A STUDY OF IONOSPHERICS AT MACQUARIE ISLAND

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Summary

Very low frequency radio emissions of natural origin, sometimes known as ionospherics, recorded at Macquarie Island have been examined and grouped into classes. The diurnal variations of all classes show a non-uniform distribution with a peak shortly before local midday. The ionospherics appeared to fall into three groups as regards dependence on magnetic K-index. Strong correlations were discovered between values of emission frequency and K-index, for several classes of ionospherics. The role of Čerenkov radiation in the generation of ionospherics is discussed. Suggested energy distributions are put forward to explain various classes of ionospherics. The magnetic associations and diurnal variation are explained on the basis of current geomagnetic disturbance theory. Ionospheric absorption is also considered to affect the diurnal variation. The phenomenon of " surf ", as reported by Campbell and Pope, is discussed.

I. Introduction

During the past few years there have been a number of reports on the occurrence of very low frequency natural radio emissions for which the U.R.S.I. (1960) has suggested the term " Ionospherics ". Several attempts have been made to explain the generation of ionospherics, such as the travelling-wave amplification model of Gallet (1959), the Čerenkov radiation model of Ellis (1959), and the Doppler-shifted gyrofrequency model of MacArthur (1959) and Murcray and Pope (1960). These all suffer from lack of generality.

The travelling-wave amplification model is based on the condition that the velocity of the ionized stream is equal to the phase velocity of electromagnetic radiation. From this, Gallet (1959) finds that two frequencies are simultaneously generated, and these are given by

$$f=\tfrac{1}{2}f_H\left[1\pm\left\{1-\left(\frac{f_p}{f_H}\,\frac{v}{\mathbf{c}}\right)^2\right\}^{\frac{1}{2}}\right],$$

where f is the wave frequency,

$f_p=(N_e\mathbf{e}^2/\varepsilon_0\mathbf{m})^{\frac{1}{2}}$=plasma frequency,

$f_H=\mu_0\mathbf{e}H/\mathbf{m}$=electron gyrofrequency,

N_e=electron density,

$\mathbf{e}$=electronic charge,

$\mathbf{m}$=electronic mass,

H=magnetic field,

ε_0=electrical permittivity of free space,

μ_0=magnetic permeability of free space,

v=velocity of ionized stream of particles,

$\mathbf{c}$=velocity of electromagnetic waves in free space.

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The lower frequency, which reduces to

$$f_1=\left(\frac{v}{\mathrm{c}}\right)^2\frac{f_p^2}{f_H},$$

explains such types of ionospherics as horizontal tones and hooks. When the inequality $(2f_p/f_H)(v/\mathrm{c})>1$ holds, no emission will take place.

The Čerenkov radiation model is based on the condition that the particle velocity is greater than the phase velocity of electromagnetic radiation in the surrounding dielectric. Ellis (1957) finds that Čerenkov radiation is possible for values of wave frequency close to the electron gyrofrequency.

In both these approaches the ionospherics are explained as arising from streams of charged particles trapped in the geomagnetic field. These particles are considered to have originally formed part of a solar corpuscular stream and to have undergone acceleration and subsequent trapping at the unstable boundary between the geomagnetic field and the solar stream (Parker 1958 ; Dessler and Parker 1959). This theory gives no guide as to the energy distribution among the particles, but it will be shown later that certain classes of ionospherics require for their explanation suitable energy distributions.

Dessler and Parker (1959) have shown that the main phase of a magnetic storm can be explained by the stresses exerted by these trapped particles from the solar plasma. Thus, on the one hand, we have a source of the corpuscular stream which may give rise to the ionospherics, and, on the other hand, an explanation for disturbances of the magnetic field. Dessler and Parker proceed to show that, just as the increase in the geomagnetic field is related to the energy of the solar plasma compressing the fields, so also the decrease in field caused by the stresses exerted by the trapped particles depends only on the total energy of the stream.

In the present paper, a systematic study of ionospherics recorded at one station is presented, together with an extension of the theory, on the Čerenkov model, for the generation of ionospherics.

II. Experimental Observations

(a) *Experimental Methods*

The recordings used in this work were obtained on Macquarie Island, latitude 54° 29′ S., longitude 158° 58′ E., geomagnetic latitude 60° S., using standard VLF recording equipment kindly lent by Stanford University. Recordings of 2 min duration were made at 35 min past each hour (U.T.). The records used in this analysis cover the period March 1958 to January 1959. Using a Kay " Sonograph ", graphical representations of frequency against time were made for all emissions of sufficient intensity other than atmospherics and whistlers. These representations are referred to as " sonograms ". Somewhat over 2400 sonograms were obtained and classified according to the method suggested by Gallet (1959), with minor additions. This classification is shown in Figure 1.

(b) *Relative Occurrence and Diurnal Variation*

An investigation of the diurnal variation of the various classes of ionospherics was carried out. Figure 2 shows the histograms obtained for the most common

CLASS NO.	TYPE	f VERSUS t REPRESENTATION
1	HOOKS	
2	RISERS (PURE)	
3	QUASI - VERTICAL (CHORUS)	
3A	HISS WITH UNRESOLVED CHORUS STRUCTURE	SUPERPOSITION OF 3 AND H
3B	"FUZZY" RISERS	
3C	"FUZZY" QUASI - HORIZONTAL TONES	
4	FALLING TONES	
5	QUASI - HORIZONTAL TONES	
5A	QUASI - HORIZONTAL PLUS RISER	
6	PSEUDO NOSES	
7	UNUSUAL AND RARE EMISSIONS	
H	HISS	CONTINUOUS BAND OF FREQUENCES

Fig. 1.—Classification of ionospherics.

classes 3, 3A, 3B, 3C, 5, and H. Table 1 shows the mean time of occurrence and standard deviation from these means for the various classes. Table 1 also indicates the relative frequency of occurrence of the various classes.

TABLE 1

RELATIVE OCCURRENCE AND DIURNAL VARIATION OF IONOSPHERICS

Class	No. in Sample	Mean Local Time of Occurrence	Standard Deviation
1	15	10·9	5·6
2	103	8·6	3·4
3	403	8·4	2·7
3A	162	9·4	2·9
3B	75	9·0	2·8
3C	133	9·0	2·6
4	21	10·7	3·6
5	110	10·2	3·0
5A	31	10·3	2·9
6	7	9·4	2·0
H	153	10·2	3·5

(c) *Long-term Variation*

For each of the nine months, March 1958–December 1958 inclusive, the occurrence of each class, as a percentage of the total emission, was calculated and the subsequent results plotted as shown in Figure 3. There appear to be

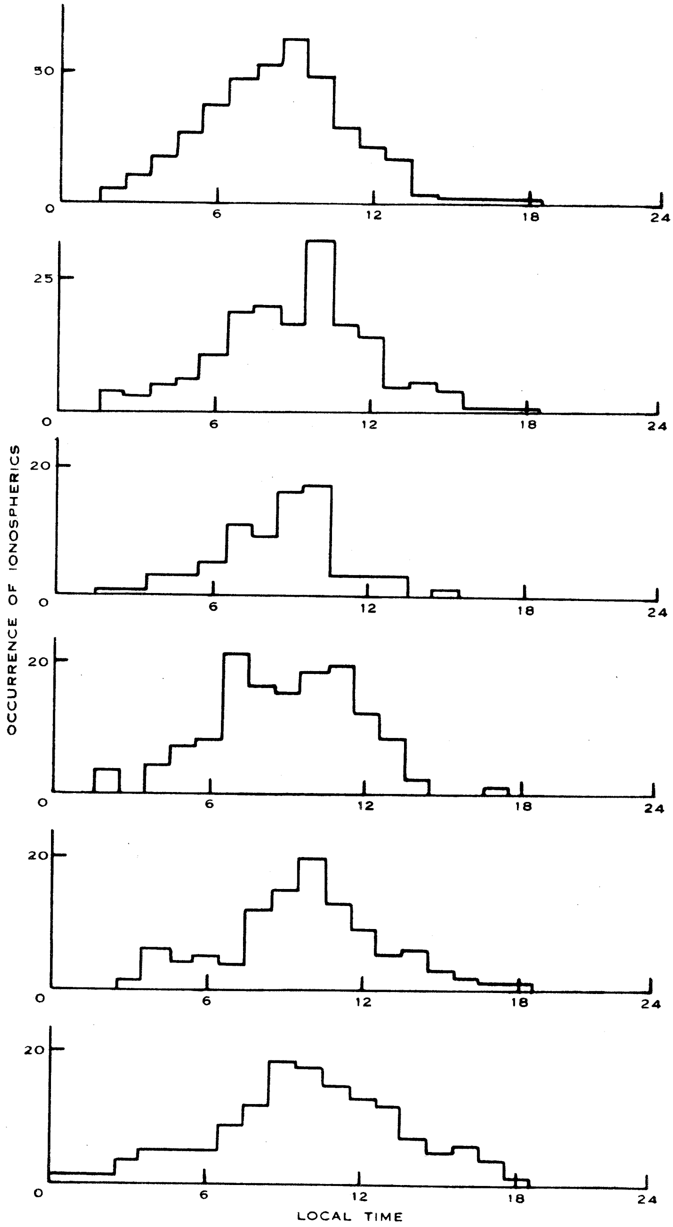

Fig. 2.—Diurnal variation of ionospherics. (*a*) Quasi-vertical emissions, (*b*) hiss with unresolved "chorus" structure, (*c*) "fuzzy" risers, (*d*) "fuzzy" quasi-horizontal tones, (*e*) quasi-horizontal tones, (*f*) hiss.

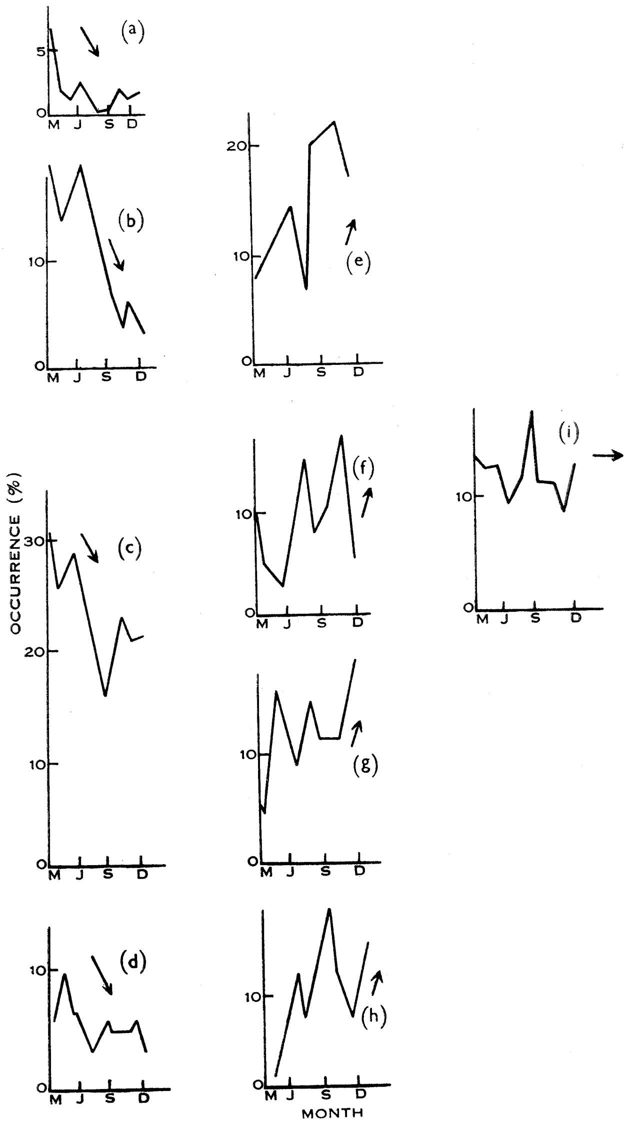

Fig. 3.—Percentage occurrence of various ionospherics over a 9-month period. (*a*) Hooks, (*b*) risers, (*c*) quasi-vertical, (*d*) quasi-horizontal plus riser, (*e*) hiss with unresolved "chorus", (*f*) "fuzzy" risers, (*g*) "fuzzy" quasi-horizontal, (*h*) hiss, (*i*) quasi-horizontal.

three general types of behaviour: (i) the " chorus " type shown by dawn chorus, risers, and hooks, the relative frequency of occurrence of which tended to decrease during the period investigated, (ii) the quasi-horizontal type, which tended to remain steady, (iii) the hiss type shown by pure hiss and ionospherics associated with hiss, namely, 3A, 3B, 3C, the relative frequency of occurrence of which tended to increase. We shall discuss later other phenomena in which a similar grouping is valid.

(d) *Frequency Range of Ionospherics*

The maximum and minimum frequencies indicated by a sonogram represent those frequencies where the intensity has fallen to about 30 dB below the maximum intensity in that particular ionospheric. The average maximum and

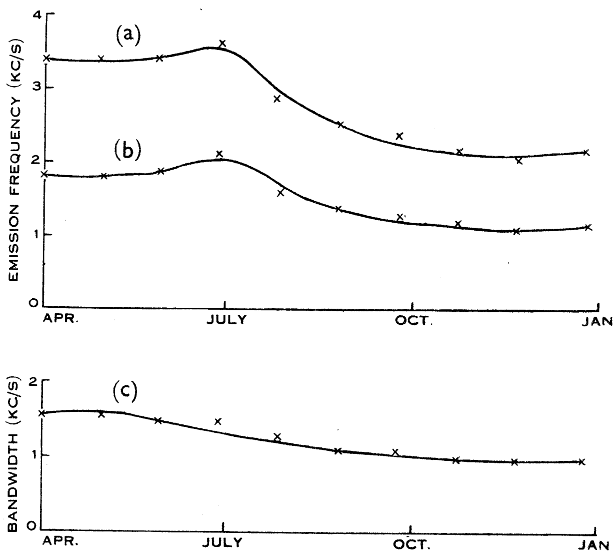

Fig. 4.—Variation of frequency parameters of ionospherics over a 9-month period. (*a*) Maximum frequency, (*b*) minimum frequency, (*c*) bandwidth.

minimum frequencies thus defined and their difference were determined for each month. These are shown in Figure 4. There are indications of a maximum in July and a minimum in December. Histograms have been plotted of the occurrence, in each class of ionospheric, and in the aggregate, of each particular frequency ($\pm 0\cdot 25$ kc/s). These distributions are reproduced in Figure 5. Most ionospherics lie between 1 kc/s and $3\cdot 5$ kc/s, but most hooks, some risers, and a little dawn chorus extend somewhat higher. The dawn chorus that is of a higher frequency than normal tends to be associated with hooks and/or high frequency risers. The hiss band covers 1–4 kc/s, the most commonly observed frequency being 2 kc/s. No recordings were found lower than 500 c/s.

(e) Association with Magnetic Activity

(i) An investigation of the relationship between the magnetic disturbance K-index and the occurrence of the various classes of ionospherics was carried out in the following manner. Using both the local K-index and the planetary K-index, the number of occasions emission occurred for each particular K value was found and the mean K value and the standard deviation from the mean were calculated for each of the various distributions. Table 2 shows the results obtained.

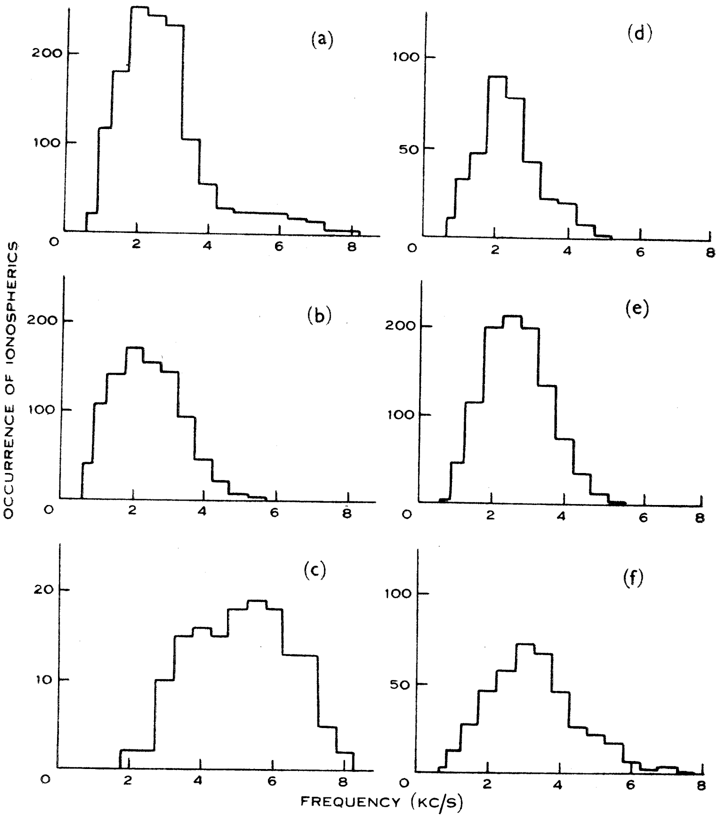

Fig. 5.—Emission frequency of ionospherics. (*a*) Aggregate, (*b*) hiss, (*c*) hooks, (*d*) horizontal tones, (*e*) quasi-vertical, (*f*) risers.

The grouping shown in Table 2 has been adopted on the basis of the statistical test of Welch and Aspin (Bennett and Franklin 1954) for determining whether a small difference in mean value (less than the variance), denotes a real difference in behaviour. The behaviour is unlikely to be similar within a particular confidence level α, if the value of their function t exceeds the corresponding value of the function $t_{\nu,\alpha}$, where ν is the number of degrees of freedom as defined by them. Table 3 gives a list of the t-values obtained and the corresponding values of $t_{\nu,\alpha}$, for $\alpha=5\%$ and 1%.

Apart from classes 3A and 3B, which appear in two groups, the test indicates a clear separation into three groups as shown in Table 2. This suggests that within a range of K values, which are themselves moderately low, horizontal tones tend to occur with low values of K, hiss type ionospherics with moderate values of K, and chorus type with high values of K.

(ii) The behaviour of certain frequency parameters, such as minimum frequency of dawn chorus, the frequency of discrete emissions and bandwidth of hiss, was investigated as a function of the magnetic K-index: Table 4 shows all results significant to a level better than 5%.

TABLE 2

ASSOCIATION BETWEEN OCCURRENCE OF IONOSPHERICS AND MAGNETIC DISTURBANCE

Group	Type	K_1		K_p	
		Mean	Standard Deviation	Mean	Standard Deviation
Chorus ..	3	3·1	0·7	3·4	1·2
	1	2·9	1·1	3·4	1·3
	2	2·9	1·5	3·6	1·3
	3A	2·9	1·6	3·2	1·5
	3B	2·8	1·3	3·2	1·5
Hiss	H	2·7	1·1	2·9	1·4
	3A	2·9	1·6	3·2	1·5
	3B	2·8	1·3	3·2	1·5
Horizontal ..	5	2·1	1·4	2·4	1·4
	3C	2·2	1·7	2·8	1·3

The significance of the test was calculated, eliminating any effect of non-normality by using the z-test (Fisher 1950). The extremely significant relationships between magnetic disturbance and certain emission frequencies (especially in the case of the quasi-horizontal tone where the measured frequency is independent of absorption) is discussed later in the paper.

(*f*) *Ionospheric Relationship*

Owing to the paucity of ionospheric records for 1958 for Macquarie Island it was difficult to investigate the association of changing ionospheric parameters and emission of ionospherics. It was found, however, that there was no tendency towards change in emission during periods of ionospheric black-out.

(*g*) *Association with Solar Flares*

For a group of 400 ionospherics, it was found that only on five occasions emissions occurred concurrently with solar flares. The emission which did occur concurrently did not tend to fall into any particular class, being divided between hiss, dawn chorus, and hiss with unresolved dawn chorus. The solar flares which occurred concurrently with ionospherics were all of importance 1,

TABLE 3

COMPARISON OF CLASSES OF IONOSPHERICS AS REGARDS OCCURRENCE WITH MAGNETIC DISTURBANCE

Classes Compared	ν	t	$t_{\nu, 5}$	$t_{\nu, 1}$	Same or Different Parent Population
H *v.* 3	126	2·61	1·98	2·61	Different
H *v.* 5	136	2·91	1·97	2·60	Different
5 *v.* 3	112	5·60	1·98	2·62	Different
1 *v.* 3	26	0·63	2·06	2·78	Same
2 *v.* 3	28	0·59	2·05	2·76	Same
3A *v.* H	58	0·63	2·00	2·67	Same
3A *v.* 3	43	0·66	2·02	2·70	Same
3A *v.* 5	75	2·40	2·00	2·65	Different
3C *v.* H	105	2·65	1·99	2·63	Different
3C *v.* 3	89	5·59	2·00	2·64	Different
3C *v.* 5	107	0·47	1·99	2·63	Same

measured on a 1–3 scale. On no occasion did the flare appear to initiate the period of emission of ionospherics, but it occurred sometime after the commencement of the period.

TABLE 4

ASSOCIATION OF FREQUENCY PARAMETERS OF IONOSPHERICS AND MAGNETIC DISTURBANCE

Class	Correlation	Size of Sample	Correlation Coefficient	Significance Level (%)
3	$F_{\text{min.}}$ *v.* K_1	82	0·38	0·1
5	F *v.* K_1	75	0·49	0·01
H	$B.W.$ *v.* K_1	70	0·23	5
	$B.W.$ *v.* K_p	70	0·31	1
4	$B.W.$ *v.* K_p	19	0·46	4
3B	$F_{\text{min.}}$ *v.* K_1	17	0·64	1

There thus seems to exist no positive evidence of a direct connection between solar flares and the occurrence of ionospherics through a non-corpuscular agent, such as X-rays, which would act immediately.

III. Discussion

(a) *Čerenkov Radiation and Hiss*

The refractive index of the ionosphere, for propagation in the whistler, or longitudinal extraordinary mode with the wave normal direction approximately the same as that of the Earth's magnetic field, as derived from magneto-ionic theory, is given by Gallet (1959),

$$n^2 = 1 + \frac{f_p^2}{f(f_H - f)},$$

where all symbols are as previously described. In this expression the effect of collisions is neglected. Figure 6 shows a plot of n^2 against f. It will be noted that n goes to infinity at $f=0$ and $f=f_H$.

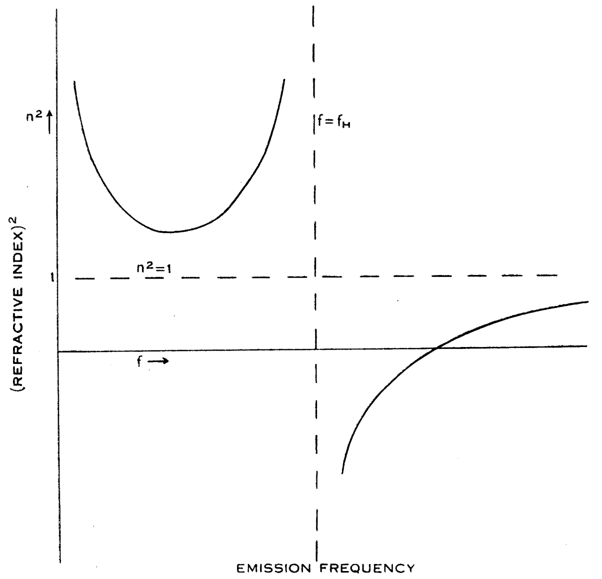

Fig. 6.—Plot of refractive index of ionosphere against frequency.

The relation between refractive index and particle velocity for emission of Čerenkov radiation is

$$vn > \mathbf{c},$$

or

$$n > 1/\beta,$$

where $\beta = v/\mathbf{c}$. Figure 6 indicates that no matter how small the stream velocity, emission should always occur at the gyrofrequency and at zero frequency. As the stream velocity increases, the two bands of emission widen but the upper limit of the upper band remains at the gyrofrequency. The mathematical problem of finding the limits of the bands is identical with that used by Gallet (1959) in his treatment of the travelling-wave model and the expressions there obtained for discrete frequencies are the values for the limits of the bands.

It has previously been seen that in the travelling-wave model no emission takes place if $2f_p v/f_H c > 1$, but in the Čerenkov model, since emission may occur if the stream velocity is greater than the phase velocity, rather than merely equal to it, this condition indicates that the two bands merge into one and emission occurs from zero frequency to the gyrofrequency.

The lower limit of the ionospherics as received may, however, not be zero. Budden (1959) in a theoretical analysis has shown that irregularities which have a total length small compared with the wavelength may prevent the propagation of very low frequency radio waves through the ionosphere. At the lowest frequencies there will be more irregularities which will come under the heading of " small compared with the wavelength " and hence greater attenuation. In any case, the flux density of Čerenkov radiation decreases with decreasing frequency. The actual cut-off frequency will depend on propagation conditions and the method of recording.

The higher emission band would normally be much more difficult to record because of the uncertainty of its frequency, which will depend on the gyrofrequency of its point of generation. In addition, as Helliwell (1958) has pointed out, attenuation is heavy for frequencies within 5% of the gyrofrequency, so unless the band is wider than this limit it will be of very low intensity. However, if the hiss is generated far out on a field line which intersects the Earth's surface at a high magnetic latitude, the electron gyrofrequency is small and the upper band will come within the scope of conventional whistler-ionospheric recorders. In this case a double band of hiss would be recorded, as has been found in fact by Martin, Helliwell, and Marks (1960) at Byrd Station, Antarctic, and by Aarons, Gustafsson, and Egeland (1960) at Kiruna, Sweden. If we consider a stream producing a double band of hiss, each of bandwidth 1·5 kc/s, as it moves from a location where the gyrofrequency is 3·5 kc/s to a location where the gyrofrequency is 5 kc/s, along a field line reaching the Earth at 65° N. geomagnetic, and remember that attenuation will affect both the lowest frequencies of the lower band and the highest frequencies of the upper band, we expect to record two bands of frequency 0·5–1·5 kc/s and 2–4·5 kc/s. This is what is actually recorded by Aarons, Gustafsson, and Egeland. Again, in accordance with their results we would not expect much variation in the emission frequencies of the lower band as compared with that of the upper band.

Dowden (1960), recording at Hobart, Australia, has observed noise simultaneously at one occasion on 4, 9, 70, and 230 kc/s, and again on 9 and 230 kc/s. In the latter case his equipment at 4 and 70 kc/s was out of action. The geomagnetic latitude at Hobart is 51° S., so the minimum gyrofrequency along the field line through Hobart will not be much less than 100 kc/s. This minimum gyrofrequency occurs at the top of the path. The lower frequency recordings obviously belong to the lower band but the origin of the higher frequencies is more doubtful. Depending on the position on the field line where they are generated, they may belong to the lower or to the upper band, or alternately, emission may be occurring at all frequencies below the gyrofrequency. Recordings made at a large number of frequencies would not necessarily clarify the situation, since, if there does exist an emission-free frequency region at one point along the field line, emission may still occur in that range at a different point along the line. The close correspondence of amplitude fluctuation at the different frequencies, which Dowden observed, is consistent with the simultaneous generation of a band of frequencies as suggested by the present theory.

(b) *Different Classes of Ionospherics*

The signal actually received at the Earth's surface will depend on the relative efficiency of the two mechanisms, the Čerenkov mechanism for the production of the band of noise and the travelling-wave mechanism for the amplification of the limiting frequency. Figure 7 shows a sonogram (of the

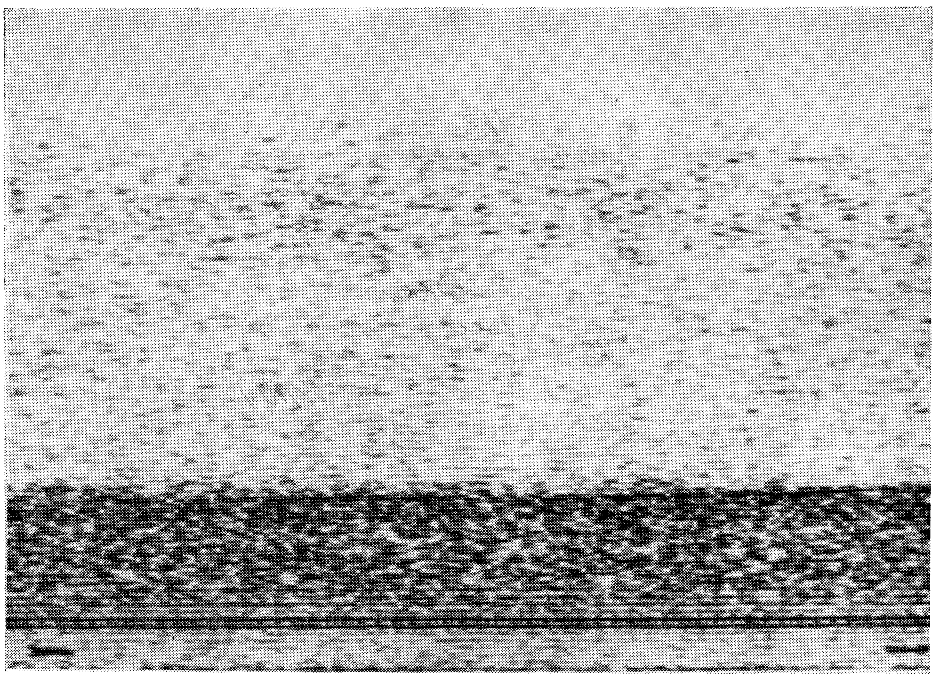

Fig. 7.—A sonogram of class 3C.

class 3C) where we have a band of frequencies possibly produced by the Čerenkov mechanism, together with a much more intense line at the upper frequency limit, possibly caused by the travelling-wave mechanism. In this case, apparently the stream of particles was uniform in energy but sufficiently powerful to produce emission strong enough to be recorded using conventional antennae.

For a stream of particles of non-uniform energy Čerenkov radiation emission can occur over a wide range of energies of the particles, but the travelling-wave amplification at any one frequency will depend critically on the distribution of energy. If the particles do not differ greatly in energy, a large amplification by the travelling-wave mechanism could occur at the appropriate frequency, giving high emission. The quasi-horizontal and the fuzzy quasi-horizontal types could be accounted for in this way. In the case of the quasi-horizontal tones, the Čerenkov radiation is not intense enough to be recorded, whereas in the case of the fuzzy quasi-horizontal tones and the quasi-horizontal plus hiss mixture, the upper part of the Čerenkov radiation band appears as well as the limiting frequency.

In his explanation of various classes of ionospherics Gallet (1959) has assumed an electron density distribution of the outer ionosphere such that f_p^2/f_H is a constant. During a period of frequent emission, such as when dawn chorus is occurring, it is to be expected that there would be an increase in electron density because of many streams of particles being trapped in the geomagnetic field, and the correct model may tend to approach f_p/f_H constant. Thus a stream of particles travelling along a field line would be entering a region where the electron density would be greater than normally the case and the resultant ionospheric would show a quasi-vertical structure. Whether this structure will appear embedded in a hiss structure, as in class 3A, or whether merely the quasi-vertical structure, class 3, will be recorded will depend on the intensity of the original Čerenkov radiation.

The rising tone often found on the end of horizontal emissions and in hooks may be explained, following Gallet (1959), by a large increase in electron density, as in the F region of the ionosphere, leading to an increase in emission frequency. Since streams of spiralling particles are normally reflected in the Earth's magnetic field at points higher than the F region, one would expect to find relatively few of these types of emissions compared with quasi-horizontal tones, as is indeed the case (see Table 1). In addition, only high energy streams would penetrate to the F region, which agrees with the fact that hooks have a higher emission frequency than other classes of ionospherics (Fig. 5).

A broad uniform energy spectrum will result in poor travelling-wave amplification at any particular frequency, and so decrease the likelihood of recording discrete tones at the Earth's surface, but it will be no less effective than a peaked spectrum for generating Čerenkov radiation. Hence, in this situation only the hiss band is likely to be recorded at the Earth.

(c) *Correlation with Magnetic Activity*

As has been noted in the introduction, the total energy of the stream will control magnetic disturbance. It has also been noted that the energy of the individual particles determines the frequency of the ionospheric. Since, in the present investigation, ionospherics of roughly the same intensity have been considered, it is reasonable to expect that the energy per particle will control both magnetic disturbance and emission frequency. This fact fits in very well with the correlation between the index of magnetic disturbance K and the emission frequency, as observed in the Macquarie Island data.

Magnetic disturbances take the form of a series of increases and decreases which may be interpreted as the effect of plasma clouds impinging on the Earth's field and then penetrating the field and being trapped therein. This situation results in a stream of particles suitable for the generation of ionospherics being continually renewed. This explains the general increase of occurrence of ionospherics with rise in K-index (see, e.g. Crouchley and Brice 1960).

The slight association indicated in Section II (*b*) between the K-index and the ratios between the frequencies of occurrence of the three groups of types of ionospheric can be roughly interpreted as follows. Where the horizontal tones are predominant, the particles in the trapped plasma stream tend to be homogeneous in energy. They will thus tend to produce a steady rather than a wildly fluctuating field change and hence give a relatively low K-index. On the other hand, where hiss is predominant the particles tend to have a wide range of energies. They will thus be more likely to produce wildly fluctuating field changes and hence give a higher K-index.

(*d*) *Diurnal Variation*

If the emissions depend on the solar wind a maximum of occurrence would be expected where the plasma cloud meets the Earth and infiltrates the geomagnetic field. However, in addition to the direct stream from the Sun, which normally consists of roughly 100 atoms/cm^3 with a velocity of 500 km/s, (the quiet day stream postulated by Parker (1960)) there is a stream caused by the orbital motion of the Earth through the permanent interplanetary gas containing around 100 atoms/cm^3, the velocity being 30 km/s.

Thus, neglecting ionospheric absorption, the diurnal variation of ionospherics should show a maximum at noon, and a much smaller maximum at 0600. Appleton (1953) has noted that the diurnal maximum of absorption in the ionosphere is reached a short time, of the order of an hour, after noon, owing to the " sluggishness " of the ionosphere. Thus absorption could move the peak a little to the morning side of noon. The absence of a gap between the early morning and the midday distributions seems to indicate that the width of the two distributions is such that they run smoothly into one another. This accounts for the distribution found in Figure 2.

Crouchley and Brice (1960) found that the time of maximum occurrence is earlier for lower latitudes. This could be caused by the different behaviour of ionospheric absorption at different latitudes. The absorption increases more markedly after sunrise at lower latitudes. Therefore the displacement of the peak of the distribution will be greater at lower latitudes.

Figure 2 and Table 1 show that all classes of ionospherics have a non-uniform diurnal distribution. Contrary to this, Gallet (1959) at Boulder has noted an almost uniform distribution for risers and quasi-horizontal tones. It may well be that the Boulder data include emissions of lower intensity than those included in the Macquarie Island data. It is possible that strong emissions occurring at distant localities will be transmitted by ionosphere plus ground reflections and will be recorded as weak emissions at the receiving station. This would tend to eliminate non-uniformity in the diurnal distribution.

(*e*) *Recordings of " Surf "*

Pope and Campbell (1960) have reported an unusual emission which consists of a family of ionospherics with increasing central frequency and increasing rate of spread with time. Because of the resemblance of the sound of the emission to that of ocean breakers during a storm, they suggest the name of "surf" to describe this emission. It is suggested that surf may be explained in the following manner. A bunch of particles travelling along the magnetic field lines with velocity slightly larger than average—the average velocity particles being responsible for the generation of a hiss band, with a maximum frequency at 2 kc/s which is simultaneously recorded—generates surf by a combination of Čerenkov radiation and travelling-wave amplification. The emission frequency of surf of 3 kc/s suggests a stream velocity of 9×10^6 m/s and this in conjunction with the average period of recurrence of $6 \cdot 3$ s and a path length of 6×10^7 m suggests that conditions may be suitable for generation of the emission in a region located between the top of the field line and the point of magnetic mirroring. The increase in frequency may be explained as due to an increase in electron density resulting from increased ionization along the path of the stream. The gradual spreading of signal may be caused by a spreading of the velocities of the particles with time. The reason for the finite lifetime of the disturbance would be a decrease in the density of the stream on account of collisions, especially in the regions of higher electron density about the mirror points.

IV. Acknowledgments

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