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Very Low Frequency Magnetospheric Research in the Antarctic

R. A. HELLIWELL

Radioscience Laboratory, Stanford University, Stanford, California

The purpose of this paper is to highlight the contributions of antarctic research to the study of low frequency (100 Hz to 100 kHz) waves in the magnetosphere. Study in this area began for all practical purposes with Storey's classic paper on the origin of very low frequency (VLF) whistlers published in 1953. With the coming of the IGY in 1957 the first exploratory measurements were made in the Antarctic at Byrd Station, where the natural VLF activity was found to be very great. A continuing program of VLF observations at antarctic stations, employing investigators from several countries, has made important contributions to our knowledge of electromagnetic waves and the properties of the magnetosphere.

An interesting feature of VLF phenomena is the way they sound to the ear. Observations are made with the aid of a high-gain audio amplifier connected to a loop or long-wire antenna. Among the many remarkable sounds that may be heard are those generally known as whistlers and VLF emissions. The whistlers are long whistling tones, usually descending in frequency, and are excited by the electrical impulse from a lightning flash. The VLF emissions are less well understood but are believed to have their origin in the ionosphere and the magnetosphere. They exhibit a wide variety of sounds, ranging from hiss to musical tones. One type called the "dawn chorus" resembles the sound of birds waking in the early morning. Remarkably similar sounds are produced by seals, whales, and other seagoing mammals. During the IGY, whistlers and related phenomena were classified subjectively by trained people listening to magnetic tape recordings. This type of aural

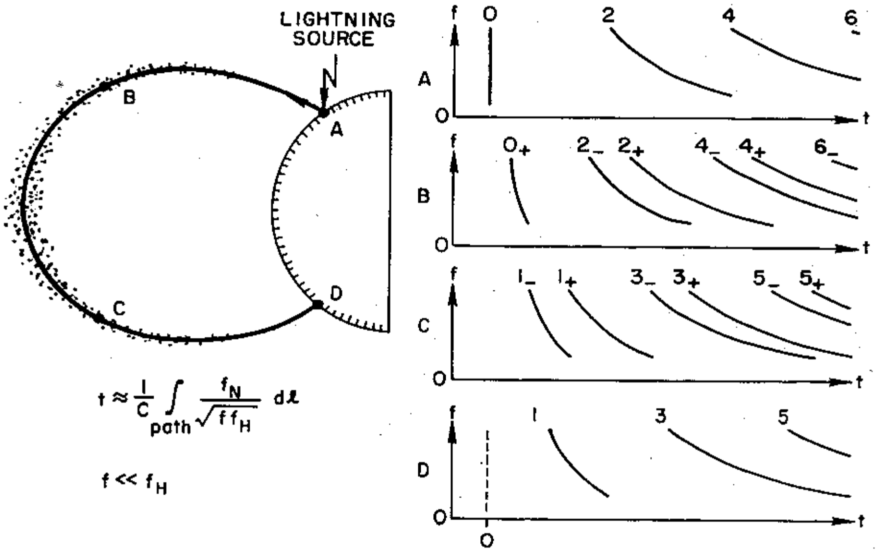

Fig. 1. Echoing ducted whistlers as observed on the ground at points A and D and in satellites at points B and C. The lighting source is located at point A, and the Eckersley approximation is used to sketch the spectra. The vertical dashed line in the lowest spectrogram represents the attenuated sferic arriving at D via the earth-ionosphere wave guide (Helliwell, 1969).

analysis has since been replaced by quantitative study of spectrograms made from the same tape recordings.

WHISTLERS

The nature of whistler propagation is illustrated in Figure 1. A single whistler duct is shown with the idealized spectra that would be observed at points A and D on the ground and at points B and C in space. The duct is a slight enhancement of electron density aligned with the earth's magnetic field within which electromagnetic waves in the audio-frequency range are trapped. Through the action of free electrons moving under the influence of the static magnetic field of the earth, the radio waves are dispersed. This effect causes a lightning impulse introduced at one end of the path to emerge at the other end as a long whistling tone. Receivers located at points A and D at the opposite ends of the duct observe the following sequence of events. First an impulse is observed at Station A, appearing as the vertical line labeled 0. Next a one-hop whistler, labeled 1, is observed at the conjugate point D. Some of this energy echoes back to point A and produces a two-hop whistler, labeled 2, and so on. Fractional-hop whistlers are observed in satellites at points B and C, as shown in Figure 1.

The time for a wave packet at the lower frequencies to travel over the path is given approximately by the equation shown in Figure 1, where f = wave frequency, f_N = plasma frequency, f_H = electron gyrofrequency (proportional to the strength of the earth's magnetic field), and c = twice the velocity of light. Since f_N is proportional to the square root of the electron density the whistler delay gives a measure of electron density. This integral is inversely proportional to the square root of wave frequency, which accounts for the falling frequency of the tone, and inversely proportional to the square root of the electron gyrofrequency. Since this latter quantity has a minimum at the top of the path, it is obvious that the time delay will be weighted toward the top of the path. This is one reason why whistlers make such good diagnostic tools for the outer magnetosphere. The low values of electron density at high altitudes are compensated by the correspondingly low values of electron gyrofrequency.

A spectrographic example of the phenomena idealized in Figure 1 is shown by the conjugate whistler echo train of Figure 2. These

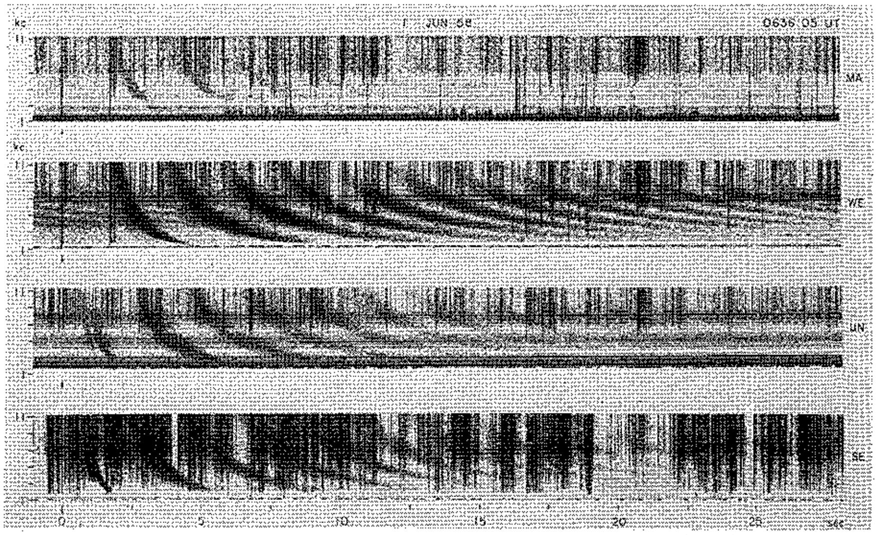

Fig. 2. Echoing whistler observed in conjugate regions. Upper two panels show even-order echo train observed at Macquarie Island and Wellington, New Zealand, in the Southern Hemisphere. Lower two panels show odd-order echo train observed at Unalaska and Seattle in the Northern Hemisphere (Helliwell, 1965).

whistlers were recorded during the IGY at Macquarie Island; Wellington, New Zealand; Unalaska; and Seattle, Washington. The lightning flash, recorded strongly at Macquarie and Wellington, is followed at Unalaska and Seattle by one-hop whistlers, exhibiting two main components corresponding to propagation in two separate ducts. The stronger component echoes between the hemispheres over a long period of time, with 12 echoes showing on the figure. It is seen that the ratio of time delays is 2, 4, 6, 8, etc., in the Southern Hemisphere and 1, 3, 5, 7, etc., in the Northern Hemisphere, in accordance with Figure 1.

As the wave frequency approaches the gyrofrequency a very interesting change occurs in the whistler spectra as compared with those shown in Figures 1 and 2. The time delay of the whistler is seen to reach a minimum at a certain frequency as illustrated by the spectra in the upper right-hand part of Figure 3. This point of minimum time delay is called the nose frequency and is labeled f_n. Two separate ducts are shown. The inner duct with the higher gyrofrequency shows a higher nose frequency and a smaller time delay. The nose frequency is closely related to the minimum gyrofrequency f_{H_0}, as indicated in the figure. By measuring this frequency the path latitude can be determined. Knowing the path latitude, the scale factor of the electron density distribution can be computed for an assumed shape of this distribution. If, in addition, several ducts are present, then a scale factor for each duct can be obtained. It is then possible by a process of curve fitting to determine the total electron distribution in the magnetosphere for simple models.

Recently it has been possible to test the duct theory of propagation using satellites. The lower right-hand spectrum shows what is observed in a satellite that happens to be situated within the lower duct at the time the whistlers pass by. The first trace shows a nose whistler which is like that seen on the ground except that the travel times are half as great. The second trace is more interesting. It represents leakage of whistler energy from the outer duct at frequencies above one-half the local gyrofrequency at which the trapping effect of an enhancement of electron density ceases. This feature of whistler transmission was discovered in the Stanford Orbiting Geophysical Observatory (OGO) 1 VLF experiment and provides strong evidence in support of the duct theory of whistlers. (The OGO 1 was an unmanned satellite sent up in 1964, number 1 of 6.)

Having considered the idealized nose whistlers of Figure 3, we can better appreciate actual examples, such as those shown in Fig-

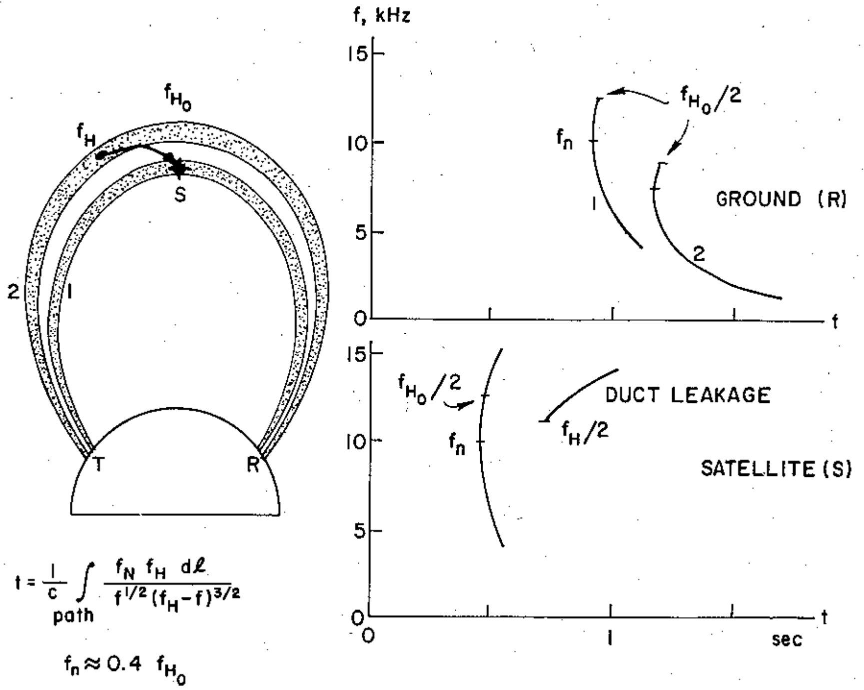

Fig. 3. Multipath ducted nose whistlers observed on ground; leakage from ducts observed on satellite for $f > f_H/2$. Nose frequency f_n gives path latitude; nose delay t_n gives electron concentration. f_H = electron gyrofrequency, f_N = electron plasma frequency, dl = element of path (l = line integral of the ray path) (Helliwell, 1969).

ure 4, recorded at Eights Station, Antarctica. In the top spectrum are many separate whistlers excited by a single impulse. The nose frequency of each trace gives the latitude of the corresponding duct, and the time delay at the nose gives a measure of the electron content in that duct. Each whistler can be scaled for its nose frequency and from this collection of data the electron density distribution can be obtained over the range of geocentric distances from 3 to 5.5 earth radii (R_E). In the lower spectrogram of Figure 4 is a train of nose whistlers obtained outside the plasmapause; each whistler is seen to have triggered a discrete VLF emission at the upper cutoff of the whistler. Artificially stimulated emissions (ASE's) triggered by station NAA on 14.7 kHz are seen in the upper panel. These emission effects are an important part of our field of study and will be discussed later.

At the conjugate point to Eights we might hope to obtain the same type of information as that shown in Figure 4. However,

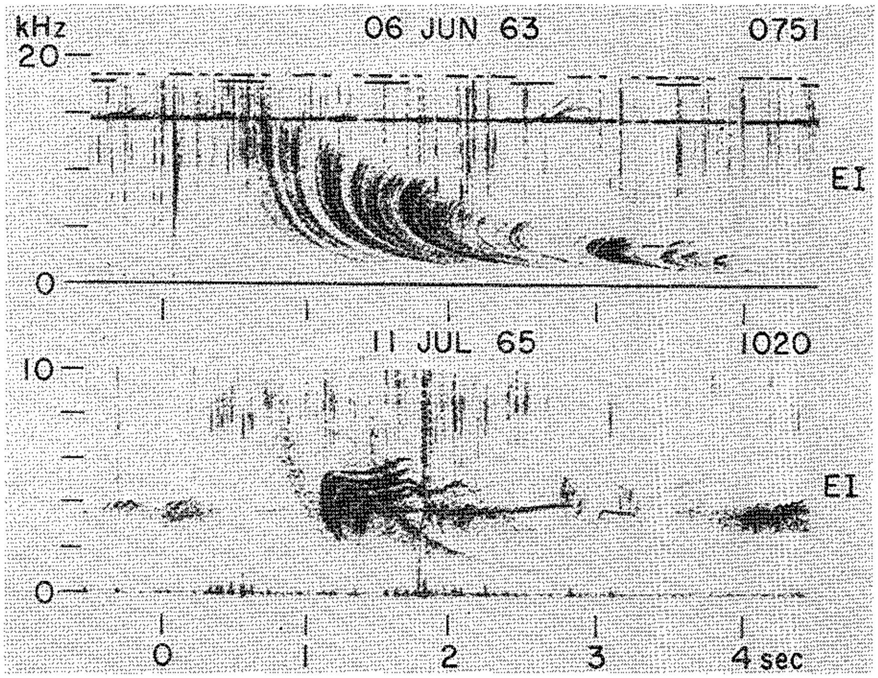

Fig. 4. Nose whistlers and triggered emissions: upper panel shows multipath nose whistler and rising tones triggered by NAA at 14.7 kHz; lower panel shows discrete emissions triggered by nose whistlers at their upper cutoff frequencies ($f_{H_0}/2$). Eights Station, June 6, 1963, 0751 UT (Helliwell, 1969).

experience shows that this is not the case, as illustrated in Figure 5. At Eights many strong one-hop whistler groups are seen in the 20-second segment of the record shown. One of these is seen to echo back to Quebec City, Canada. Much of the detail seen at Eights is missing in the Quebec City record. Thus both the quantity and quality of two-hop whistlers is low on this meridian. Few one-hop whistlers are seen at Quebec City because of the rarity of occurrence of lightning near Eights. The ideal situation is to observe one-hop whistlers from an active lightning region. Eights and other nearby stations meet this requirement and are among the best producers of usable whistlers in the world.

ELECTRON DENSITY MEASUREMENTS USING WHISTLERS

The application of whistlers to the study of electron distribution in the magnetosphere is illustrated in Figure 6. Three separate

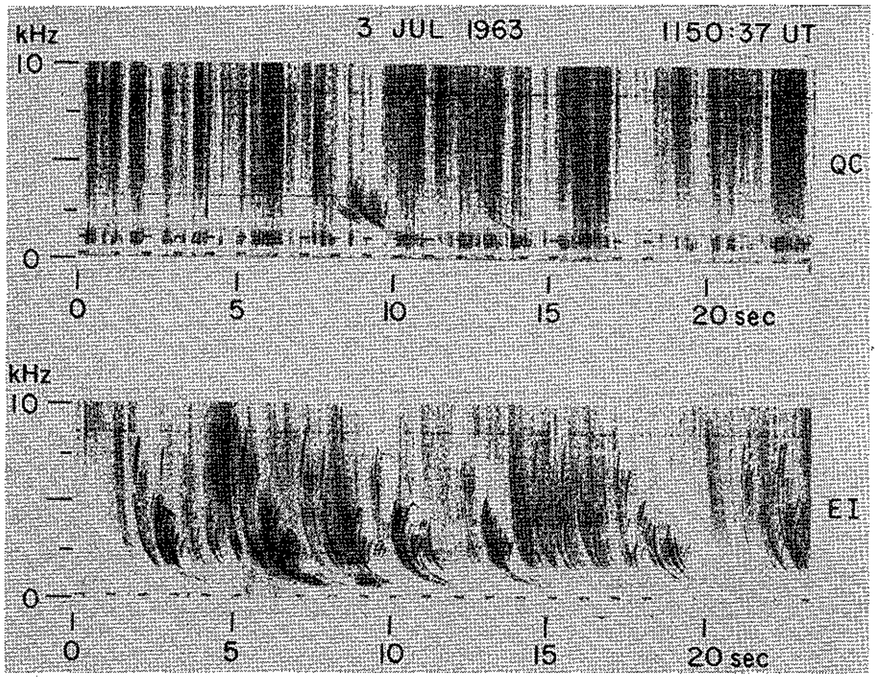

Fig. 5. Nose whistlers observed at conjugate stations Quebec City and Eights on July 3, 1963. One-hop whistlers from many sources are seen at Eights; only two relatively weak groups of echoes are seen at Quebec City. Each source excites many separate ducts.

ducts are assumed, the inner two showing greater time delays than the third. In the right-hand diagram is a meridional cross section of the magnetosphere indicating the location of the ducts corresponding to each of the whistlers. From the travel times and nose frequencies we can obtain the electron density profile in the equatorial plane shown in the lower right-hand corner. A remarkable feature exhibited by these data is the sharp drop or "knee" in electron density occurring between whistler 2 and whistler 3. This has been studied extensively using whistlers from the Antarctic and has been called the "plasmapause." The plasmapause was totally unexpected and is still not completely understood. Whistler data have demonstrated that the distribution of electrons inside the plasmapause, in a region called the plasmasphere, can be described by a diffusive equilibrium model requiring no input from sources other than the ionosphere. Outside the plasmapause, where the density tends to be very much lower, the electron distri-

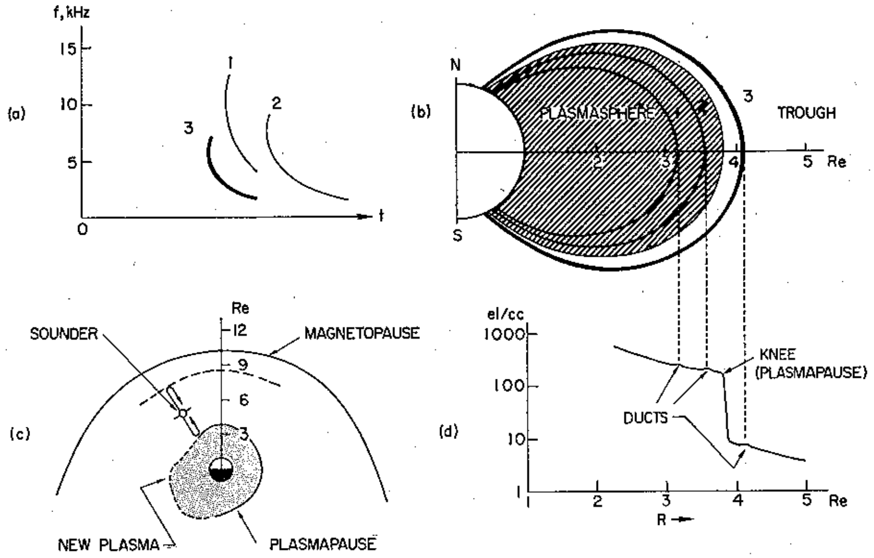

Fig. 6. (a) Nose whistler train, with knee trace; (b) meridional plane showing whistler ducts; (c) boundary of plasmasphere deduced from knee trace; possible detection of plasmapause and magnetopause by low frequency sounder located in trough; (d) equatorial profile of electron density deduced from (a) (Helliwell, 1969).

bution tends to be collisionless in form and appears to be closely connected with events in the tail of the magnetosphere and in the solar wind. The position of the boundary of the plasmasphere shown in the lower left-hand diagram varies with the local time of day, and the plasmasphere exhibits a pronounced bulge on the evening side. This is thought to be the region where high-latitude flow from the magnetospheric tail and the flow impressed by the earth's rotation are opposed. The boundary of the plasmasphere tends to move inward with magnetic disturbance, varying all the way from 6 down to less than 3 earth radii, depending upon the level of magnetic activity.

The differences in the distributions inside and outside the plasmapause are illustrated in Figure 7. Here the equatorial profile shown in Figure 6 reappears in terms of distance along the field lines to the equatorial plane beginning at 1,000 km altitude. The thin lines show the distribution of electron concentration along the lines of force terminating at the indicated radial distance from the center of the earth. It is seen that these lines have very different slopes depending on whether the line falls inside or outside the plasmapause. It is particularly interesting to note that within the

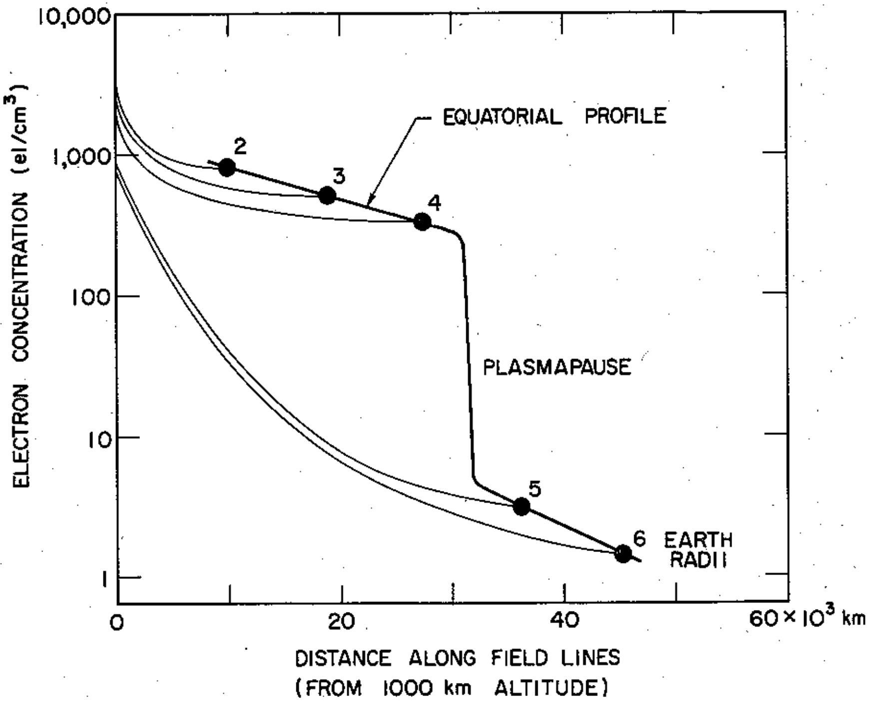

Fig. 7. Electron concentration along field lines beginning at 1,000 km altitude. Numbers indicate geocentric distance to top of field line and heavy lines indicate equatorial profile of electron density.

plasmapause, where diffusive equilibrium applies, the electron density near the equator is nearly constant. On the other hand, outside the plasmapause the variation of electron density with distance along the field line is much more rapid.

In addition to variations with local time and magnetic activity, the ionization of the plasmasphere has recently been found to drift in a systematic way. These drifts were discovered by observing systematic changes in the nose frequencies of ducted whistlers at Eights Station. Each duct drifts as a whole in response to east-west electric fields. Large portions of the magnetosphere can be observed to move inward or outward, depending on the local time at the station and the phase of the associated substorm. Drift rates as high as an earth radius per hour near 4 earth radii have been observed. The whistler has thus revealed a new feature of the magnetosphere and has introduced a new technique for measuring DC electric fields, so difficult to detect by other methods.

EMISSIONS

Closely associated with waves generated by ground sources are the wave phenomena that seem to have their origin inside the magnetosphere or ionosphere. These have been called emissions and fall roughly into two basic categories, the discrete type (chorus), and the steady type (hiss).

Figure 8 shows examples of emissions which include falling tones, rising tones, hooks, combinations of various kinds of discrete emissions and more or less steady bands of noise or hiss. Discrete emissions may be triggered by whistlers, or by man-made signals, or they may appear spontaneously. Hiss at mid-latitudes is often associated with discrete emissions. At high latitudes hiss is more often associated with the aurorae and usually occurs at higher frequencies (> 4 kHz) than mid-latitude hiss.

At conjugate points, such as Great Whale River in Quebec and Byrd Station, we find that the discrete type of emission (and associated hiss) is usually seen nearly simultaneously at the two ends of the path. The example of Figure 9 shows strikingly similar

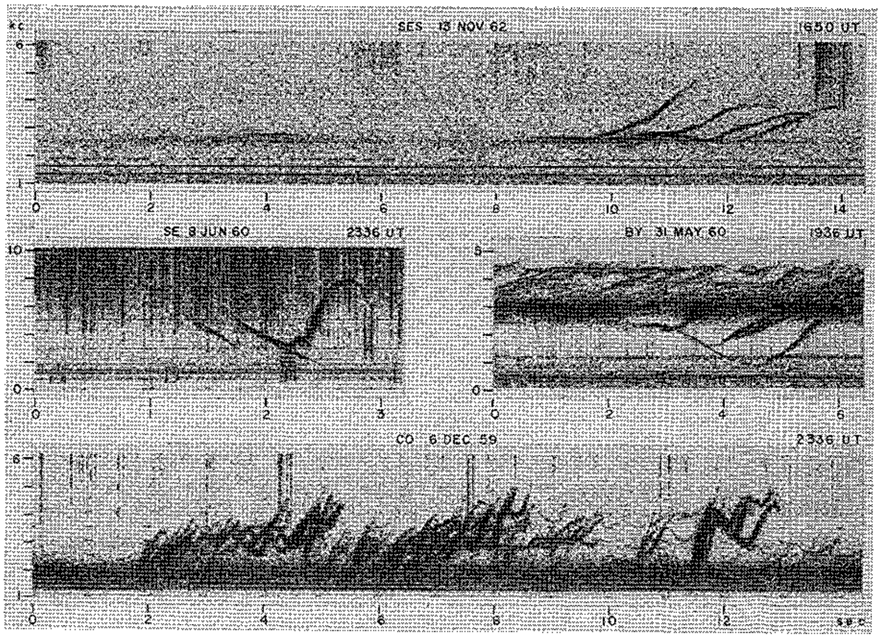

Fig. 8. Discrete emissions including rising tones, falling tones, hooks, and various combinations of these (Helliwell, 1965).

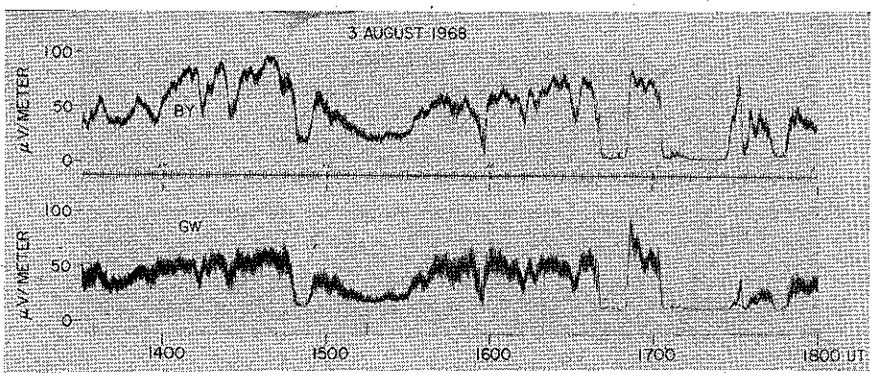

Fig. 9. Noise observed in the band of 1–2 kHz at Great Whale River, Canada, (lower trace) and Byrd Station (upper trace) on August 3, 1968.

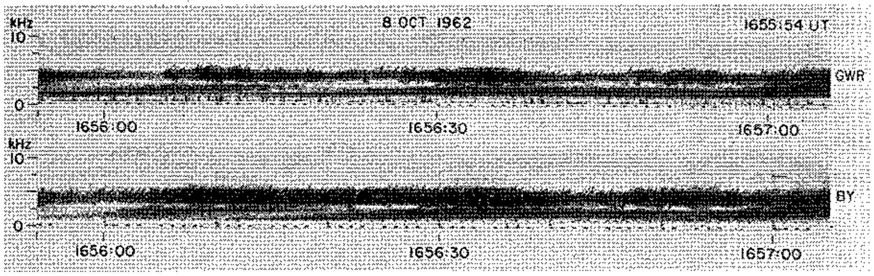

Fig. 10. Conjugate noise spectra recorded at Great Whale River, Canada, (upper panel) and Byrd Station (lower panel) (Helliwell, 1965).

intensity variations at both stations. The time scale is considerably compressed, however, covering five hours of time. When the time resolution is improved, then interesting differences appear in the conjugate noise patterns. Thus in Figure 10 we see another example of conjugate recordings covering 30 minutes of time. Here the dynamic spectrum is shown, rather than just the total field in a limited passband. Again, the gross features are the same at both stations, including the splitting of noise into two principal bands, one centered at roughly 2 kHz and the other at 4 kHz. However, close study shows differences in the fine structure of the discrete emissions appearing in the two records. Faint suggestions of periodic fluctuations can be seen in the upper band, with a period of about 3 seconds.

Detailed study of the differences in conjugate point recordings requires even better time resolution. An example of good time

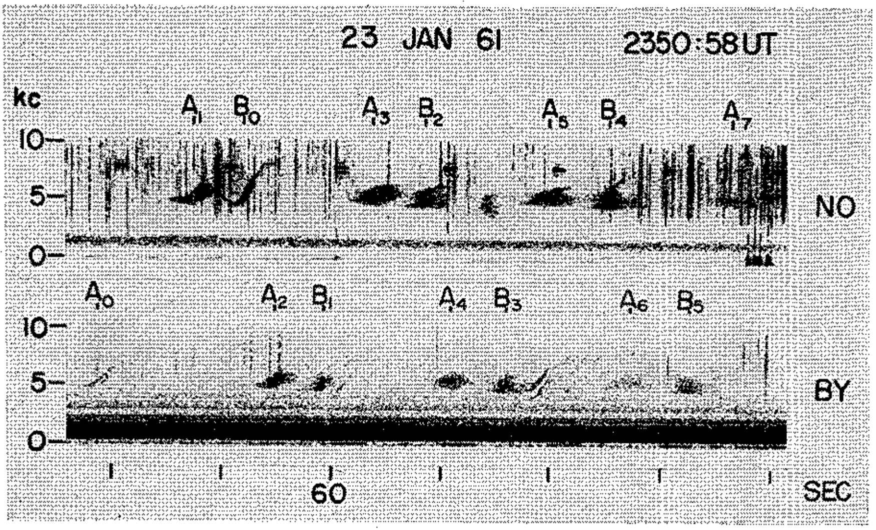

Fig. 11. Conjugate noise spectra recorded at Norwich, Vermont, (upper spectrum) and Byrd Station (lower spectrum). (Helliwell, 1965).

resolution records obtained at the roughly conjugate stations, Byrd, Antarctica, and Norwich, Vermont, is shown in Figure 11. In this series of noise bursts we see a very interesting relation between the events at the two ends of the path. First, we see a weak emission labeled A_0 at Byrd, followed about 1 second later by a stronger burst labeled A_1 at Norwich. This emission triggers a second emission labeled B_0 and both of these are seen to echo back to Byrd with a slight change in form and are labeled A_2 and B_1. This echoing process continues and, as is easily seen, produces a double sequence of periodic emissions (i.e., a two-phase emission) that are exactly 180° out of phase at the two ends of the path. It is known from other evidence that this entire sequence was started by the 9th hop of a whistler. The period between emissions was exactly equal to the echoing period of the whistler at the starting frequency of the emissions. It is deduced from data of this kind that the periodic emissions are in fact nothing more than emissions triggered by the whistler mode echo of the previous emission.

Discrete emissions triggered by man-made signals are called artificially stimulated emissions (ASE's). The example of Figure 12 shows Morse-code dashes from Station NAA located at Cutler, Maine, triggering strong discrete emissions (mainly of the rising type) that were observed on the research ship *Eltanin* near the con-

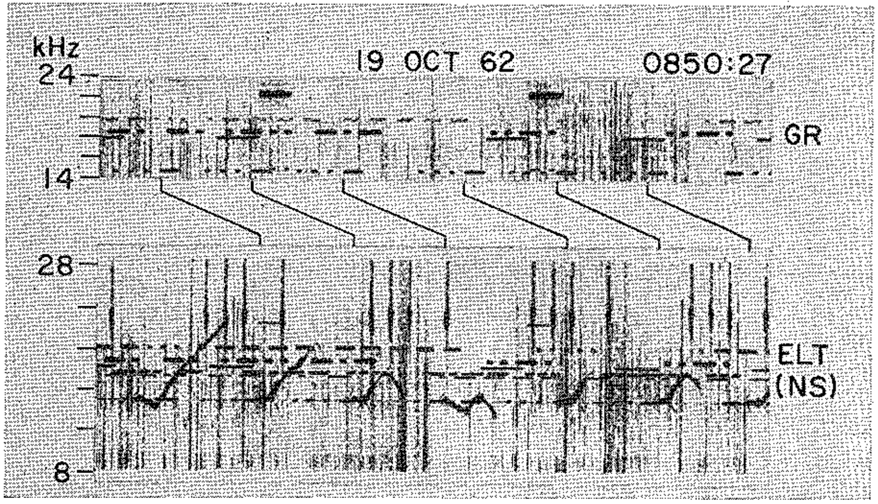

Fig. 12. Artificially stimulated emissions triggered by Morse code dashes from Station NAA. Upper spectrum shows code transmissions recorded at Great Whale River, Canada. Lower spectrum shows the emissions observed on the *Eltanin* in the Southern Hemisphere. Inclined lines connect each transmitted dash with its corresponding emission, observed 0.7 seconds later (Helliwell, 1965).

jugate point. Only the dashes (150 msec duration) produced emissions while the dots (50 msec duration) produced nothing. This result has been observed in nearly all cases of ASE's and suggests that the emission process is dependent on the duration of the triggering signal, with the critical duration being about 100 msec.

To explain the occurrence of triggered emissions, the model shown in Figure 13 has been suggested. It is supposed that the emissions are produced as a result of cyclotron resonance between energetic electrons and whistler-mode waves. The generation region is located at the top of the line of force and the emissions are triggered by an incoming wave packet interacting with electrons streaming in the opposite direction. The radiation is essentially backward-traveling cyclotron radiation which follows the same path as the whistlers. The oscillation is maintained by feedback between the incoming particles and the outgoing waves.

The magnetic field of the outgoing wave causes the electrons to be phase bunched. This phase bunching depends upon the magnitude of the output field and the transverse velocity of the electrons and occurs over a distance of several hundred kilometers. When these particles are phase bunched their radiation goes up by a very

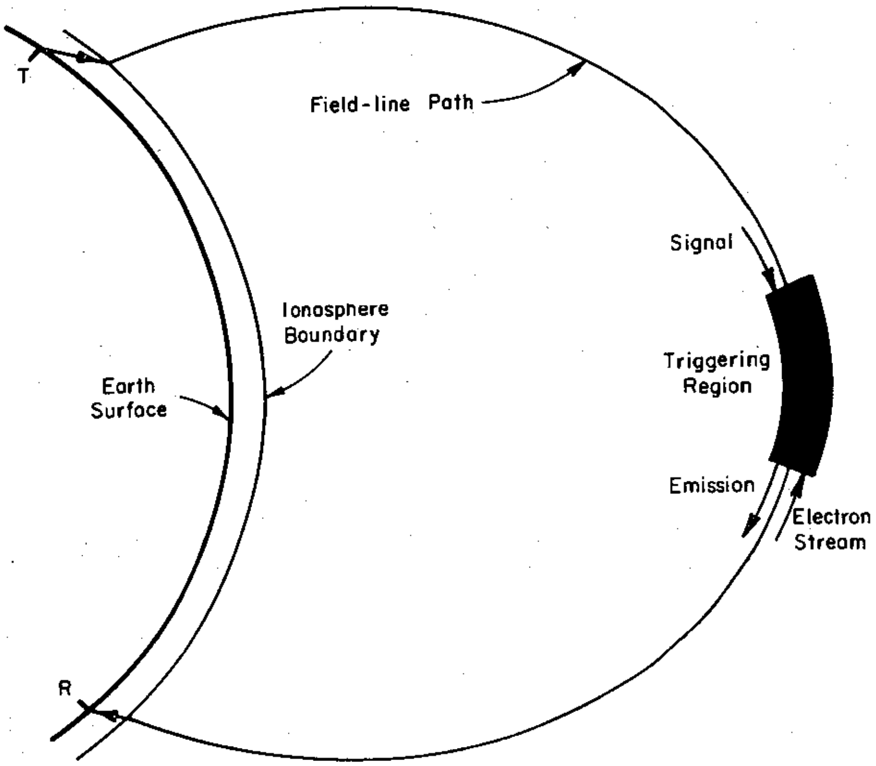

Fig. 13. Model of the generation of discrete VLF emissions based on electron cyclotron resonance (Helliwell, 1969).

large factor; it is this radiation that provides the fields in which the next entering particles are phase bunched. Thus there is established a kind of feedback loop in which the oscillation continues as long as the overall loop gain is greater than unity. Spatial inhomogeneities introduced by the earth's dipole field and the electron density distribution are thought to cause the oscillation frequency to change with time.

Although much remains to be learned about the processes of triggering and evolution of the discrete VLF emission, it appears that this phenomenon could become a powerful new tool for the study of energetic particles in the magnetosphere. Furthermore, the existence of these phenomena suggests the use of the magnetosphere as a kind of plasma laboratory that is free of the size and boundary limitations of man-made laboratories. Thus with the aid of large variable frequency transmitters on the ground or in satellites it should be possible to exercise detailed control of the emission process. In addition, it may be possible to inject energetic electrons of known characteristics that can interact with injected waves so that nearly all of the parameters of the magnetospheric laboratory could be placed under man-made control.

The other main class of emissions is the phenomenon known as auroral hiss. Observations made at Byrd Station first showed that this type of noise is closely connected with the aurora. Auroral hiss is important not only in the study of propagation and emission processes but also in the study of auroral phenomena.

The source of the hiss is not known. One theory suggests that it may be produced by incoherent Cerenkov radiation from intense streams of 1 kev electrons penetrating to the auroral zone. The experimental evidence to date suggests strongly that the mechanism of generation of auroral hiss is not connected with the generation of discrete VLF emissions and its associated hiss. However, much more research will be required to establish quantitatively the origin of auroral hiss. Interest in these relations is great because the aurora is still an enigma in science. Auroral hiss is a relatively new aspect of auroral phenomenology. Because of its quantitative nature and the ease with which it can be observed both on the ground and in satellites, it is possible that it will provide essential information from which a complete theory of auroral phenomena can ultimately be developed. Although the main thrust of this work is scientific, it has already produced a practical application. The intensity of the auroral hiss usually far exceeds the intensity of any other noise source in the Antarctic. As a result, it sets the ultimate limit on the sensitivity of a VLF receiver at high latitudes. Hence a knowledge of its occurrence both in time and space is needed for the design of high-latitude VLF communication and navigation systems as well as for VLF propagation experiments.

SUMMARY

I should like to summarize this brief review with the sketch of Figure 14, a model of the relation of VLF phenomena to the magnetosphere. The region beyond the plasmapause might be termed the polar magnetosphere since it is closely connected with high-latitude phenomena. Here are shown the polar chorus (a high-latitude form of chorus appearing near 700 Hz), auroral hiss, and other types of chorus and hiss that are not ducted and hence are the December solstice, it is constantly in sunlight. On the other hand, its conjugate point experiences day and night at all seasons. Thus it is possible by studying events at the conjugate points to have a wide range of combinations of orientation of the magnetosphere with respect to the solar wind while at the same time varying the amount of illumination on the lower ionosphere. Finally we note that the location of Eights maximizes the variation in the angle between the solar wind and the geomagnetic equatorial plane at noon and midnight. This situation should make it easier to detect north-south asymmetries in the magnetosphere resulting from the tilt of the earth's dipole with respect to the solar wind.

As a result of over ten years of study, much of it in the Antarctic, the propagation and emission of low frequency waves in the ionosphere and magnetosphere is much better understood. Our knowledge of the phenomena extends from well-documented, widely accepted interpretations to completely unexplained effects. Much work remains to be done before known questions can be completely answered. For example, it will be desirable in the future to develop improved methods for making simple, reliable measurements of the direction of arrival of whistler-mode signals. This will aid in the location of emission sources and in the tracking of ducts carrying whistler-mode signals. Because of the ease with which waves may be injected into the magnetosphere from the ground, it appears that controlled experiments employing ground-based VLF transmitters offer much promise for the future. Of special interest in this connection are the experiments currently being undertaken at Byrd Station using a long-wire VLF transmitter. While these are in the preliminary stages, available evidence suggests that with an improved antenna located at a lower geomagnetic latitude ($L \cong 4$), important contributions to the understanding of wave-particle interactions can be obtained. Closely related to the ground-based controlled experiments are those that might be conducted from satellites employing large antennas excited by very low frequency transmitters. Ultimately it is conceivable that means will be found to modify the magnetospheric environment itself through the effect of VLF waves on the concentration of energetic trapped radiation.

Back on the ground we can see an increasing need for quantitative studies of the correlation between VLF auroral effects and other auroral properties such as the light output and associated absorption and micropulsation events. Especially interesting in this connection is the possibility of coordinating VLF experiments with auroral TV experiments.

Finally, we should note the possibility that some of the research in the Antarctic might be carried on using unmanned geophysical observatories. These would be placed on the ice at appropriate locations and telemeter their data back to the home laboratory via communication satellite. This scheme would make possible the rapid analysis of data and could greatly advance the rate of research. (At present up to a year may elapse before data analysis can begin.) A "talk-back" circuit could be used to optimize experiment parameters in the light of the received data.

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