Figure 2 shows two frequency-time spectrograms of VLF recordings made at Eights, Antarctica (75°S, 77°W). Strong horizontal striations in Fig. 2a are due to PLR and associated emissions. The emissions show noticeable frequency-broadening, but they remain close to the triggering PLR frequencies. The periodic amplitude modulation of PLR-induced emissions can be understood with the aid of Fig. 1. When an amplified PLR wave or an emission reaches the southern ionosphere, a part of the wave energy penetrates the ionosphere and is received on the ground. The rest is reflected back into the magnetosphere where it may grow or retrigger a new emission in the interaction region, or both. The resulting wave is again partially reflected in the northern ionosphere and reinforces the upgoing PLR. This process can go on for hours. The amplitude modulation periods in Fig. 2 are consistent with known echo periods. In the case of Fig. 2b, the emissions break away from triggering frequencies to form broad rising structures. Examples of different spectral

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forms can be found in (*1*) and (*3*). More subtle forms of power line effects include wave-wave interactions through which even weak PLR waves can control the behavior of other waves of different origin by enhancing their intensity, suppressing them, or modifying their frequency.

The characteristics of PLR waves are also associated with signals from VLF transmitters that operate around the world for navigation, communication, and scientific research. Thus, studies of transmitter signals can provide information on PLR effects, and vice versa. Historically, power line effects were noticed as early as the late 1950's (*5*); however, their association with power lines was not discovered until many complex wave-particle and wave-wave interaction processes in the magnetosphere were demonstrated by controlled transmitter experiments at Siple, Antarctica (76°S, 84°W) (*2*). Today the same experimental transmitter, along with an array of monitoring instruments, is being used in an effort to understand power line effects by controlled simulations.

Quite apart from their use as a tool to study the effects of PLR, VLF transmitters themselves may cause significant precipitation from the radiation belts. However, because of their generally higher frequencies (> 10 kilohertz except in the case of a few relatively low-power experimental transmitters) compared with PLR (1 to 8 kHz) (Fig. 3), VLF transmitter effects are expected to be confined to a relatively low altitude range [< 2.5 earth radii (R_E)].

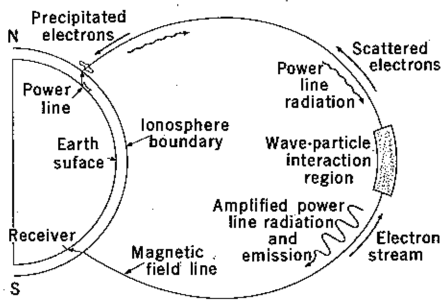


Fig. 1. A schematic diagram illustrating the effects of PLR. Harmonic radiation from power lines in the range of several kilohertz penetrates the ionosphere and is guided by the earth's magnetic field to the equatorial region where it can strongly interact with counterstreaming energetic electrons. This wave-particle interaction leads to the amplification of PLR and the triggering of emissions whose power level typically exceeds the input level by a factor of about 10^3. The same interaction scatters energetic electrons and causes some of them to precipitate into the upper atmosphere with estimated energy fluxes that are 10^6 or more times the input wave power.

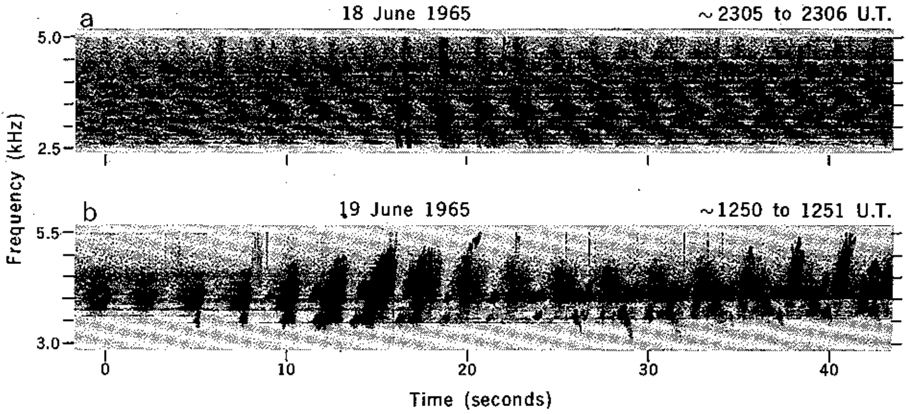
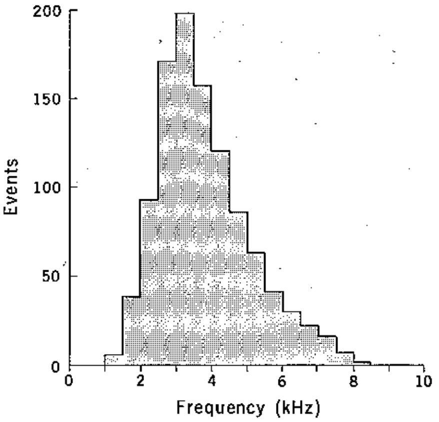


Fig. 2. Two examples of radio emissions triggered by PLR leaking into the magnetosphere: (a) 18 June 1965; (b) 19 June 1965. The data were recorded at Eights, Antarctica, in the aftermath of a magnetic storm. The degree of darkness indicates the wave intensity.



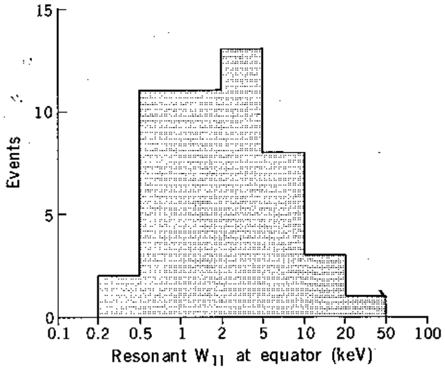


Fig. 3 (left). Frequency distribution of power line harmonics that triggered strong radio emissions in the magnetosphere. Fig. 4 (right). Energy (parallel component) distribution of electrons that resonate with PLR in the equatorial plane.

Once the existence of man-made phenomena is recognized, the next question that comes to mind is how do they compare with naturally occurring processes. The magnetosphere abounds with a wide variety of wave phenomena that affect the energetic particle population in varying degrees. Some are stimulated or triggered by man-made waves as discussed above, whereas others originate in natural sources such as lightning or spontaneous plasma instabilities within the magnetosphere. An example of the last kind is broadband noise below about 1 kHz, commonly known as "plasmapheric hiss" and believed to play an important role in the depletion of energetic electrons in the slot region between the inner and the outer radiation belts (*6*). The physical mechanisms of wave generation and particle precipitation are not well understood at present, and there is no general agreement on the relative importance of man-made and natural processes. These and related questions are currently under intensive study by several groups in the United States and abroad. In this short article, it is not possible to give a comprehensive review or to acknowledge all the scientists who deserve credit.

Statistical Summary

We now review some statistical results on PLR-induced emissions based on observations at Siple and Eights in Antarctica and at Roberval, Quebec. Roberval is near the magnetic conjugate points of Siple and Eights. These three stations are expected to show high levels of PLR activity because of heavy power usage in northeastern North America. The data used in this study come mainly from 1965 (Eights) and from 1973 through 1976 (Siple and Roberval). The PLR events used here were identified from a subset of these data that had already been analyzed for other purposes. A systematic search through all the recorded data should reveal many more events than are shown here.

The frequency distribution of PLR that triggers emissions is shown in the histogram of Fig. 3. To obtain these data, broadband VLF recordings were sampled for 1 minute every 15 minutes. If PLR effects were present in a 1-minute sample interval, it was counted as an "event." The frequency distribution has a well-defined peak at 3 to 3.5 kHz, corresponding to the 50th to 58th harmonics of the 60-Hz power frequency.

If PLR waves show echoing, as in Fig. 2, it is often possible to identify their propagation path by comparing the echo period with the propagation delays of whistlers. [A whistler is VLF radiation from lightning that travels from hemisphere to hemisphere following the earth's magnetic field. The travel time is of the order of a few seconds and varies with frequency. The travel time as a function of frequency provides information about the propagation path and the cold ambient plasma density along the path (5).] The PLR paths thus determined have equatorial crossing radii that range from 3.4 to 5.5 R_E, the most probable value lying between 4.5 and 5 R_E.

When the parameters of the propagation path are known, it is possible to estimate the energy of electrons that interact with the waves. The interaction mechanism is believed to be cyclotron resonance in which the wave frequency is Doppler-shifted by the electron velocity parallel to the magnetic field to match the electron gyrofrequency. The resonance condition is given by

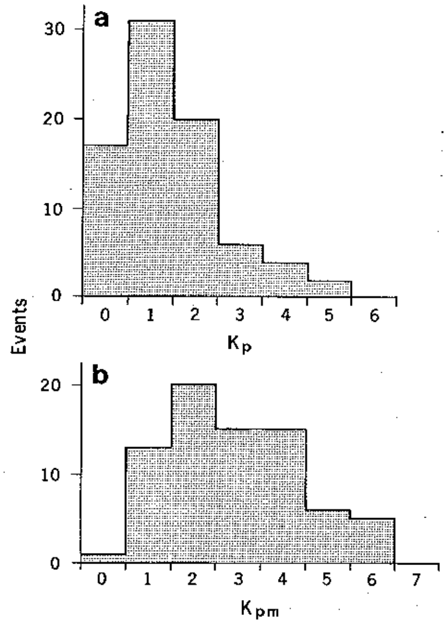
$$f\left(1 + \frac{v_\parallel}{v_p}\right) = f_H$$

where f is the wave frequency, f_H is the electron gyrofrequency, $v_\parallel$ is the electron velocity along the geomagnetic field, and v_p is the wave phase velocity in the opposite direction. The parallel energy of resonant electrons is given by

$$W_\parallel = \frac{1}{2} m v_\parallel^2$$

where m is the mass. $W_\parallel$ is a function of position along the path; it reaches a minimum at the equator, where the conditions for wave growth and emission generation are usually optimal.

Figure 4 shows a histogram of equatorial resonant energy. The important energy range is ~ 0.5 to 10 kiloelectron volts. The sampling scheme used in compiling these statistics was different from that used in Fig. 3 for the following reason. Once a favorable propagation path is established in the magnetosphere, it frequently persists for several hours with little change in position. During this time, ambient cold plasma densities also remain nearly constant, thus maintaining essentially the same resonance conditions. In such cases, only one sample was taken to represent each long-enduring event. A fixed sampling rate would introduce a bias by giving too much weight to long-enduring events.



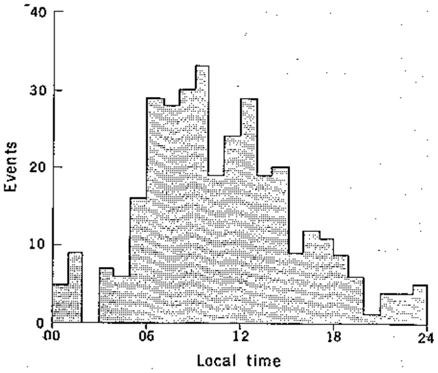


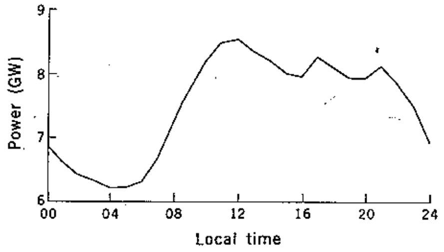
Fig. 5 (left). (a) Power line-induced emission events as a function of the planetary magnetic disturbance index, K_p. (b) Power line-induced emission events as a function of the maximum value of K_p during the preceding 24 hours. Fig. 6 (right). Local time dependence of the occurrence of power line-induced emission events.

The important energy range implied in Fig. 4 refers only to the energy of electrons that generate and amplify the waves near the equator. After the waves leave the equator, they propagate toward the earth along magnetic-field lines and precipitate electrons with energies extending up to hundreds of kiloelectron volts.

Next we consider the dependence of PLR activity on the level of magnetospheric disturbance. Large-scale magnetospheric disturbances, called storms or substorms, inject energetic electrons into the inner magnetosphere, increasing the flux by orders of magnitude (7). Such flux enhancements subsequently decay over a few days. Moreover, during storms and substorms wave propagation conditions deteriorate as a result of increased absorption in the ionosphere and perhaps as a result of other unexplained processes as well. The propagation condition generally recovers more quickly than the trapped electron flux. As might be expected, PLR events tend to occur during quiet times immediately following disturbances, when good propagation conditions are combined with the enhanced electron fluxes needed for strong wave-particle interaction. This trend can be seen in Fig. 5, where the number of PLR events is plotted against the planetary magnetic disturbance index, K_p, and against the maximum value of K_p during the preceding 24 hours; K_p indicates the degree of magnetospheric disturbance for each 3-hour interval in universal time. The value of K_p is based on observations of magnetic field fluctuations at a number of stations around the world and ranges from 0 for the most quiescent condition to 9 for the most severe storm condition. Figure 5a shows that PLR events tend to occur in quiet times, but relatively small substorms with K_p = 1 to 2 are as important in providing conditions favorable for PLR events as more severe storms (Fig. 5b). For Fig. 5, "event" means that PLR activity was present during at least one of the 12 1-minute samples (one sample taken every 15 minutes) during a 3-hour interval for which a K_p value is given.

Figure 6 illustrates how the PLR activity depends on the local time of the observing station. All three stations used in this study are within ½ hour in magnetic local time. The probability of PLR occurrence increases sharply near 6 a.m. and decreases steadily throughout the afternoon. There is roughly a 6:1 difference in occurrence probability between the daytime peak and the nighttime lull.

The following two-part explanation for the local time variation of PLR activity seems plausible, although more experimental data are needed to demonstrate its validity. The sharp increase in PLR activity at 6 a.m. may be due to increased power usage around that time. As an example, Fig. 7 shows hourly power demand on Hydro Quebec, the major power supplier in the province of Quebec, during a typical week in August 1974. (Data supplied by G. Blais, Hydro Quebec.) However, power demand remains at a fairly high level throughout the afternoon until past 8 p.m. Thus we must seek another explanation for the decrease in PLR activity throughout the



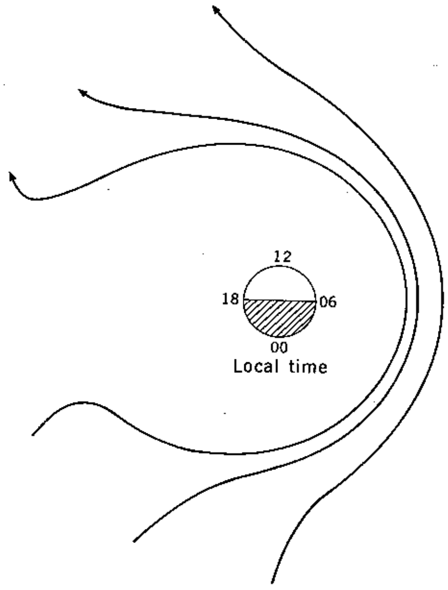


Fig. 7 (left). Local time variations in the electrical power demand on Hydro Quebec during a typical week (*10*) Fig. 8 (right). Trajectories of 1-keV electrons in the equatorial plane of the magnetosphere based on model calculations by Roederer, using models described in (*11*).

afternoon. We believe that this decrease is associated with the trajectory of resonant energetic electrons (Fig. 8). When energetic electrons are injected from the magnetotail on the nightside of the earth, they drift around through the dawn and noon sector but in the afternoon sector they become dispersed and move away from the earth. Energetic electrons that are needed for wave-particle interaction have difficulty gaining access to the afternoon-dusk sector. Thus there are fewer electrons available in the evening, and PLR activity diminishes as a result.

Future Work

The efficiencies of PLR are difficult to calculate, owing to the large uncertainties in the magnitudes of the harmonic currents and the nature of the corresponding circuit paths. For example, some lines are balanced three-phase circuits with small net magnetic moments, whereas others are single-phase ground-return circuits with relatively large moments. The most satisfactory approach to this problem may be simply to measure the harmonic fields at high altitudes by using VLF receivers mounted on aircraft, balloons, or satellites. In this way we could make a world map showing the intensity of PLR as a function of geographic location at various frequencies. Thus the influence of PLR on the earth's atmosphere could be explored systematically. However, it is important to realize that PLR is sensitive to a number of factors (load balance, grounding, harmonic generation, and the configuration of the transmission lines) other than the total power carried by the system. Thus we should not expect that PLR effects will correspond in detail to worldwide power distribution patterns, even though a gross correspondence has been demonstrated (*4*).

A further extension of the PLR studies would be to compare the VLF waves in the earth's magnetosphere with those in the magnetosphere of another planet. The obvious choice is Jupiter, where conditions favorable for the generation of whistler-mode waves are known to exist. Since there are (presumably) no power lines on Jupiter, we might expect to see a very different noise spectrum and a different relationship between the trapped particle density and the wave intensity. In fact, Jupiter's magnetosphere may be superior to the earth's as a place in which to test the predictions of the Kennel-Petschek (*8*) theory of particle diffusion by incoherent whistler-mode waves. According to this theory, energetic particles generate broadband noise, which in turn causes the particles to precipitate into the atmosphere. In a steady state, this interaction between waves and particles sets an upper limit on the flux of energetic particles that can remain stably trapped in the magnetosphere. This theory, however, does not apply to discrete coherent waves such as the emissions generated by PLR.

Since PLR is a controlling factor in the generation of discrete VLF emissions that are known to be effective in scattering energetic electrons (*9*), we can expect to find a correlation between PLR and energetic electron fluxes. The effect would be qualitatively similar to the South Atlantic anomaly where the unusually weak geomagnetic field causes trapped electrons to descend to lower altitudes, with a consequent increase in precipitation. In regions of high power consumption more VLF waves are generated, which in turn causes enhanced scattering and precipitation of energetic electrons. How important are such man-made effects as compared to natural processes in shaping the radiation (high-energy particle) environment of the earth? This question will be a subject of intensive research and debate in the coming years.

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