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VLF NOISE OF MAGNETOSPHERIC ORIGIN

by

R. A. Helliwell
Stanford University

ABSTRACT

Periodic emissions were found to have the same period as two-hop whistlers at the same frequency, giving further support to the hypothesis that each emission is triggered by the whistler-mode echo of the previous emission. The predominance of symmetrical three-phase emissions was explained in terms of a "recovery" time for the generation region.

Detection of discrete emissions triggered by vlf Morse-code dashes (150 ms), but seldom by dots (50 ms), showed that the medium tends to be continuously susceptible to triggering and that the process of triggering is strongly dependent on signal duration.

Aurora-associated hiss was found to center in the auroral zone and to extend in frequency from 4 kHz to well over 20 kHz. The variation of hiss with absorption was positive for small absorption and negative for large, indicating at least partial control of hiss intensity by D-region absorption. Associations were found between hiss and other phenomena, including sporadic E, 28 Mc/s noise bursts and 18 Mc/s radar echoes from field-aligned ionization in the auroral zone.

Polar chorus, a diffuse type of auroral-zone emission, peaking near 700 Hz, showed a diurnal maximum near magnetic noon and a seasonal minimum during local winter and has been attributed to cyclotron radiation from protons.

Correlation of auroral zone emissions with other phenomena showed hiss (> 4 kHz), type B aurora, absorption and impulsive micropulsations peaking near magnetic midnight. Near magnetic noon the principal events are strongly correlated absorption and chorus at 1 kHz.

Quasi-periodic emissions or long-period pulsations, having periods of the order of a minute, were found to consist of bursts of recognized types of emissions. They were shown to appear simultaneously in opposite hemispheres and have been attributed to modulation by hydromagnetic waves of the parameters of the emission mechanism. A new class of quasi-periodic emissions was identified, in which the period is an integral multiple of the period of a whistler-mode periodic emission contained in the quasi-periodic bursts.

Rocket and satellite observations show strong emissions that often are not seen on the ground. Satellite observations have revealed an unusual band of noise, that is frequently stimulated by whistlers and is apparently related to the lower hybrid resonance frequency.

Theoretical work confirmed the inadequacy of known single particle radiation mechanisms to explain the observed intensities of vlf emissions. Mechanisms based on the assumption of coherently radiating bunches of electrons were advanced and criticized. The transverse resonance instability was proposed to avoid the limitations of the 'particle-bunch' theories, but the spectral shapes of discrete emissions still remain unexplained.

The precipitation of energetic particles was theoretically linked to the generation of vlf emissions. It was shown that whistler-mode noise leads to electron pitch angle diffusion which in turn results in particle precipitation.

I. Introduction

This paper reviews progress in the study of vlf emissions during 1963-1965. The vlf emissions considered in this paper are found principally in the range 100 to 30,000 cps and appear to originate in the ionosphere and magnetosphere. Propagation phenomena, such as the proton whistler, are not considered. Work is reviewed under three main headings, ground-based observations, rocket and satellite observations, and theories.

II. Ground-based Observations

A. Types of Emissions

Before discussing recent results from ground-based observations, it will be helpful to review briefly the classification of emissions as determined from their spectral forms. Two main types are recognized. The first, called discrete emissions, are limited in duration and are distinguished by a relatively small bandwidth. They typically show marked frequency-time variations over periods of a few seconds or less. Elementary forms include rising and falling tones and hooks. These may join in various ways to form combinations of discrete emissions. When individual discrete emissions appear in rapid sequence, with individual elements often overlapping in time, the result is called chorus because of its resemblance to the sound of birds waking in the early morning. The second type, called diffuse emissions, or hiss, resembles band-limited thermal or fluctuation noise, and includes auroral hiss, mid-latitude hiss and polar chorus. The latter is dominated by continuous noise but often shows structure. Most diffuse emissions observed on the ground tend to last for periods of minutes or more.

Periodic emissions constitute an important sub-class of discrete emissions, and consist of a sequence (called a set) of individual events with regular spacing. Periodic emissions are classified as either dispersive or non-dispersive depending on whether their period, respectively, does or does not vary with frequency. Frequently two or more sets of periodic emissions appear to be superimposed with different phases. These are called multi-phase periodic emissions and will often be identified aurally as chorus.

Quasi-periodic emissions (or long period pulsations) consist of bursts of recognized types of vlf emissions. The periods are measured in tens of seconds and although well defined usually show quite noticeable irregularities, in contrast to the relative constancy of the periods in the periodic emissions.

Triggered emissions include any emission that appears to have been initiated by another event such as a whistler or a signal from a vlf transmitter or another discrete emission.

Representative spectra of the presently recognized types of emissions have been published elsewhere (Helliwell, 1965). It should be noted that present schemes for the classification of emissions are based to a considerable extent on the appearance of their dynamic spectra. These may change as our understanding of the phenomena improve.

B. Periodic Emissions

Comparison of periodic emissions with whistlers has shown that the fundamental period of the emission is the same as the two-hop whistler-mode period over that path. (Helliwell, 1963; and Helliwell and Brice, 1964) These results support the echoing-wave-packet hypothesis in which each element of a periodic vlf emission is assumed to be triggered by the whistler-mode echo of the preceding wave packet. When the absorption of the triggering signal is strong, only the resulting emission is seen and hence the train of emissions is non-dispersive. On the other hand, when the triggering signal is not absorbed, it will show ordinary whistler-mode dispersion and will appear superimposed on the triggered emission. The result is often a rather complicated record in which dispersion is evident but not easily interpreted. In the extreme case of weak generation and weak absorption, each individual element in the train closely resembles the whistler-mode echo of the previous emission.

The echoing-wave-packet hypothesis has shown better agreement with the data than the previous model based on the assumption of a bunch of radiating particles echoing between their mirror points. This mechanism also has application to the problem of hydromagnetic emissions of the periodic variety. (Brice, 1965b)

Observations of multi-phase periodic emissions show that the three-phase symmetrically-spaced type is surprisingly common, whereas the two-phase type is relatively rare (Brice, 1965a). This result has been interpreted by Brice to mean that the emission region has a recovery time, in this case of the order of seconds. Multi-phase emissions with an odd number of phases tend to be self-stabilizing while those of even order are unstable and hence rare.

C. Artificially Stimulated Emissions

Discrete vlf emissions of various forms have been stimulated artificially by the Morse-code signals radiated from vlf transmitters (Helliwell et al, 1964). On many occasions it was observed that each Morse-code dash (150 ms duration) produced a strong discrete emission, but the Morse-code dots (50 ms duration) produced nothing. The starting time of these emissions was delayed with respect to the leading edge of the triggering dash by times of the order of 70 - 140 milliseconds. This time range lay between the lengths of the dot and dash and led to the suggestion that a certain minimum length of signal, of the order of 100 ms was required to initiate the emission. Triggering of the transverse resonance instability was suggested as the cause of the emissions (Brice, 1963; Bell and Buneman, 1964).

D. Mid-latitude Hiss

Hiss found in close association with chorus and whistlers, and appearing mainly at frequencies below 4 kHz, can be called mid-latitude hiss because the associated phenomena are known to appear most frequently at mid-latitudes. Mid-latitude hiss does not appear to be related to visual aurorae. The upper edge of a band of mid-latitude hiss usually is the starting frequency for discrete emissions of the rising type. Associated whistlers often show increased intensity and lower echo decrements within a band of mid-latitude hiss.

E. Auroral Zone Hiss

Auroral zone hiss is often associated with aurorae and is usually seen above 4 kHz, with upper cutoffs extending as high as several hundred kHz. These high values of the upper cutoff can be observed at auroral zone latitudes where propagation near the top of the line of force would not be expected because the minimum gyrofrequency is below the wave frequency. Since these frequencies are above the minimum gyrofrequency, generation at the top of the path is considered unlikely.

Hiss intensities measured in both the southern (Morozumi, private communication) and northern (Harang et al, 1965) auroral zones are similar and show a definite increase with frequency, at least up to 20 kHz. Values of the order of $10^{-15} Wm^{-2}(c/s)^{-1}$ are found in hiss bursts at 15 kHz. Hiss was observed simultaneously in E-W and N-S loop antennas, with the intensities tending to be higher in the E-W antenna. It was suggested that the noise was arriving simultaneously from various directions. (Harang et al, 1965)

Observations by Ondoh and Isozaki (1965) in Japan showed that hiss in the 4 - 6 kHz band can be detected at Hiraiso (geomag. lat. 26°N) and Moshiri (34°N) which are located well below the peak in occurrence of whistlers and vlf emissions. The observed intensities indicated that the locations of origin were at high latitude, possibly in the auroral zone.

Studies of hiss in the northern auroral zone by Harang and Larsen (1965) have confirmed the association between auroral zone hiss and the aurorae previously noted in the Antarctic. In addition it was found that when the riometer measurements on 28 mHz gave absorption in the range .3 to .9 db, the correlation with hiss was positive. For large values of absorption, in the range 5 to 9 db, the correlation was strongly negative. These results were interpreted to mean that the generation of hiss is related to the absorption-producing particles but originated above the absorption region and hence was strongly absorbed in passing through the D and E regions.

From hiss data obtained in the 4 - 9 kHz range from 13 stations in both hemispheres, the morphology of hiss zones has been estimated (Jørgensen, 1966). The hiss zones are centered close to auroral zones and peak up on the evening side of the earth close to the magnetic midnight meridian.

Hiss has been found on occasion to correlate with sporadic-E (Jørgensen, 1964); bursts of hiss have also been associated with 28 mHz bursts observed with a riometer at times of sudden change in the earth's field (Harang & Larsen, 1965).

Hiss has been found to correlate with 18 Mc/s radar echoes from F-region field-aligned irregularities located in the auroral zone (Hower and Gluth, 1965). On some occasions the association between the two measurements was very close with both phenomena beginning at the same time and passing through several maxima and minima together. This result raises some interesting questions regarding the nature of propagation across the lower boundary of the ionosphere. The authors suggest that Budden's hypothesis regarding the effects of small irregularities on propagation might be important in this connection. D and E region absorption variations would appear to be another possible cause of the observed variation. Satellite measurements should aid in solving this problem.

F. Polar Chorus

The diffuse type of emission called polar chorus (also called auroral zone emissions) is observed frequently at high latitudes in a band centered near 700 Hz. Using data from Kiruna (geomagnetic latitude 65.3°N), Egeland et al (1965) find that this emission band lies between 500 and 1000 cycles and that the intensity variation is assymetric, falling off less rapidly on the high frequency side of 700 cps. The diurnal maximum occurs at magnetic noon. They attribute this radiation to protons gyrating in the earth's magnetic field.

A comparative study of polar chorus at Godhavn (geomagnetic latitude 80°N), Narssarssuaq (71°N) and Tromsö (67°N) (Jørgensen et al, 1965) showed that the diurnal variation peaks at approximately magnetic noon at each of the three stations. Although the seasonal variation is not nearly as pronounced as the diurnal, there is a definite tendency for a minimum to appear in winter.

Although polar chorus generally does not appear to be connected with the aurorae, a recent observation (Ungstrup, 1966) shows that flickering aurorae is sometimes accompanied by an unusual type of chorus appearing below 2 kHz.

G. Quasi-periodic Emissions

Quasi-periodic emissions, or long period vlf pulsations, have been shown to appear simultaneously, or nearly so, at conjugate points (Carson et al, 1965). The spectral peak of micropulsations correlates well with the periods of the vlf pulsations, suggesting that the generation mechanism for the vlf emissions is modulated by the hydromagnetic waves which are thought to produce the micropulsations. In another study of quasi-periodic emissions recorded at Byrd Station, Helliwell and Flint (1966) have found that certain quasi-periodic emissions appear to result from the interaction of periodic emissions on two different frequencies. The period of the quasi-periodic fluctuation (evidenced by both amplitude and frequency variations) was found to be an integral multiple of the period of the lower frequency periodic. This observation indicates that some of the quasi-periodic emissions can be explained without invoking modulation of the emission process by fluctuations in the earth's field.

H. General Relationships

In a study of the relation between auroral radio absorption and very low frequency emissions (Ecklund et al, 1965), it was found that the occurrence of vlf emissions increased with increasing absorption if there was an area of low absorption within about 150 kilometers of the observation site. On the other hand if the absorption was widespread, the emission occurrence decreased with increasing absorption. Chorus was associated with absorption and hiss with the absence of absorption.

From a study of the relation of discrete vlf emission to absorption (Yoshida, 1965b), it was concluded that enhanced vlf emission activity during magnetic storms is generated in the co-rotating region of the magnetosphere but not in the tail region. These results are in accordance with the idea that discrete emissions are generated at the top of a closed line of force.

In a study of very low frequency emissions, whistlers and magnetic activity, Yoshida (1965a) found that the correlation of whistlers with chorus is somewhat higher than with hiss. This result is in accord with the previously reported occurrences of chorus triggered by whistlers. However it is not clear whether the correlation results from dependence of the generation mechanism on whistlers or simply on the presence of whistler ducts which permit the chorus to be observed.

Studies of aural data on the occurrence of vlf emissions as recorded by the whistlers-east network (Laaspere et al, 1964) suggest that source variations rather than propagation conditions tend to control vlf emission occurrence except during intense magnetic disturbance. Vlf emissions at Dartmouth increase with K_p up to values of 7 or 8, then decrease greatly at $K_p = 9$, presumably because of increased absorption. Chorus shows no seasonal variation in occurrence but does show a strong diurnal variation whose peak is later on quiet days than on disturbed.

In another study of emissions and ionospheric absorption, Ondoh (1963) finds that the maximum occurrence rate of f_{min} and chorus moves southward from the auroral zone to a latitude range of 61^o to 58^o during a magnetic disturbance. Chorus intensity and absorption maximize some 30 to 40 hours after the sudden commencement. He postulates that this maximum is related to betatron acceleration of electrons by rapid variations of the magnetic field during the storm. On the other hand he finds hiss to occur mostly during the main phase of the geomagnetic storm on the order of 5 to 15 hours after the sudden commencement.

In still another study of correlation between magnetic activity and emission at Poitiers (geomagnetic latitude 49.5^oN), Mme Leduc (1965) finds the maximum of mid-latitude hiss to come about 9 to 18 hours after the magnetic activity. Furthermore, the time delay increases with K_p. She finds chorus is delayed about 9 hours after the magnetic perturbation whenever K_p exceeds 6. For K_p-values less than 6, however, there is no time delay. It might be postulated that this difference arises from absorption which is directly associated with particle precipitation.

A study of vlf emissions and other geophysical phenomena at Byrd Station shows distinct nighttime and daytime regimes (Morozumi, 1965). Peaking near magnetic midnight are vlf hiss, type B aurora, absorption and impulsive micropulsations. A typical night event shows all of these phenomena beginning nearly simultaneously. Hiss and discrete vlf emissions around 1 kHz may appear after the cessation of the higher frequency hiss, their duration being comparable with that of absorption. This result indicates that the 1 kHz emission is closely connected with the particles which produce the absorption that is responsible for cutting off the hiss. The day regime, peaking near magnetic noon, includes vlf chorus, occasionally preceded by hiss bursts and micropulsations of the continuous type (P_c). In the day event, chorus intensity at 1 kHz correlates strongly with absorption as in the case of the 1 kHz emission observed during the night event. Comparison of these results with satellite data suggested that the vlf hiss occurs beyond the region of trapped electrons, whereas vlf chorus is produced in the region of connected lines of force.

III. Rocket and Satellite Observations

A number of rockets and satellites have been flown with vlf receiving equipment on board. One clear result is that many more events, both whistlers and emissions, can be observed above the ionosphere than below. In the rocket flights from Wallops Island, Cartwright (1964) found strong hiss not seen on the ground. At night the hiss centered at 2.8 kHz and showed a marked variation with altitude of the rocket. The variation of magnetic intensity of the hiss was found to correlate closely with the magnitude of phase refractive index obtained from another experiment on the same rocket. This variation was explained in terms of the change in wave impedance assuming a constant power flux into the region. Spin modulation data indicated that the wave normal was at least 60° away from the magnetic field, suggesting that the energy should be totally reflected at the lower boundary of the ionosphere, thereby accounting for the absence of the noise on the ground. In the daytime flight, hiss was seen only in the vicinity of 800 Hz. In a rocket launched in Japan, strong noise was found in the 400 - 600 cycle band in addition to whistlers (Iwai et al, 1965).

Observations by the Injun III satellite (Gurnett and O'Brien, 1964) showed a close association between vlf hiss, aurora and particle precipitation. Evidence was found that vlf hiss is generated at and above the high latitude trapping boundary for 40 Kev electrons and that it correlated with fluxes of precipitated electrons whose energies are greater than 10 Kev. Later study of these data (Gurnett, 1966) showed that vlf hiss occurred in a zone about 7° wide centered at 77° invariant latitude at 1400 magnetic local time (MLT) and decreasing to 70° invariant at

2200 MLT. The satellite vlf hiss occurs predominantly in the period from 12 to 24 hours MLT, while ground observations show the period to be roughly 19 - 21 MLT. It was suggested that during local nighttime it might be plausible to assume that the ground and satellite observations were the same; however, no correlated data were available to test whether the noisebands were in fact identical in the satellite and on the ground.

Observations by the Alouette and OGO satellites have shown a number of interesting phenomena. The same periodic emissions and whistlers are often seen over large ranges of latitude, indicating considerable leakage of the energy from the discrete paths. Data from Alouette I have led to the discovery of a new noise band (Belrose and Barrington, 1965) which was not seen on the ground and has been related to the lower hybrid resonance (LHR) for the transverse mode of propagation (Brice and Smith, 1964). The frequency f_r of this resonance is given by equation $1/f_r^2 = F_o^2 + 1/f_h(F_h)$, where f_h is the electron gyrofrequency, F_h is the ion gyrofrequency and F_o is the ion plasma frequency. Assuming that the LHR interpretation is correct, this noise provides new information on the mean ionic mass at the height of the satellite (Barrington et al, 1965; 1966). As yet no satisfactory explanation of its origin has been advanced. However, it has been observed that this noise is frequently enhanced at the time of reception of whistlers of all kinds. This fact has led to the conclusion that the noise must be produced close to the satellite. Smith (1966) has suggested a mechanism involving the trapping of vlf waves, introduced by whistlers and other emissions, in a trough defined by the lower hybrid resonance frequency.

Preliminary data from the OGO-I vlf experiment performed jointly by Stanford University and the Stanford Research Institute have shown that the intensity of emissions is roughly independent of position along a line of force. The upper cutoff frequency appears to relate to the minimum gyrofrequency on the line of force passing through the satellite rather than the gyrofrequency at the satellite. This result suggests that the noise is generated near the top of the line of force.

IV. Theories

No completely satisfactory theory of the origin of vlf emissions has yet been promulgated. However, a number of advances have been made in the understanding of various suggestions. Most detailed proposals for the generation mechanism are based either on the Cerenkov or the cyclotron radiation mechanisms. In the case of cyclotron radiation both the normal and anomalous doppler-shifted radiations have been considered. Past attempts to explain observed emission intensities in terms of incoherent radiation by either the Cerenkov or cyclotron processes have failed by many orders of magnitude. Liemohn (1965) considered the details of radiation by individual electrons in the whistler medium through these two mechanisms. He found, using certain approximations, that the radiation per electron is of the order of 10^{-30} watts per cycle per second and that with known quantities of electrons, the resulting levels were inadequate. It is recognized, on the other hand, that if a sufficient degree of coherence among the radiating particles was assumed, then the observed levels of radiation could be reached.

One approach to the problem of obtaining adequate radiation is by analogy with the traveling wave tube amplifier. In this theory ambient noise provides the input signal which is then amplified by a postulated bunch of trapped electrons whose streaming velocity equals the longitudinal component of the wave velocity. This analogy was suggested by Gallet and Helliwell, (1959) and has been extended by Dowden (1962b) and more recently by Gallet (1964). In the case of discrete emissions, the theory requires a spatially restricted bunch of electrons but the existence of such a bunch has never been demonstrated.

Use of cyclotron radiation to explain discrete vlf emissions was first made by Dowden (1962a). Assuming a small bunch of gyrating electrons radiating doppler-shifted, backward-traveling whistler-mode waves, several features of the observed spectra could be explained.. It was shown, for example, that rising tones would be produced by an electron bunch traveling down a magnetic line of force and conversely falling tones by a similar bunch traveling up a line of force. When a bunch crossed the magnetic equator, a "hook" was produced. Agreement between experiment and theory, however, was questioned, (Brice, 1962) and it was further pointed out that Dowden's particle bunch theory was unable to explain long-enduring quasi-constant tones (Brice, 1964a). Still another mechanism employing particle bunches was suggested by Ellis (1964) and was based on anomalous doppler radiation.

As mentioned earlier, the observation data appeared to require that the medium be more or less continuously susceptible to emission triggering by a passing whistler-mode wave. These facts led Brice (1963) to suggest the transverse resonance instability to avoid the difficulties encountered by the particle bunch theory. It differs fundamentally from Dowden's model in that it depends on feedback between the backward traveling waves and the forward traveling electrons. This feature allows the interaction region to remain fixed in space with the duration and changes in spectral shape being dependent in some way on the feedback process. Further support for Brice's hypothesis was obtained by Bell and Buneman (1964) who calculated the conditions for the growth of the transverse resonance instability and showed their compatibility with experimental data on artificially-triggered emissions (Helliwell et al, 1964).

The transverse resonance instability was related to the diurnal variation of chorus by Brice (1964b) who noted that convection in the outer magnetosphere could explain the morning chorus peak.

A connection between emissions and particle precipitation was suggested by Brice (1963) who showed that the generation of emissions by the transverse resonance instability would be accompanied by lowering of the particle mirror points and possible subsequent dumping of electrons.

A quantitative analysis of this relation, made by Kennel and Petschek (1966), showed that a loss cone in the particle distribution could be supported by the transverse resonance instability. Given a loss cone, it can be shown that the stream, if sufficiently dense, will be unstable. When the stream is unstable, emissions are generated, causing scattering of electrons into the loss cone. Continued absorption of electrons in the ionosphere maintains the loss cone which in turn maintains the emissions. From the fluxes of precipitating particles these authors predict a level of vlf emissions somewhat higher than that observed.

Although the transverse resonance instability provides an explanation for many features of the data, there is still no satisfactory explanation of the detailed frequency/time behavior of the discrete emissions.

V. Conclusions

Rapid advancement in our understanding of vlf emissions can be expected as data from rockets and satellites become available. Close coordination of satellite observations with measurements on the ground is required in future work. In view of the complexity of the phenomena, it is especially important to obtain as much detailed spectral information as possible. On the theoretical side, it is important to examine all possible resonances in the magnetosphere and try to determine quantitatively which ones can be expected to contribute to vlf emission activity. In this connection it is suggested that efforts be made to produce controlled emission by means of suitable signals transmitted from the ground or from satellites or rockets. In this way it may be possible to determine the dependence of the emission process on various parameters of the triggering signal, such as power, duration, frequency and modulation. Considerable effort should be made to explain the energy densities and the spectral shapes of discrete emissions. Effort should be applied to the problem of the generation of hiss. Middle latitude hiss associated with discrete emissions may very well find its explanation in the same mechanism which generates discrete emissions. This same mechanism may also be applicable to hiss observed in the auroral zone. However, other possibilities may have to be considered.

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