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NATURAL ELECTROMAGNETIC PHENOMENA

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WHISTLERS AND VLF EMISSIONS

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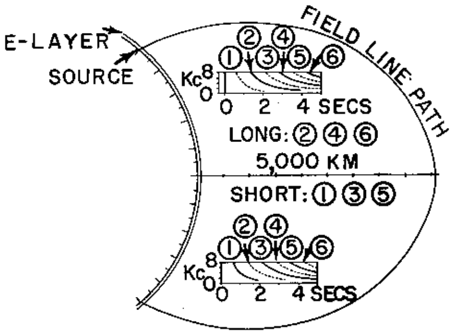
INTRODUCTION

The purpose of this paper is to review briefly some of the research on whistlers and VLF (very low frequency) emissions, and to present the spectra of VLF phenomena observed at geomagnetically conjugate points.

Before reviewing the results of some of the research, a brief description of the phenomena should be helpful. Whistlers are produced by the electromagnetic impulses from lightning and are observed mainly in the range of frequencies from 300 cps to 30,000 cps. Much of the energy of the impulse is reflected from the ionosphere back to the ground where it is the main source of interference to radio communication from very low to high frequencies. Some of the energy enters the ionosphere, where it is guided by the earth's magnetic field into the opposite hemisphere. Dispersion in the ionosphere stretches the original impulse into a gliding tone (order of one second in duration), which is called a whistler. A typical whistler path is shown in Fig. 1, and the associated spectra which would be observed at the two ends of the path are sketched in the figure inserts. An actual recording is shown in Fig. 2. Whistler paths appear to be fixed in the ionosphere at any given time and often two or more such paths can be observed simultaneously, giving rise to what is known as the multiple path whistler. The shape of the frequency vs. time curve of the whistler is determined by the dispersion, which is controlled by the electron density and the earth's magnetic field. Details of the dispersion and guiding of whistlers are treated elsewhere (Storey, 1953; and Helliwell, 1964).



DASHED LINES: HYBRID TRACES

Fig. 1. Dipole field line model with inserts of even and odd whistler echo trains.

A second class of phenomena, known as VLF emissions, are observed at whistler frequencies. These phenomena are less well understood than whistlers, but are believed to originate in the ionosphere.

VLF emissions can be detected and recorded with the same equipment employed in the study of whistlers. In fact, several types of emissions are often observed in close association with whistlers. Emissions appear in a wide variety of spectral forms; an emission may be relatively steady over a period of minutes, or even hours, or occur in discrete bursts as short as a fraction of a second. The amplitude of emissions frequently fluctuate in a periodic or quasi-periodic manner, with periods ranging from less than a second to more than a minute.

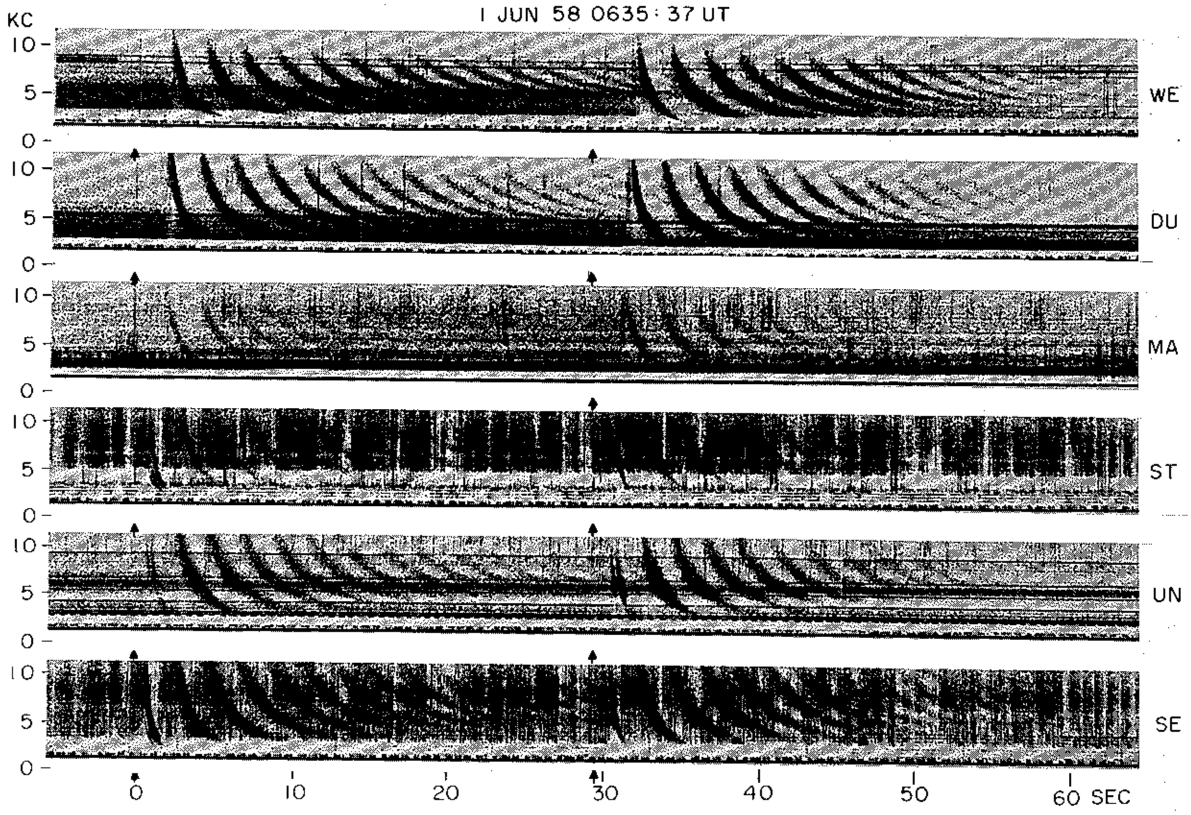


Fig. 2. Long enduring echo trains recorded at Wellington, New Zealand; Dunedin, New Zealand; MacQuarie Island; Stanford, California; Unalaska, Alaska; and Seattle.

VLF emissions, like whistlers, are localized geographically and are observed most commonly at middle and high latitudes. Particularly intense emissions are found in the auroral zone. At locations which are geomagnetically conjugate to one another, emissions are often closely related in form as well as time of occurrence.

As a function of magnetic activity, emission activity generally increases at low latitudes and decreases at high latitudes. The latitude of peak activity descends with increasing K_p. A close association exists between auroral phenomena and certain types of emission.

Before the beginning of the IGY, the understanding of whistlers and related phenomena was relatively limited. Whistlers were first described by Barkhausen (1919), who heard them while eavesdropping on Allied telephone communications at the front lines during World War I. In 1928, Eckersley (1928) in England reported an association between whistlers and lightning and also between whistlers and solar activity. The first evidence of VLF emissions was reported by Marconi workers, who heard and described the so-called "dawn chorus" in 1931. Measurements of the dispersion of a whistler were reported by Burton and Boardman (1933) of the U.S.A., following which Eckersley published an approximate form of the dispersion law which provided an explanation for the observed dispersion. Further research on whistlers was interrupted by World War II, following which, Storey began his investigations (1953) at Cambridge, England. He published his well-known paper in which the field aligned whistler path was proposed and a calculation of the outer ionosphere electron density was made. Storey's results were first presented to the scientific community by J. A. Ratcliffe at the URSI General Assembly held in Sydney, Australia, in 1952, and stimulated a number of groups in various countries to begin studies of this fascinating topic. Several tests of Storey's theory of the field-line path were carried out including the observation by Morgan and Allcock (1956) of whistlers at conjugate points showing approximately the relationship sketched in Fig. 1. Extension of observations to high latitudes revealed a new type of whistler which showed in addition to the falling tone a rising component that was joined smoothly to the descending component at the beginning of the whistler. This strange shape was called the "nose" whistler and was explained by the magneto-ionic theory after the limiting restrictions of Storey and Eckersley were removed. Later, nose whistlers were discovered at middle latitudes in accord with predictions of the theory. A multiple-path nose whistler is illustrated in Fig. 3. The nose whistler provides a means for determining the latitude of the associated field-line path, called the path latitude, necessary in using dispersion data for the study of the electron density in the magnetosphere.

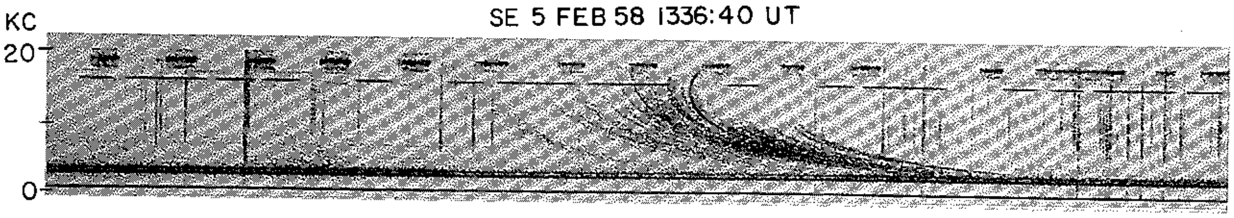


Fig. 3. A multi-path nose whistler recorded at Seattle, Washington.

The plan of the paper is to present introductory remarks on whistler theory, and follow this with three main sections, the first devoted to some recently obtained experimental results on the shape and variations of the equatorial profile of magnetospheric electron density, the second describing periodic emissions and their probable generating mechanisms, and the third an Atlas of whistlers and emissions recorded at geomagnetically conjugate points.

WHISTLER PROPAGATION THEORY

Whistler dispersion is essentially the result of an interaction between the wave, free electrons, and the geomagnetic field. Since the number density of electrons with low thermal energies ($T \sim 1500^\circ K$) is usually far greater than the density of energetic electrons, a cold plasma theory is sufficient to predict the dependence of dispersion on electron concentration.

The principal features of whistler propagation can be deduced from the magneto-ionic theory, which shows that in the ionosphere, a very low frequency wave can propagate freely in the circularly polarized ordinary mode. At very low frequencies the refractive index of the ionosphere can be represented by the quasi-longitudinal approximation of the magneto-ionic theory (Budden, 1961). This is given by

$$n^2 = 1 - \frac{X}{1-iZ \pm |Y_L|} \qquad (1)$$

where

n = complex refractive index = $\mu - i\chi$

$X = f_O^2/f^2$

$Z = \nu/2\pi f$

$Y_L = f_L/f$

f = wave frequency

θ = angle between wave normal and earth's magnetic field

f_O = plasma frequency

ν = electron collision frequency

f_H = electron gyrofrequency

$f_L = f_H \cos\theta$

Because most of the whistler path is characterized by the conditions

$$Z \ll Y_L \quad \text{and} \quad X/|Y_L| \gg 1$$

it is convenient to neglect the effect of collisions as well as the first term on the right side of Eq. (1). When this is done, the expression for the refractive index is

$$n^2 = \mu^2 = \frac{X}{Y_L - 1} = \frac{f_O^2}{f(f_L - f)} \qquad (2)$$

The expression for the group refractive index is obtained from the relation

$$\mu_g = \frac{d}{df}(\mu f) \qquad (3)$$

which gives

$$\mu_g = \frac{f_O f_L}{2f^{1/2}(f_L - f)^{3/2}} \qquad (4)$$

In order to make ray-path calculations using Eq. (4), it is necessary to make an additional assumption about the distribution of f_O (or N) in the magnetosphere. If a "smooth" model is used, with electron density decreasing smoothly with height, the calculations predict that whistler ray paths will depart significantly from the direction of the geomagnetic field. On the other hand, if the distribution is assumed to involve field-aligned irregularities, then it is possible to cast the ray path problem in terms of trapping and guiding along field-aligned ducts. Fortunately, the question of a choice between the two assumptions is easily resolved in favor of the latter, since experimental data provide an unambiguous indication that whistlers propagate on discrete, field-aligned paths.

A study of guiding along ducts (Smith, 1961a) has shown that the actual travel time on a duct may be closely approximated by assuming strictly longitudinal field-line propagation. Use of this important simplifying assumption means that: (1) all frequencies are considered to travel along the same path; (2) the complications of a twisting, only approximately field-aligned ray path, are avoided. In Eq. (4) we set $f_H + f_L$, and for the travel time at a given frequency obtain the expression

$$t = \frac{1}{c} \int_{path} \mu_g ds = \frac{1}{2c} \int_{path} \frac{f_o f_H ds}{f^{\frac{1}{2}}(f_H - f)^{3/2}} \qquad (5)$$

where c is the velocity of light and ds is an element of the field-line path.

The justification of the assumption of strictly longitudinal propagation is obviously of crucial importance, and it is discussed in detail in Helliwell (1964). For the present, we shall take the assumption to be justified, and will remark briefly on the properties of Eq. (5).

This equation shows that whistler travel time is proportional to a weighted integral of plasma frequency ($f_o \propto N^{\frac{1}{2}}$, where N is the number of density electrons). The incremental travel time of a whistler varies approximately as $f_H^{-\frac{1}{2}}$, which means that the observed frequency vs. time, or dispersion curve of a whistler will be particularly sensitive to electron density and magnetic field strength along the outer, equatorial portion of the path. It is this sensitivity which is used to advantage in deducing equatorial profiles of electron density from whistler data (Smith, 1961b; Helliwell, 1961; Carpenter, 1962a, 1963a).

THE EQUATORIAL PROFILE OF MAGNETOSPHERIC ELECTRON DENSITY

Studies of electron density distribution using whistlers made rapid progress following the IGY. An initial survey of temporal variations in the equatorial profile has been provided by: (1) low-frequency dispersion measurements, which essentially follow variations in the profile at a given height; (2) nose-frequency measurements, which can follow temporal variations over significant segments of the profile. These initial results will be briefly summarized in this section. Limitations of space prevent detailed remarks on regions of applicability. [Present methods of studying temporal density variations assume that the field-line model of f_o used in the calculations does not change between successive measurements. Removal of this assumption will make it possible to present a more physically detailed picture, particularly in the case of the diurnal and solar cycle variations.]

The Diurnal Variation.

This variation is one of the most difficult to study because of the amount of data and analysis required. As reported, the diurnal variation involves an afternoon density maximum and a post-midnight minimum, the amount of the reduction being about 30 per cent in many cases. (Iwai and Outsu, 1958; Rivault and Corcuff, 1960; Allcock, 1960). The diurnal variation may exhibit important changes in amplitude with season and solar epoch (Kimpara, 1962 and Corcuff, 1962). As yet, no detailed diurnal study based on nose-frequency information has been reported.

The Annual Variation.

The annual variation in electron density in the magnetosphere shows a maximum near the December solstice and a minimum near June (Smith, 1961c and Helliwell, 1961). This variation has been studied over a relatively wide range of geomagnetic longitudes and is found to show a declining amplitude with decreasing solar activity, (Carpenter, 1962a and Gomez et al, 1962). From nose-frequency data at Stanford and Seattle for the range 2 to 4 R_E (R_E is the radius of the earth), Carpenter (1962a) observed a reduction from January to June in 1958 by about 35 per cent and a corresponding reduction in 1961 by about 20 per cent. It is interesting that the phase of the annual variation agrees with the corresponding observations made by satellite drag measurements, which show a December maximum and June minimum in air density in the height range 200 to 600 km (Paetzold and Zschörner, 1961a).

The Semi-Annual Variation.

The semi-annual variation of magnetospheric electron density has recently been studied by Corcuff (1962), who reports finding density maximums in the October-November period and in the April-May period. For dispersion data taken at Poitiers, France (49.5°N geomagnetic) in the period June 1957 to December 1958, Corcuff finds a density ratio of minimum to maximum of about 0.75. As in the case of the annual variation, the semi-annual variation is approximately in phase with the air-density variations deduced from satellite drag (Paetzold and Zschörner, 1961b; Martin et al, 1961; Jacchia and Slowey, 1962).

The Solar Cycle Variation.

Beyond 2 R_E (geocentric distance), the change in electron density over the solar cycle appears to be relatively small. From Stanford and Seattle nose-frequency data, Carpenter (1962a) estimated the density reduction from early 1958 to early 1961 to be 20 to 25 per cent, in contrast to a corresponding reduction in f_oF2, (at Washington, D. C.) of about 60 per cent. The density reduction in the magnetosphere from 1958 to 1961 was found to be most pronounced near the December solstice (Carpenter, 1962a, and Gomez et al, 1962). More detailed studies will probably reveal a relatively large solar-cycle variation in the profile between 3000 and 7000 km altitude. If the plasma frequency below about 2 R_E (geocentric) drops significantly, this would probably be evident in the dispersion of Alouette satellite whistlers (Barrington and Belrose, 1963) recorded at low latitude. The drop in f_o might also be manifested by anomalous behavior of the extraordinary trace on topside ionograms, an effect discussed by Thomas et al (1963).

The Magnetic Storm Variation.

During the main phase and recovery phase of magnetic storms, electron-density levels in the magnetosphere are often depressed. The effect has been observed at relatively low latitudes following severe storms (Kimpara, 1962, and Outsu and Iwai, 1962) and it is regularly observed at latitudes corresponding to the equatorial range 2 R_E to 7 to 8 R_E (Carpenter, 1962a, 1962b, 1963b, and Corcuff, 1962). In the geocentric range 2 to 4 R_E, storm-period density levels are often depressed by 15 to 20 per cent, occasionally being reduced by a factor of as much as 10. The "knee" in the profile has a strong dependence on geomagnetic activity and appears to account for a substantial number of the observations of deep density depressions.

Conclusions.

An initial survey of the temporal variations in magnetospheric density has been made. Future investigations will present a more detailed picture of this subject through considerations of variations with time in the form of the field-line distribution of ionization.

The whistler technique has proven relatively easy to use. As a passive technique, it is relatively inexpensive, and is logistically flexible. The method appears capable of increasing theoretical and experimental refinement.

PERIODIC VLF EMISSIONS

Among the many remarkable types of VLF emissions is one which consists of short bursts of noise repeated at a regular interval, the length of which is of the order of a few seconds. These events we shall call periodic VLF emissions, examples of which have been reported by a number of investigators.

The first spectra of periodic emissions were presented at a meeting of the U.S.A. National Committee of the URSI, by Dinger (1957). Other examples have been published by Gallet (1959), Pope and Campbell (1960), Lokken et al (1961), and Brice (1962).

Periodic VLF emissions can be classified as either "dispersive" or "non-dispersive." In the dispersive type the period between bursts varies in a systematic way with frequency. Often this variation is exactly the same as that found in associated echoing whistlers, from which it is deduced that each burst is the result of whistler-mode echoing of the previous burst. In non-dispersive periodic emissions there is little or no observable systematic change in period with frequency.

The dispersive type of periodic emission is illustrated in Fig. 4, which shows

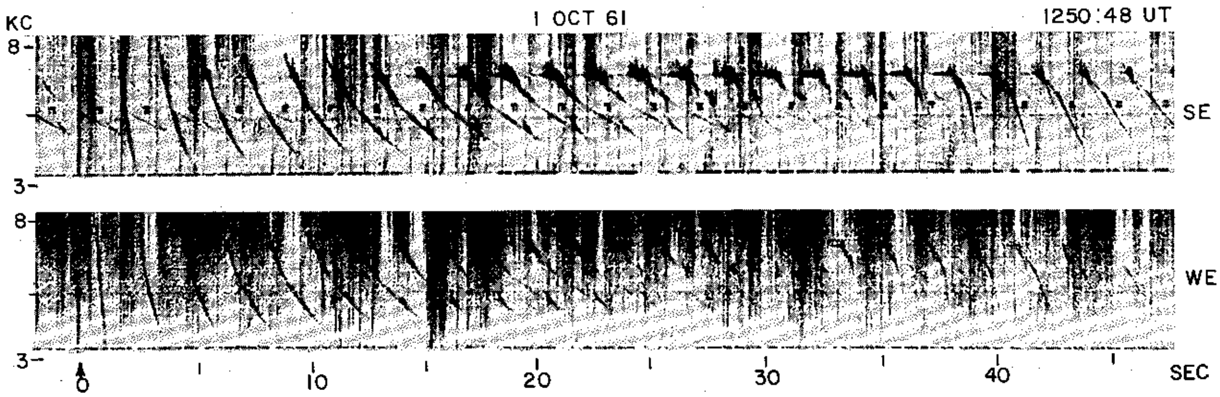


Fig. 4. Whistler-echo trains and associated VLF emissions recorded simultaneously at Seattle, Washington, and Wellington, New Zealand.

the spectra made from tapes recorded simultaneously at Seattle, Washington (North geomagnetic latitude 53°), and Wellington, New Zealand (South geomagnetic latitude 45°), on 1 October 1961, 1250 UT (Helliwell et al, 1962, and Helliwell, 1963). The period of observation was preceded by a sudden commencement magnetic storm beginning at 2109 UT, September 30, 1961. A magnetic K_p index of 8 was observed during the associated three-hour period. The echo train is of the two-hop, or "long" type at Seattle, and of the one-hop, or "short" type at Wellington.

The same whistler-echo train and related noise bursts were observed at several other stations (spectra not shown), including Stanford, California; Logan, Utah; Lauder, New Zealand; and Byrd Station, Antarctica. Since the details of the spectral shapes recorded at these other stations are identical to those presented in Fig. 4 from Seattle and Wellington, only the latter two recordings are presented. It is concluded that the whistlers and associated noise traveled over the same magnetic field-line path and, after exiting from the ionosphere, reached the receivers by propagating in the earth-ionosphere wave guide.

The echoing of the whistler can clearly be detected up to about the 26th hop on the Seattle record. After the first one or two hops, an emission appears in the form of a slight irregular broadening on the trailing edge of the whistler trace, mostly in the frequency range 6 to 7 kcps and to a lesser extent in the range 4 to 5 kcps. With each successive echo the intensity of the emission in the upper frequency range increases while the echo of the original whistler becomes weaker.

The difference between the echoing emission and the echoing whistler is especially obvious at and following the 16th hop, after which the emission appears to be stronger than the associated whistler echo. On the 39th hop, at Wellington, a marked downward extension of the noise burst (a falling tone) appears for the first time and then echoes in the whistler mode to the end of the record. On the 40th hop at Seattle a similar downward extension occurs, preceding the echo of the first falling tone at Wellington, and it too echoes in the whistler mode. The echoing periods of both of the falling tones are exactly the same as those of the parent whistler at corresponding frequencies.

It will be recalled that an association between emissions and whistlers was reported by Storey (1953), who observed that if a whistler occurred during a period of general riser activity, it would usually be followed by a riser. He cited spectrograms of such events which were published by Potter (1951). The relationship between whistlers and "triggered" emissions is covered by Helliwell (1963). There is a clear suggestion of a cause and effect relationship in which the emission is initiated or "triggered" by the whistler. A logical extension of this idea is to suggest that an emission may also be triggered by another emission propagating in the whistler mode. If this triggered emission echoes in the whistler mode at the appropriate frequency, then the triggering process is repeated, giving rise to a set of periodic emissions in which the period is equal to the whistler mode group delay at the triggering frequency. Strong absorption of the whistler-mode echo of the emission over most of its frequency range coupled with strong emission gives non-dispersive periodic emissions, while the reverse situation gives the dispersive type (Helliwell, 1943).

In all attempts to explain the non-dispersive periodic emissions, the authors assume the a priori existence of a small bunch of charged particles that oscillates between mirror points in the earth's magnetic field. It is also assumed that the bunch radiates a noise burst each time it passes through a favorable region of the ionosphere plasma, so that the emission period is the same as the mirror period of the bunch. We shall refer to this explanation as the "particle-bunch" theory of non-dispersive periodic VLF emissions.

For the particle-bunch theory of non-dispersive periodic emissions to be acceptable, the particle-bunch would have to be related to the whistler producing atmospheric and the mirror period for the particle-bunches would have to be the same as the whistler-mode echo period at the triggering frequency. Furthermore, the nearly identical periods for several sets of periodic emissions would require that the several corresponding particle-bunches have almost exactly the same mirror period. Since these conditions appear most unlikely, the particle-bunch theory is ruled out as an explanation of non-dispersive periodic emissions.

Acceptance of the triggering hypothesis, on the other hand, leads to explanations of other emission phenomena not previously understood. Under conditions similar to those which yield non-dispersive emissions (Helliwell, 1963), a parent whistler might be undetectable because of absorption, so that only the triggered emissions would be observed (Fig. 5 could be placed in this category).

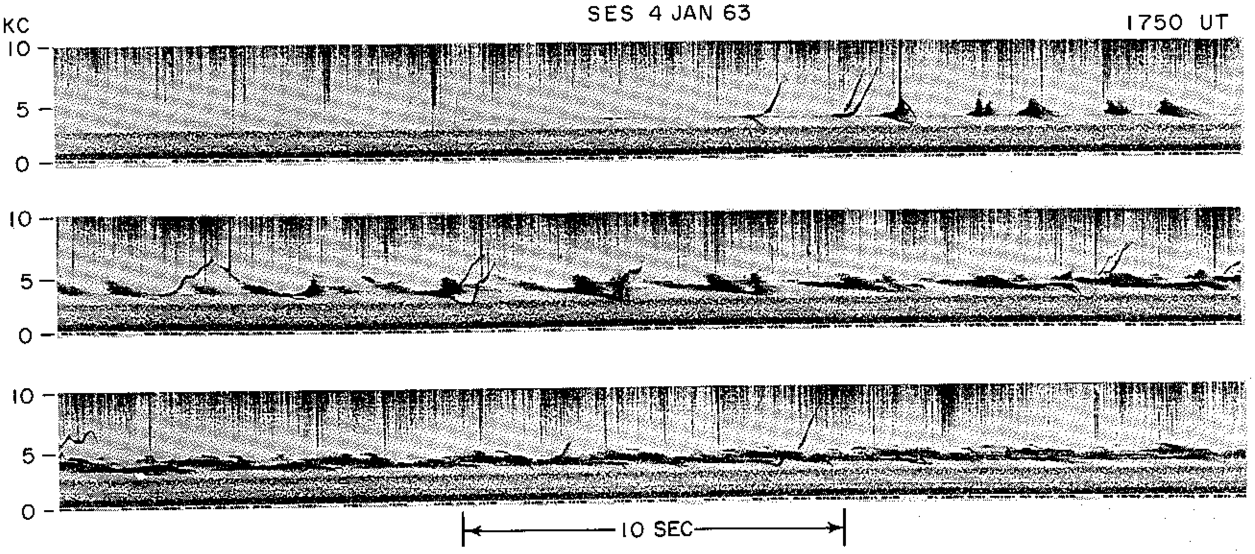


Fig. 5. Multi-phase periodic emission recorded at Suffield Experimental Station, Alberta, Canada.

Multi-phase periodic emissions are a common occurrence. An example of three phases is shown in Fig. 6. The sets appear in a limited frequency band and are identified by the letters A, B, and C. An example of twelve phases is shown in Fig. 7. Also in Fig. 7 can be seen an emission, which then echoes, triggered by $W_{4,T}$ of whistler W_O. A multi-phase non-dispersive periodic emission which goes from a three, to a two, to a one phase emission twice in thirty minutes is shown in Fig. 8. A superposition of multi-phase emissions is shown in Fig. 9 and Fig. 10.

The cause of the equal spacing between sets of emissions in Fig. 8 is not known but it may be related to a "recovery" time in the medium. Let us suppose that the

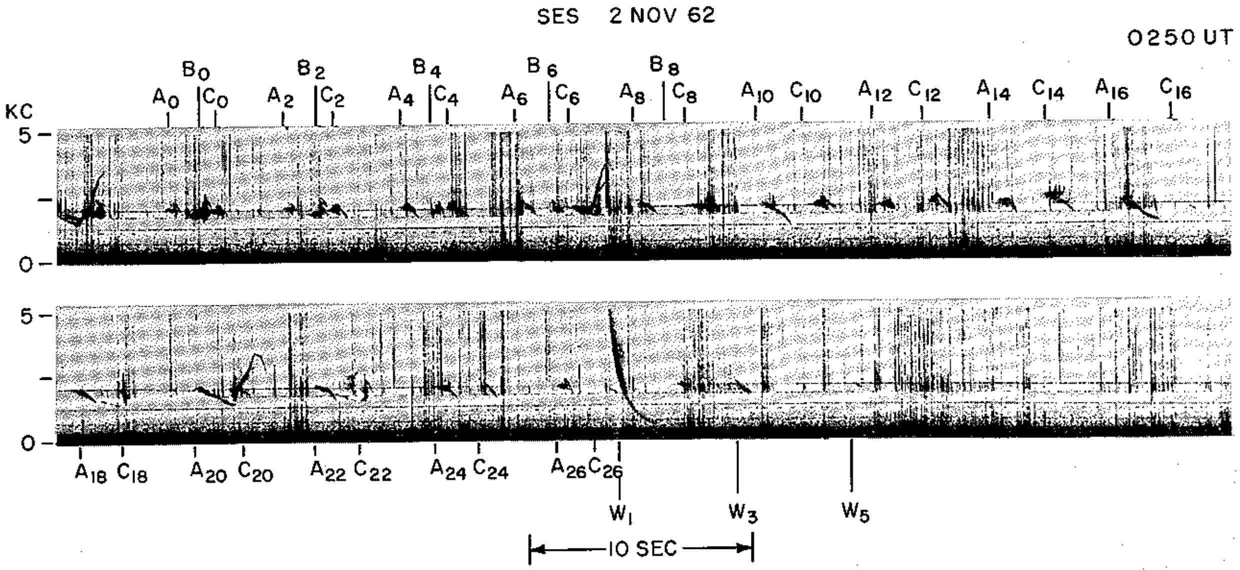


Fig. 6. Multi-phase periodic emission recorded at Suffield Experimental Station, Alberta, Canada.

emitting region is temporarily disorganized after each burst, and so any attempt by a wave packet to stimulate a new emission will be resisted. The new effect is to delay very slightly the generation of a burst with respect to the preceding burst (or a different set, of course). After many periods this tendency would produce roughly equal spacings, as observed.

Of particular interest in multi-phase emissions are those cases in which the number of phases is even and the spacings between phases the same. The conjugate point records would then show an in-phase relationship if the basic period were taken (incorrectly) to be the true period divided by an even integer equal to or less than the number of phases. On three-phase emissions one must be sure that he is not misinterpreting the basic period, taking the true period to be one-third of the basic period.

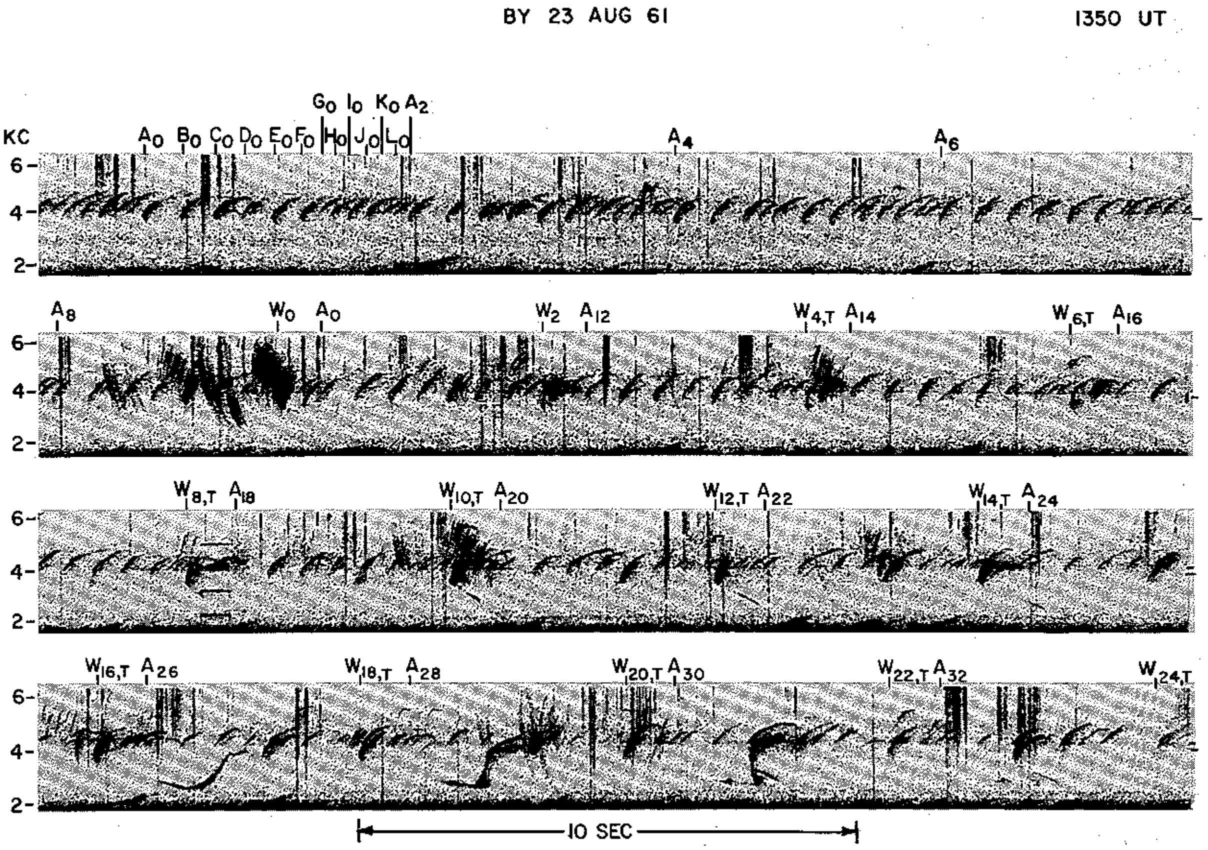


Fig. 7. Multi-phase periodic emission and triggered emission recorded at Byrd Station, Antarctica.

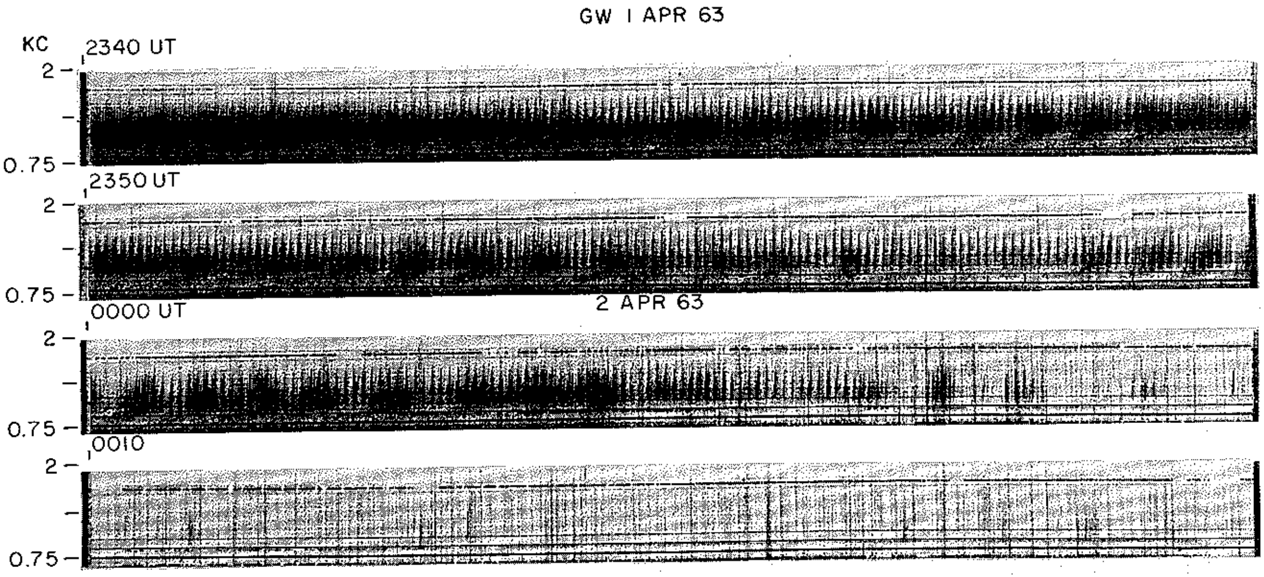


Fig. 8. Multi-phase periodic emission recorded at Great Whale River, Canada.

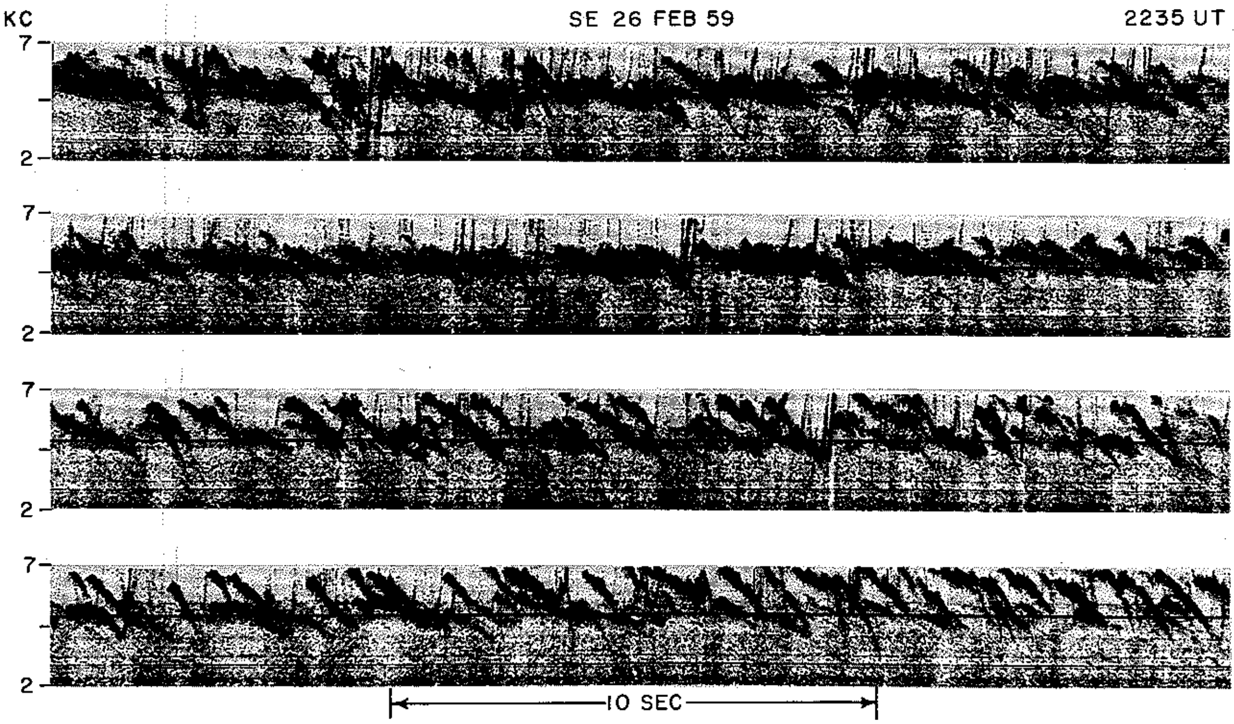


Fig. 9. Multi-phase periodic emissions recorded at Seattle, Washington.

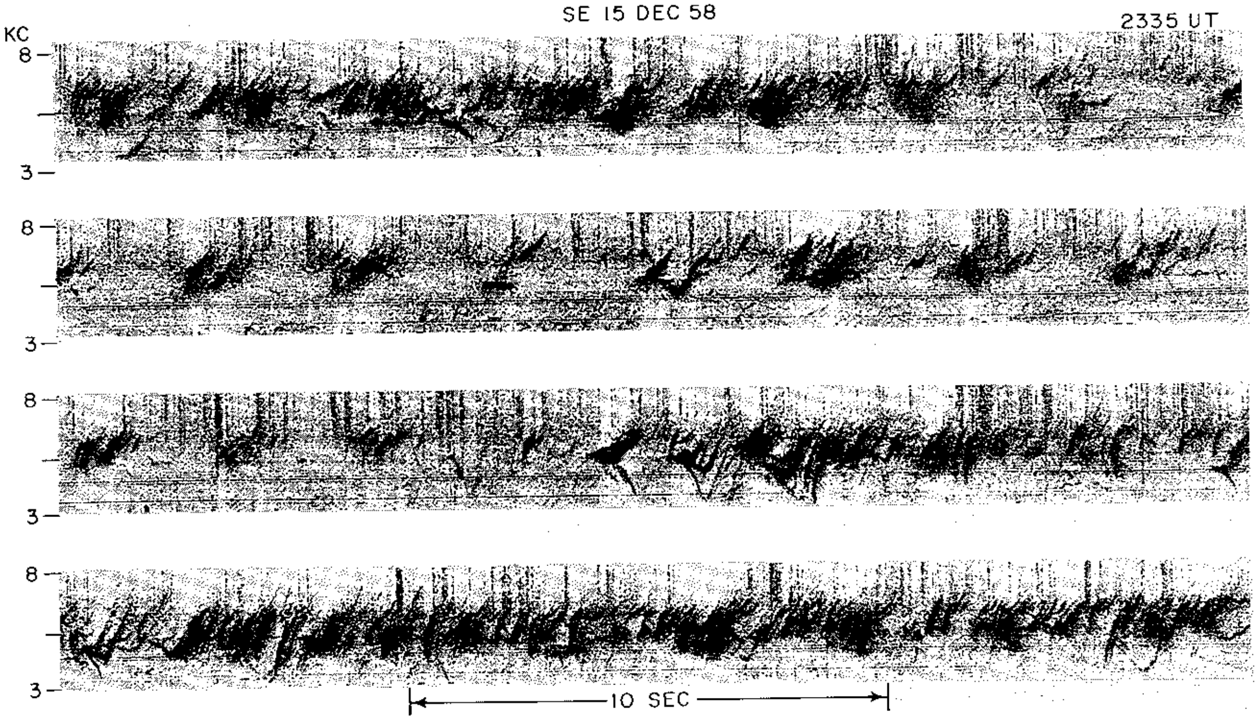


Fig. 10. Multi-phase periodic emissions recorded at Seattle, Washington.

Emission Mechanisms.

Although no detailed theory of VLF emissions has yet been developed, there is general agreement that their sources must be situated in the ionosphere. Extra-terrestrial sources have not been considered because the magnetosphere is thought to be opague to VLF energy from outside and because the noise is often closely related to whistlers. In current theories the electromagnetic energy of the emission is derived primarily from the kinetic energy streams of charged particles trapped on the lines of force of the earth's magnetic field. Possible sources of power for the streams and mechanisms for conversion of this power are considered by Sturrock (1962).

Conversion mechanisms that have been considered can be divided into two main categories, depending on whether the longitudinal motion or the transverse motion of the charged particles is the controlling factor. Mechanisms depending on longitudinal motion include Cerenkov radiation and a kind of amplification somewhat analogous to that observed in a laboratory traveling wave tube. The transverse motion of charged particles in the earth's magnetic field is very nearly circular and the associated radiation is of the cyclotron type.

A mechanism for "organizing" the transverse radiation from the particles has been proposed by Brice (1963). An instability in the transverse interaction has been demonstrated by Bell and Buneman (to be published), an important step in establishing the validity of this mechanism.

AN ATLAS OF VLF PHENOMENA RECORDED AT GEOMAGNETICALLY CONJUGATE POINTS

The whistlers and emissions presented here were recorded at three pairs of conjugate stations as shown in Fig. 11. The three are:

(1) Unalaska - Dunedin

(2) Great Whale River - Byrd Station

(3) Carde (near Quebec City) - Eights Station (also known as Sky-Hi during the Austral Summer of 1961-62)

The spectra were prepared at Stanford University with the aid of the Rayspan spectrum analyzer (Helliwell et al, 1961). The phenomena spectrum analyzed were recorded in real time on magnetic tape.

Simultaneous spectrograms have been accurately synchronized by comparing the VLF transmitter signals that are included in the broadband information recorded on the tapes. Frequency conversion of these signals places them at the bottom of the spectrogram. The same technique has been used in some illustrations to provide absolute time reference using transmitter NBA, which transmits 300 ms pulses whose leading edges mark the beginning of each second, except for the 29th, 56th, 57th, 58th, and 59th seconds, at which the pulses are omitted.

ATLAS OF FIGURES

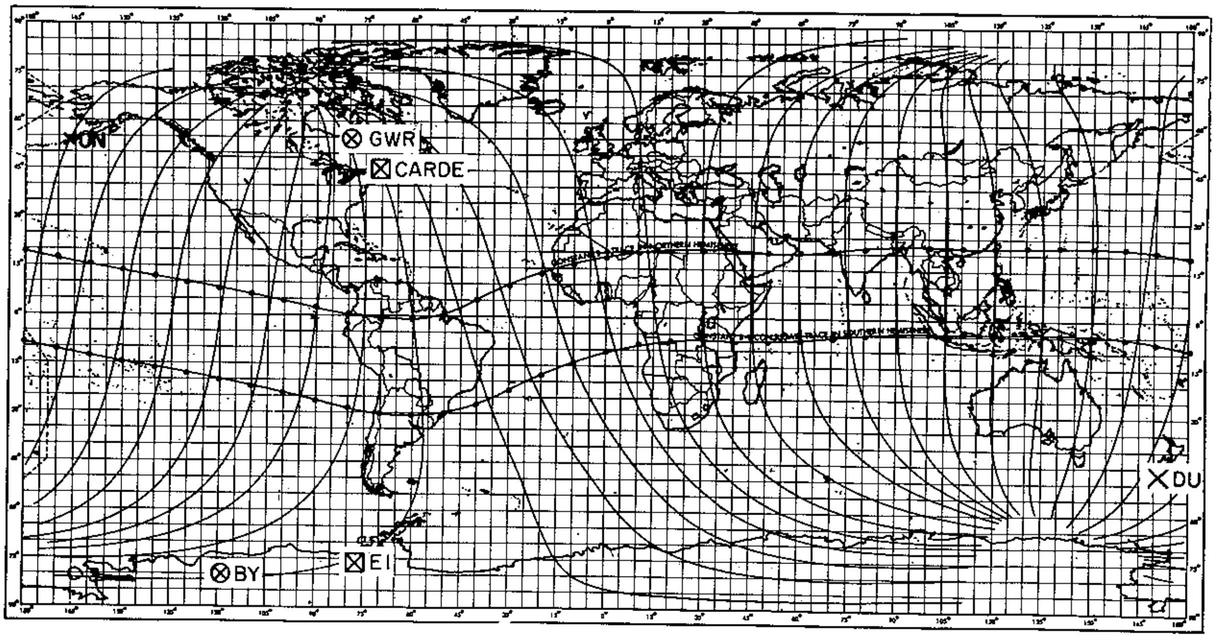


Fig. 11. Map showing the location of Byrd Station (BY), Carde, Dunedin (DU), Eights Station (EI), Great Whale River (GWR) and Unalaska (UN).

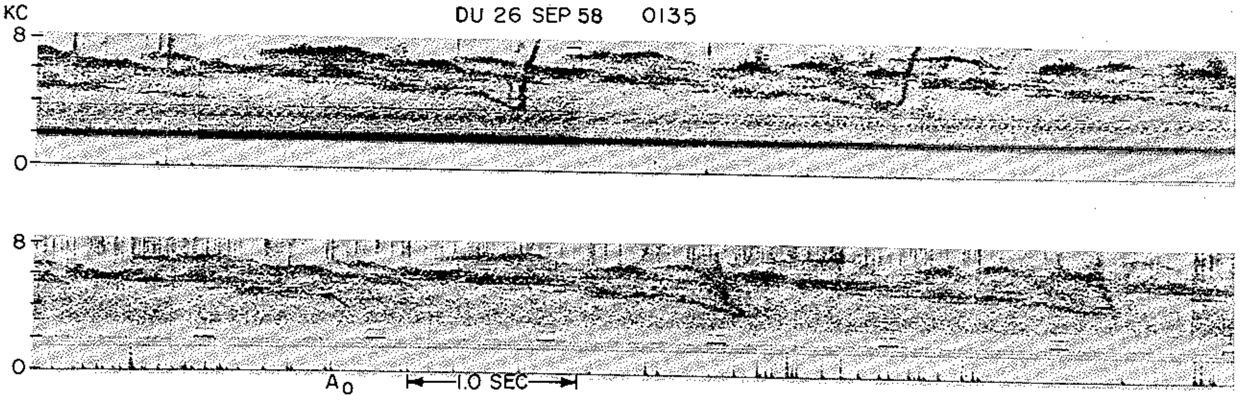


Fig. 12. Echoing hooks and quasi-constant periodic VLF noise recorded at Dunedin, New Zealand and Unalaska, Alaska, on 26 September 1958.

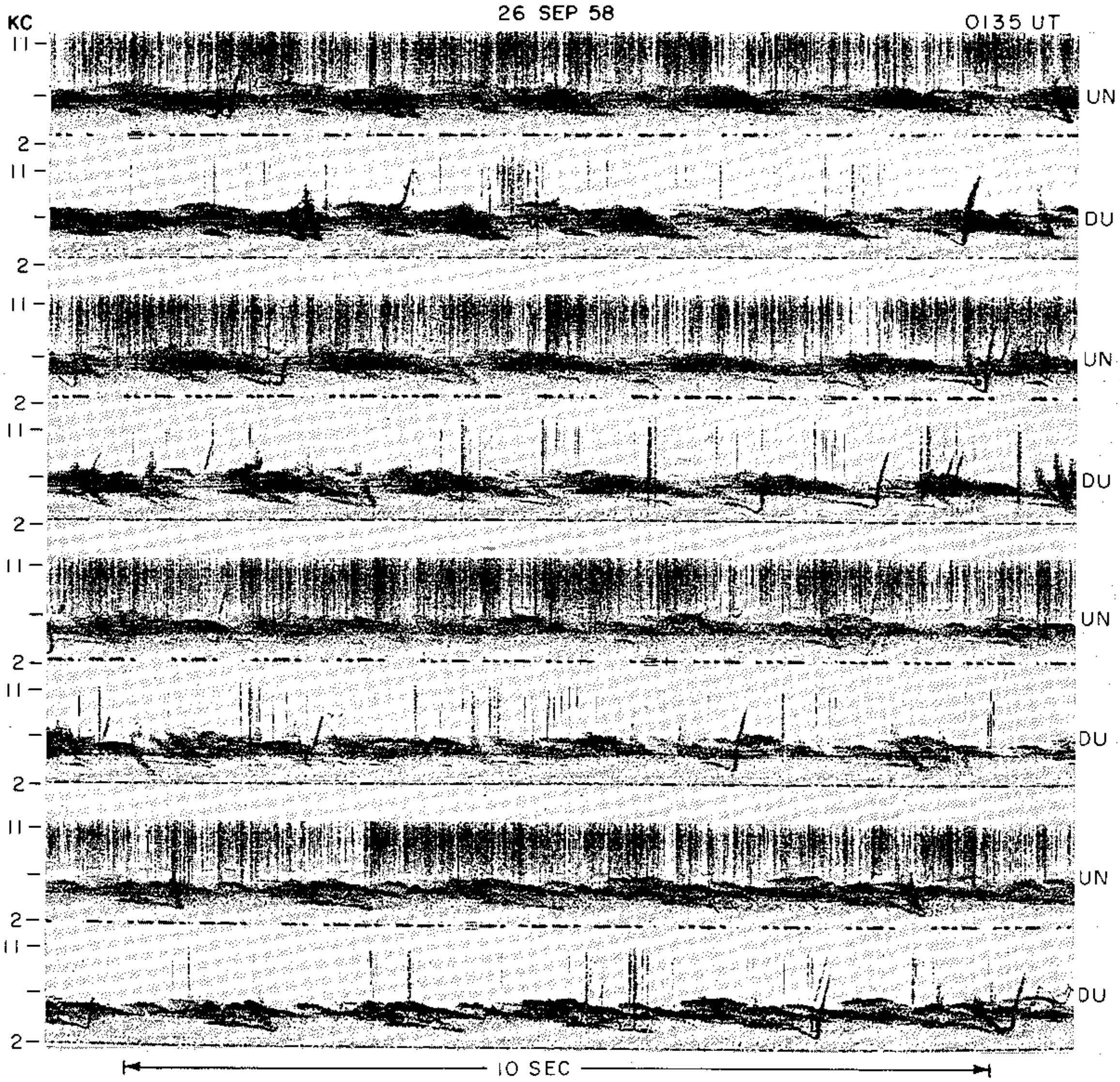


Fig. 13. Echoing hooks and quasi-constant periodic VLF noise recorded at Dunedin, New Zealand and Unalaska, Alaska, on 26 September 1958.

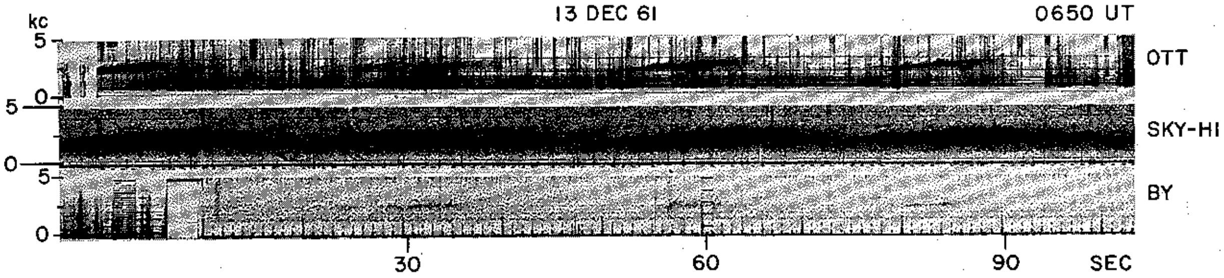


Fig. 14. Periodic emissions with a period of 30 seconds recorded at Ottawa, Canada; Sky-Hi, Antarctica; and Byrd Station, Antarctica. Periodic emissions with this long a period are always observed to be in phase in opposite hemispheres.

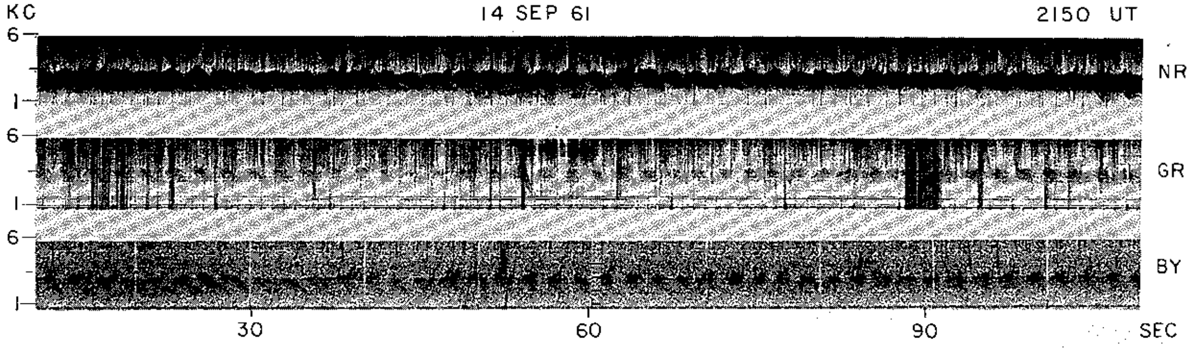


Fig. 15. Periodic emissions recorded at Norwich, Vermont; Greenbank, West Virginia; and Byrd Station, Antarctica. The emissions are in anti-phase in opposite hemispheres.

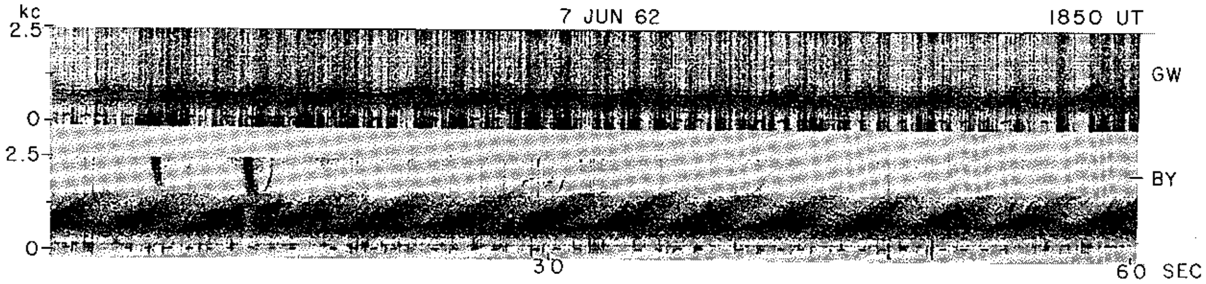


Fig. 16. Periodic emissions recorded at Great Whale River, Canada, and Byrd Station, Antarctica. The emissions are in anti-phase in opposite hemispheres.

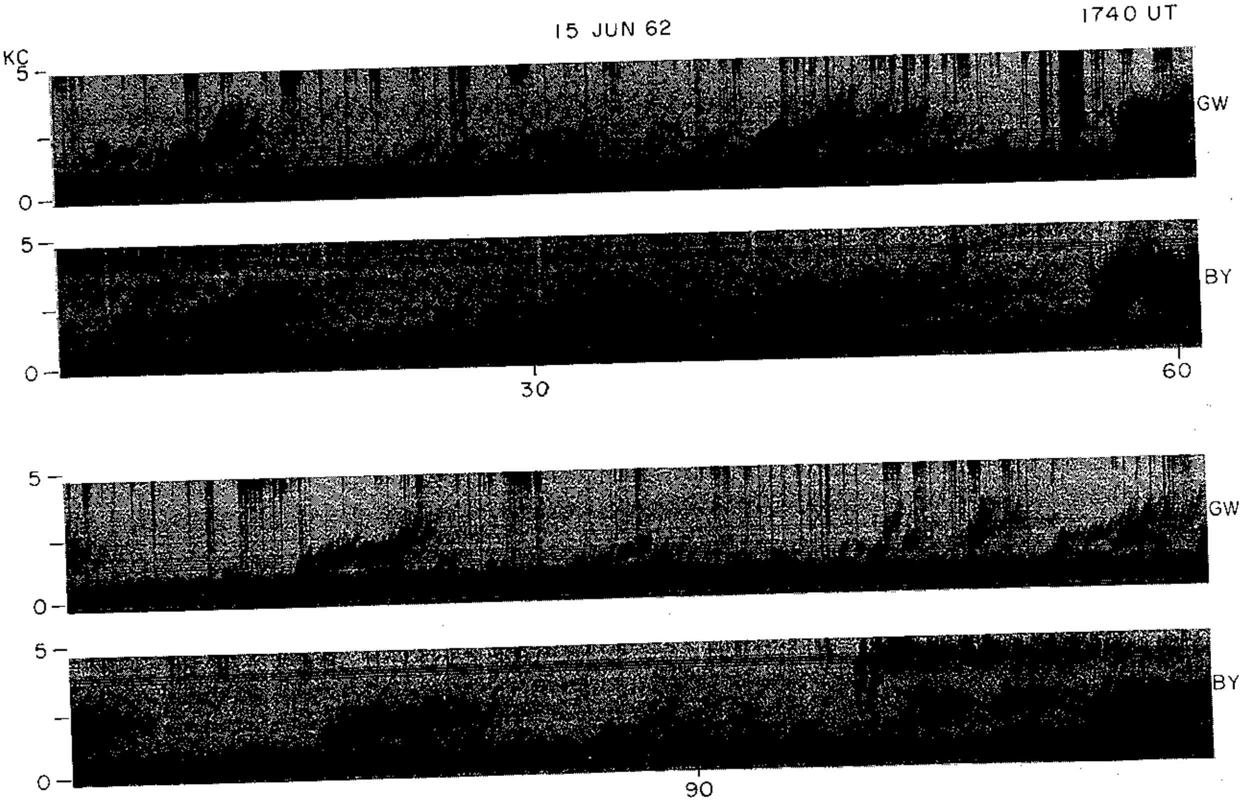


Fig. 17. Chorus bursts and triggered risers observed at Great Whale River and Byrd Station.

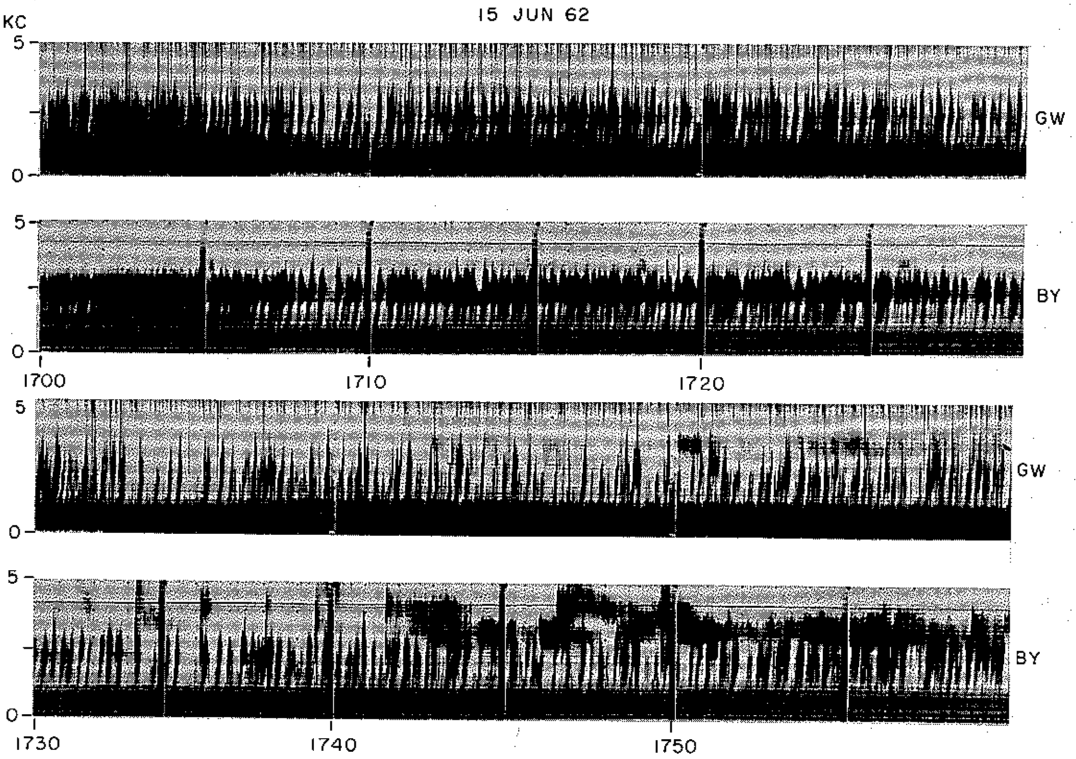


Fig. 18.
A low time resolution spectrogram of the phenomena like that in Fig. 17.

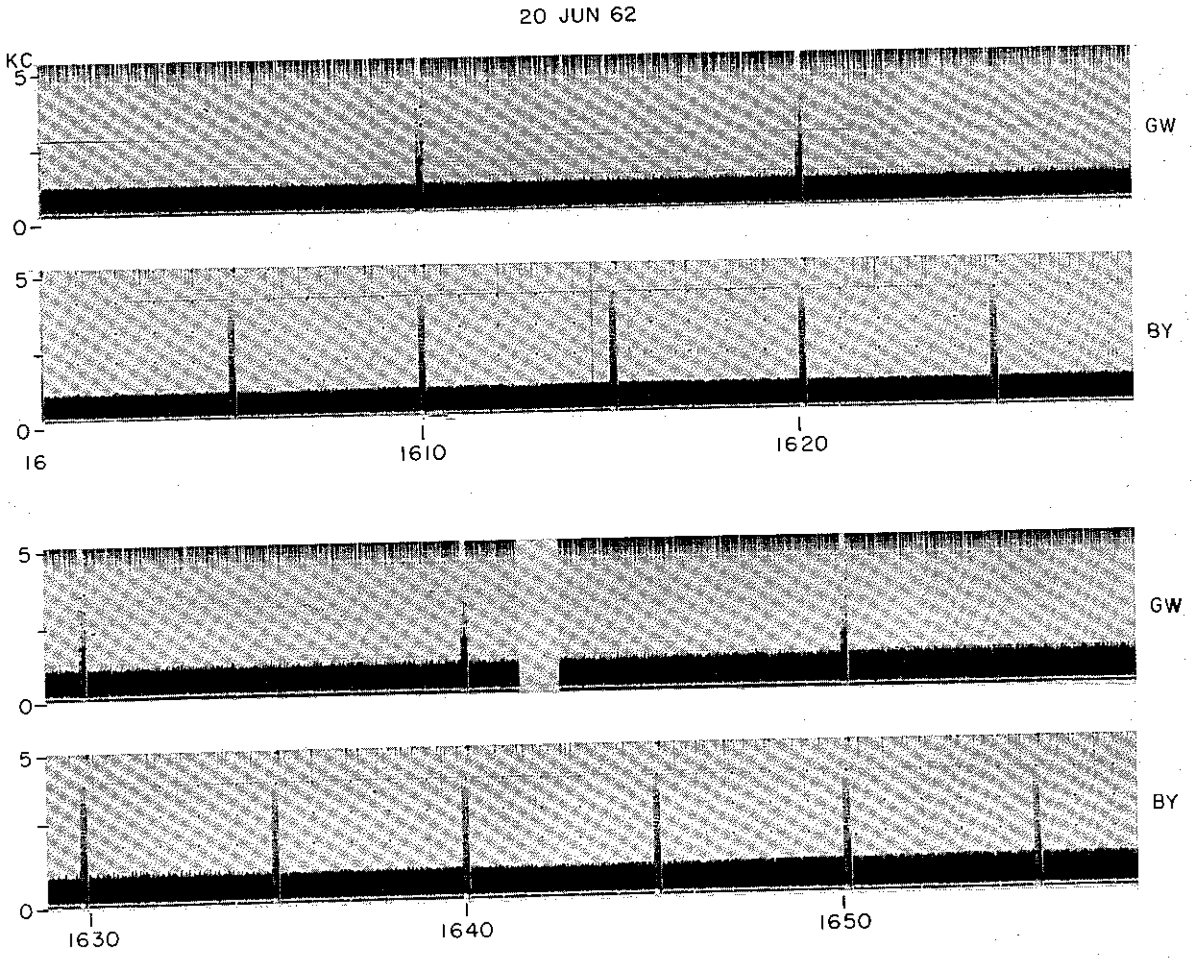


Fig. 19. A low time resolution spectrogram of polar chorus observed at Great Whale River and Byrd Station.

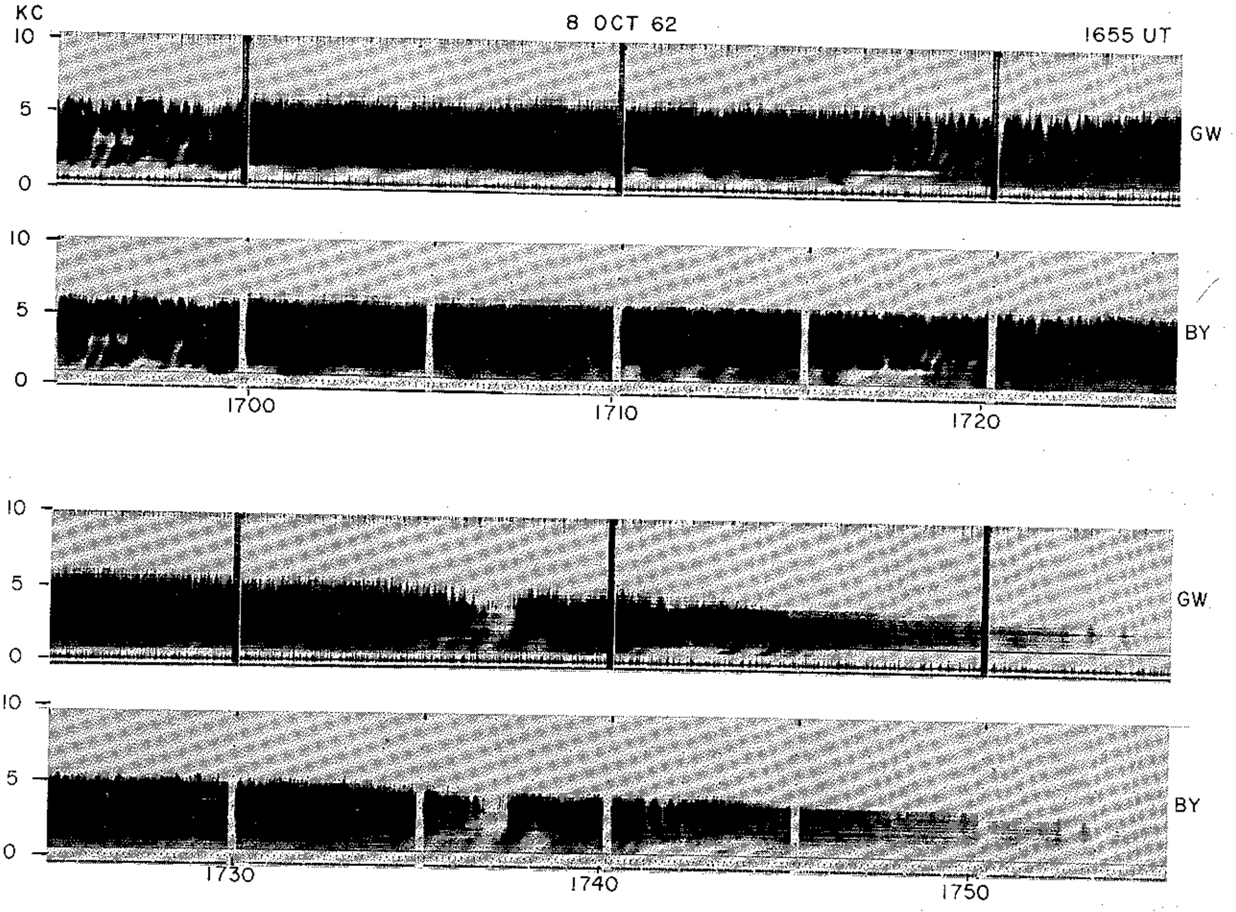


Fig. 20. A low time resolution spectrogram of hiss and chorus recorded at Great Whale River and Byrd Station.

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