An Investigation of Whistling Atmospherics

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Phil. Trans. R. Soc. Lond. A 1953 **246**, 113-141
doi: 10.1098/rsta.1953.0011

AN INVESTIGATION OF WHISTLING ATMOSPHERICS

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(*Communicated by J. A. Ratcliffe, F.R.S.—Received* 28 *November* 1952)

CONTENTS

The paper, which is in two parts, describes an investigation of the nature and origin of the 'whistling atmospherics' or 'whistlers' which are sometimes observed at frequencies below 15 kc/s. The first part describes an experimental study of their properties, in the course of which a considerable number of whistlers were recorded and analyzed, and the law of the variation of their frequency with time determined. Some whistlers are heard to follow impulsive atmospherics, and these are found to be produced in the normal way by lightning strokes taking place within a distance of about 2000 km. Other whistlers are unaccompanied by atmospherics; they differ from the former type in several further respects. The diurnal and annual variations of the properties of both types of whistler have also been studied.

In the second part of the paper a theory of the origin of the whistling atmospherics, originally due to Barkhausen (1930) and Eckersley (1935), is developed in detail. The theory proposes that they are due to waves which originate in normal impulsive atmospherics and travel through the outer ionosphere, following the lines of force of the earth's magnetic field and crossing over the equator at a great height. During their journey they become dispersed so as to arrive as 'whistlers'. They may be reflected from the earth's surface back along the same path, one or more times, to produce whistlers with increased dispersions. The effects responsible for the guiding of the waves along the

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[Published 9 July 1953

lines of the geomagnetic field provide sufficient focusing action to prevent the energy from being spread unduly.

Measurements of the degree of dispersion of the whistlers have been interpreted to yield information about the density of electrons in the atmosphere at very great heights. The density required seems considerably larger than could reasonably have been expected. If the free electrons are produced by ionization of the terrestrial atmosphere its temperature in these regions must be at least 7200° K. The results might alternatively be explained on the assumption that the electrons are falling in from outside, and if this were so it might account for the relationship between the occurrence of whistlers and magnetic activity.

1. Introduction

Between about 15 kc/s and 20 Mc/s the only important natural sources of radio waves are lightning flashes, and the impulsive atmospherics to which they give rise can be heard as clicks on a receiver tuned to any point in this band. On going, however, to the very lowest frequencies, in fact to radio waves of audible frequency, there appear atmospherics of a totally different and more musical, tonal kind. Chief among these is an atmospheric which in its commonest form consists of a whistling tone of steadily falling pitch; starting above the upper limit of hearing the frequency falls at first rapidly, then more slowly at the lower frequencies, sweeping down through several octaves in the space of one or two seconds. This forms the subject of the present investigations.

Different workers have referred to these atmospherics by different names, principally 'swish', 'whistler' and 'long whistler', this last to distinguish them from the 'short whistler', 'tweek', or 'chink', which is the short (about 20 ms) musical tone produced by repeated reflexion between the earth and the ionosphere of the waves from a distant lightning flash. Here they will simply be called 'whistlers'.

The existence of these whistlers has been known for many years, but they have received little systematic study. None the less they are of considerable scientific interest.

The present paper is divided into two parts. The first is concerned with the results which have been obtained from an experimental investigation of whistlers, while in the second a theory is developed to account for their origin.

PART 1. OBSERVATIONS AND EXPERIMENTS

2. Outline of earlier work

Whistlers were discovered by Barkhausen in the course of some investigations of earth currents, and he published the first account of them in 1919. A much earlier note by Preece (1894) on some telegraph-line interference may possibly relate to whistlers, but his description is too vague to make the identification certain. Subsequently they were studied both in England by Eckersley (1925, 1926, 1928, 1931), of the Marconi Wireless Telegraph Co., Chelmsford, and in America by Burton (1930) and Burton & Boardman (1933) at the laboratories of the Bell Telephone Co. The last named secured recordings of the whistlers and related phenomena, some of which have recently been analyzed by Potter (1951) on the 'sound spectrograph'. Through these investigations the following facts were known at the outset of the present work.

Whistlers are often heard to come one or two seconds after 'click' type atmospherics. The nature and location of the sources of these atmospherics were both uncertain; there was a single observation of whistlers following lightning strokes, and another of them following discharges in the Aurora.

Various types of multiple whistler had been observed. Sometimes whistlers occurred in groups or trains of many 'echoes' following a single atmospheric, with a constant spacing between successive whistlers and increasing dispersion from one whistler to the next. Another type of multiple whistler consisted of a close overlapping pair.

More complicated atmospherics of whistler type were also known. In some there was a rise of frequency instead of the usual fall, and 'reversing tones' had been observed in which the sense of the frequency change reversed during the whistler.

As to the occurrence of whistlers, it was known that in general they were more frequent during the night than the day. There was little systematic seasonal variation, but there did appear to be an indefinite association with magnetic storms.

Based chiefly on the observation that whistlers sometimes followed impulsive atmospherics, a theory of their origin had been put forward by Barkhausen (1930) and developed by Eckersley (1935). This theory suggested that all whistlers originated in atmospherics, and predicted that at a time (t) after the atmospheric the frequency (f) of the whistler should obey the relation $(f)^{-\frac{1}{2}} = t/D$. This result had been confirmed in the case of a single analysis published by Burton & Boardman. In what follows we shall refer to the constant D as the 'dispersion' of the whistler.

3. Experimental methods

The whistlers were received by means of a straightforward audio-amplifier with an available gain of about 80 db, its input being connected to a vertical aerial and its output to a loudspeaker. The frequency response was limited by filters to a band from 400 c/s to 10 kc/s. Permanent and objective records of whistlers were obtained in a convenient form by the use of a magnetic tape recorder. These could be 'played back' and listened to at leisure, and could be subjected to detailed analysis and measurement.

The property of the whistlers which one is primarily concerned to measure is the variation of their instantaneous frequency with time. The 'instantaneous frequency' of a gliding tone is here defined as the frequency of that Fourier component of the tone for which the phase is stationary with respect to variation of frequency at the given instant. The time at which the instantaneous frequency of a gliding tone takes a certain value can be determined by passing the tone through a narrow-band filter and noting the instant of the maximum of the response.* The response of the filter is sharpest and the peak signal-to-noise ratio at its output greatest if its band-width is set approximately equal to the square root of the rate of change of the frequency (Barber & Ursell 1948). The shape of the complete frequency/time curve for the tone can be determined by analyzing it with a bank of such filters with their resonant frequencies suitably spaced through the spectrum. The bulk of the routine analyses of whistlers were carried out with an instrument of this type, which was based on the 'sound spectrograph' described by Homer & Gruentz (1946). It consisted of twelve selective amplifiers with their inputs connected in parallel and supplied from the tape recorder with the

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* Actually for all physically realizable filters a slight correction should be applied to the time of the maximum, depending on the band-width of the filter and the rate of variation of the frequency of the tone, but in the present case this correction was always negligible. Its values for a tuned L-C circuit are given in a paper by Barber & Ursell (1948).

signal to be analyzed, while their outputs were arranged to control the brightness of a row of midget neon lamps. The lamp display was photographed on a continuously moving film. If the signal was a gliding tone it would excite each of the tuned amplifiers in turn and draw its frequency/time curve across the film. The resonant frequencies of the filters and the spacing of the lamps were so chosen that if the frequency variation of the whistlers followed the theoretical law given by Eckersley the lines which they traced out would be straight, inclined to the width of the film to a greater or lesser extent according to their degree of dispersion. Normal impulsive atmospherics, on the other hand, would excite all channels simultaneously and so draw lines directly across the film.

An example of the type of record which the instrument produced is shown in figure 1, together with axes of time and frequency. The record is in effect a graph of $(\text{frequency})^{-\frac{1}{2}}$ (linearly across the film) against time (along the film), with the former increasing towards the bottom so that a line sloping downwards from left to right represents a descending tone. The whistler in the figure followed an atmospheric, and this has been set at the origin of the time axis.

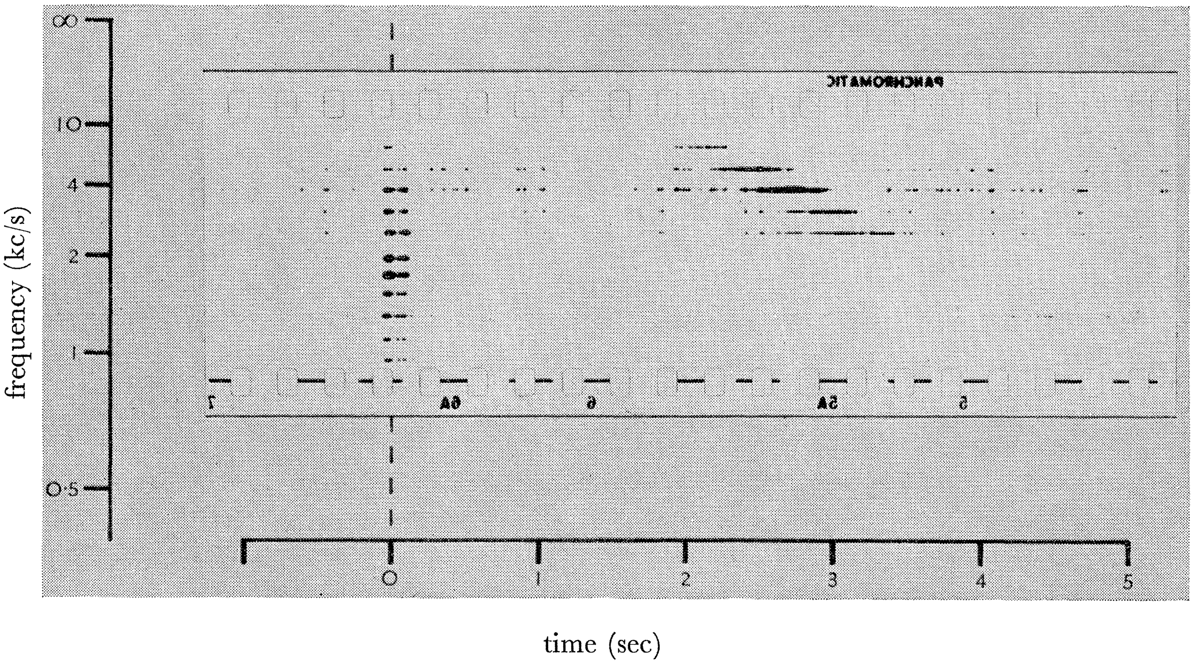

FIGURE 1. Sound spectrograph record of a whistler following an atmospheric click.

This instrument was adequate for making dispersion measurements of moderate accuracy. For more precise frequency measurements and for measurements of amplitude a wave analyzer was built comprising a single tuned amplifier with an adjustable band-width and a resonant frequency which could be set at any of ten spot values. The envelope of the output from the amplifier was recorded on a cathode-ray oscillograph. By playing the tape recording into the analyzer separately for each of the ten frequencies it was possible to determine the way in which the amplitudes of each of them varied with time.

Routine observations of the occurrence and properties of whistlers were conveniently made by arranging that the magnetic tape recorder should record the output from the atmospherics receiver automatically for a period of one minute at each half-hour, day and night. Once a day the records of the preceding twenty-four hours were played back, the whistlers counted, and any good specimens analyzed on the sound spectrograph.

4. The relation of whistlers to ordinary atmospherics

Loud whistlers are found to fall into two distinct classes. The whistler either comes after a loud click or none at all, never after a weak click. When the whistlers themselves are weak it is, of course, often difficult to decide whether or not they followed clicks. Atmospheric clicks do not produce whistlers on all occasions, but at a time of general whistler activity a loud click is always followed by a whistler.

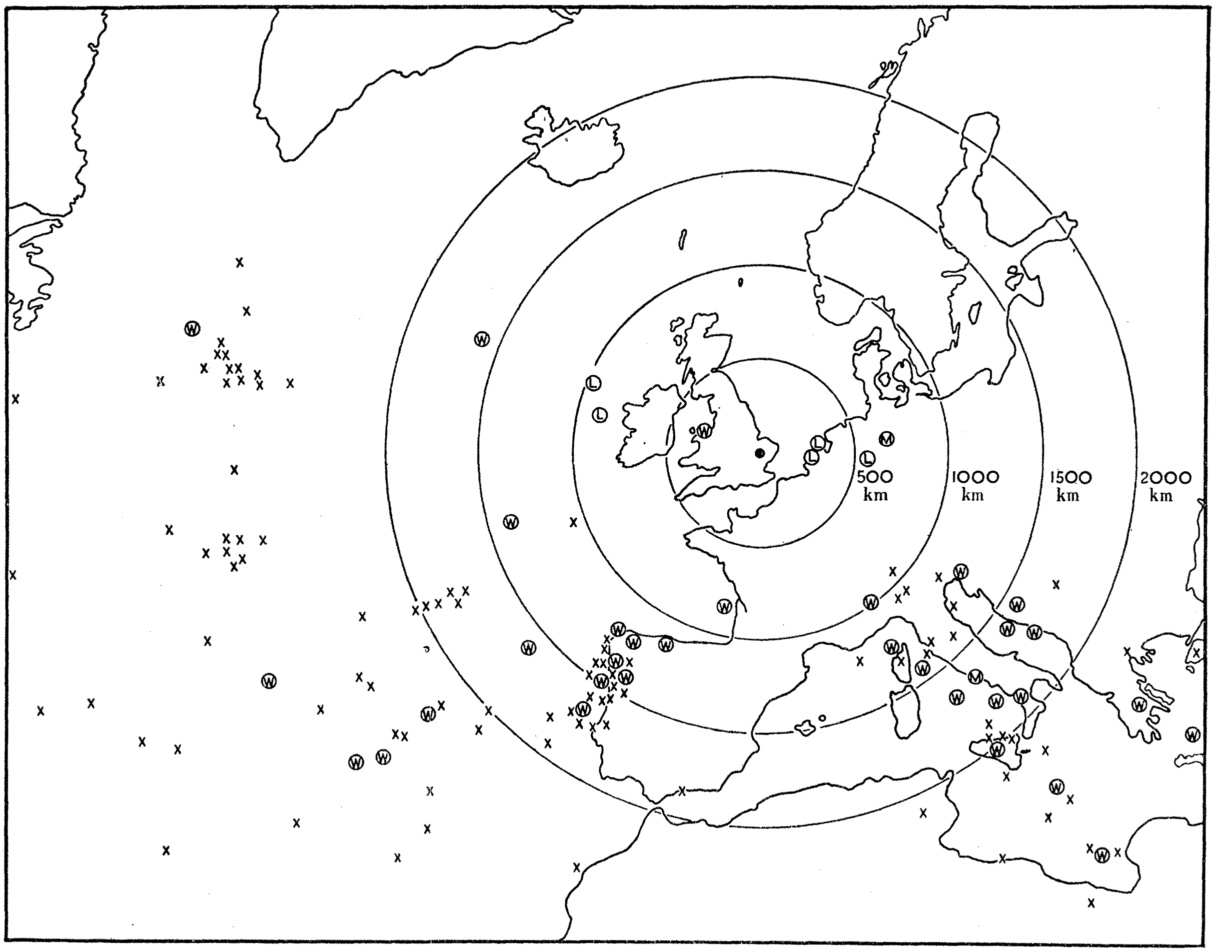

Figure 2. Results of C.R.D.F. experiment. Map showing positions of lightning strokes which gave rise to loud (*L*), medium strength (*M*), and weak whistlers (*W*), or no whistlers (*X*).

The nature of those atmospheric clicks which were followed by whistlers was investigated in a series of special experiments. The 'Sferic' organization of the Air Ministry Meteorological Office (Ockenden 1947) was used to locate the origin of the click, and its radio waveform was photographed at Cambridge by Mr P. W. A. Bowe with apparatus which he was also using for another purpose (Bowe 1951).

The arrangement of the experiments was as follows. The 'Sferic' organization 'fixed' the atmospherics and sent a short tone by telephone to Cambridge immediately after each fix. At Cambridge the output of the whistler receiver, together with this tone, was recorded on magnetic tape. One could later play the recordings back and find out which of the fixed atmospherics were followed by whistlers. The tone was also arranged to actuate a device which made a mark on the film on which the wave-forms were photographed. The work was mostly carried out in the late afternoon and early evening, and as far as possible only on days of general whistler activity.

All the atmospheric clicks examined appeared to possess ordinary properties, i.e. they were normally located by C.R.D.F. in storm areas, and their wave-forms were of the normal type. There can be little doubt, therefore, that they had their origin in lightning strokes.

The results of the C.R.D.F. work are portrayed on the map of figure 2, on which the positions of all the successful fixes are plotted out. Atmospherics which did not produce detectable whistlers are represented by crosses. If the atmospherics were followed by whistlers these were judged by ear to be weak, medium strength, or loud, and their strengths on this subjective scale have been indicated by the letters W, M or L on the map.

It is immediately clear from the map that the loudness of the whistler depended on the distance of the lightning stroke. Loud whistlers were only heard from strokes within 1000 km. Strokes at a greater distance than 2000 km seldom gave detectable whistlers. At intermediate ranges the whistlers grew weaker with increasing distance. This suggests that whistlers are produced by waves which originate in a lightning flash and return, after some time, to an area of radius about 2000 km in the neighbourhood of the original flash.

5. VARIATION OF FREQUENCY

As already mentioned, the theory of Barkhausen & Eckersley predicted that the frequency (f) in the whistler should be related to the time (t) after the original lightning flash by the expression

$$t = D \times f^{-\frac{1}{2}}.$$

Here we have called D the 'dispersion' of the whistler. It is measured in (seconds)$^{\frac{1}{2}}$.

In all the whistlers examined in the present work it was confirmed that the quantity $f^{-\frac{1}{2}}$ increased linearly with time, and in analyses of those whistlers which followed atmospheric clicks it was found, furthermore, that the intercept of the $f^{-\frac{1}{2}}$ against t graph on the time axis always coincided with the time of the click within the limits of experimental error, which were about $\pm 0{\cdot}1$ s. The chief sources of error were the high level of interfering atmospheric noise, and also the fact that the whistlers were by no means pure tones. The spread of their spectrograms in the frequency direction was much greater than that of a pure gliding tone with the same rate of variation of frequency.* This spread varied widely from one whistler to another, tending to increase with increasing dispersion.

These points are illustrated by figure 3, which is a typical analysis of a whistler following an atmospheric. The atmospheric has been set at the origin of the time scale. Each horizontal bar represents the approximate time limits of the response of a tuned filter to the whistler, and the circle indicates the position of its maximum. These responses were often of irregular shape, and the widths shown were measured between the points at which they disappeared into the noise. The filters used in these analyses had Q-factors of approximately 100. This particular whistler is followed by a doubly dispersed 'echo' (see below).

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* This depends on the band-widths of the filters used in the analysis, but has a minimum value of the order of $\sqrt{|\mathrm{d}f/\mathrm{d}t|}$.

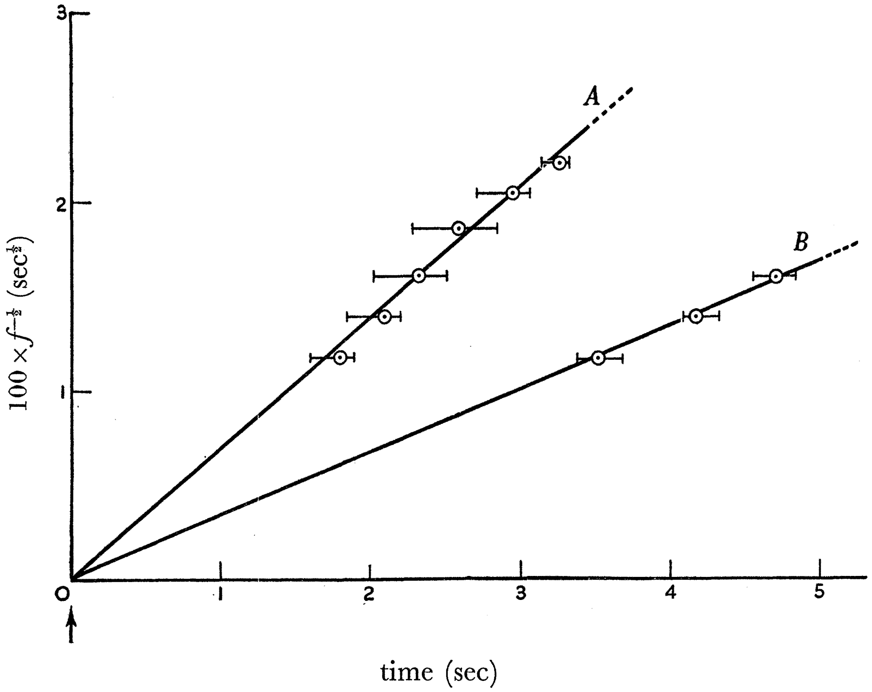


FIGURE 3. Analysis of a long whistler, with doubly dispersed 'echo', following an atmospheric click. *A*, first whistler; *B*, second whistler ('echo'); ↑ atmospheric click.

6. 'SHORT AND 'LONG' WHISTLERS

It was stated earlier that while some whistlers definitely follow atmospheric clicks, others do not. Measurements of the dispersions of the whistlers have been made at times when both types could be heard, and have established that the whistlers which are accompanied by clicks are consistently about twice as much dispersed as those with no clicks. This fact is illustrated by figures 4 and 5.

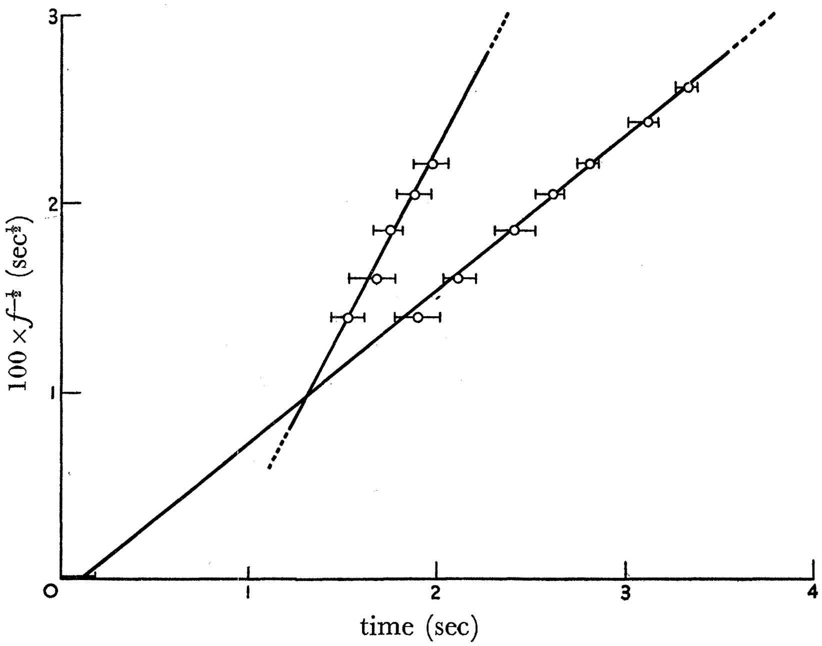


FIGURE 4. Short and long whistler overlapping.

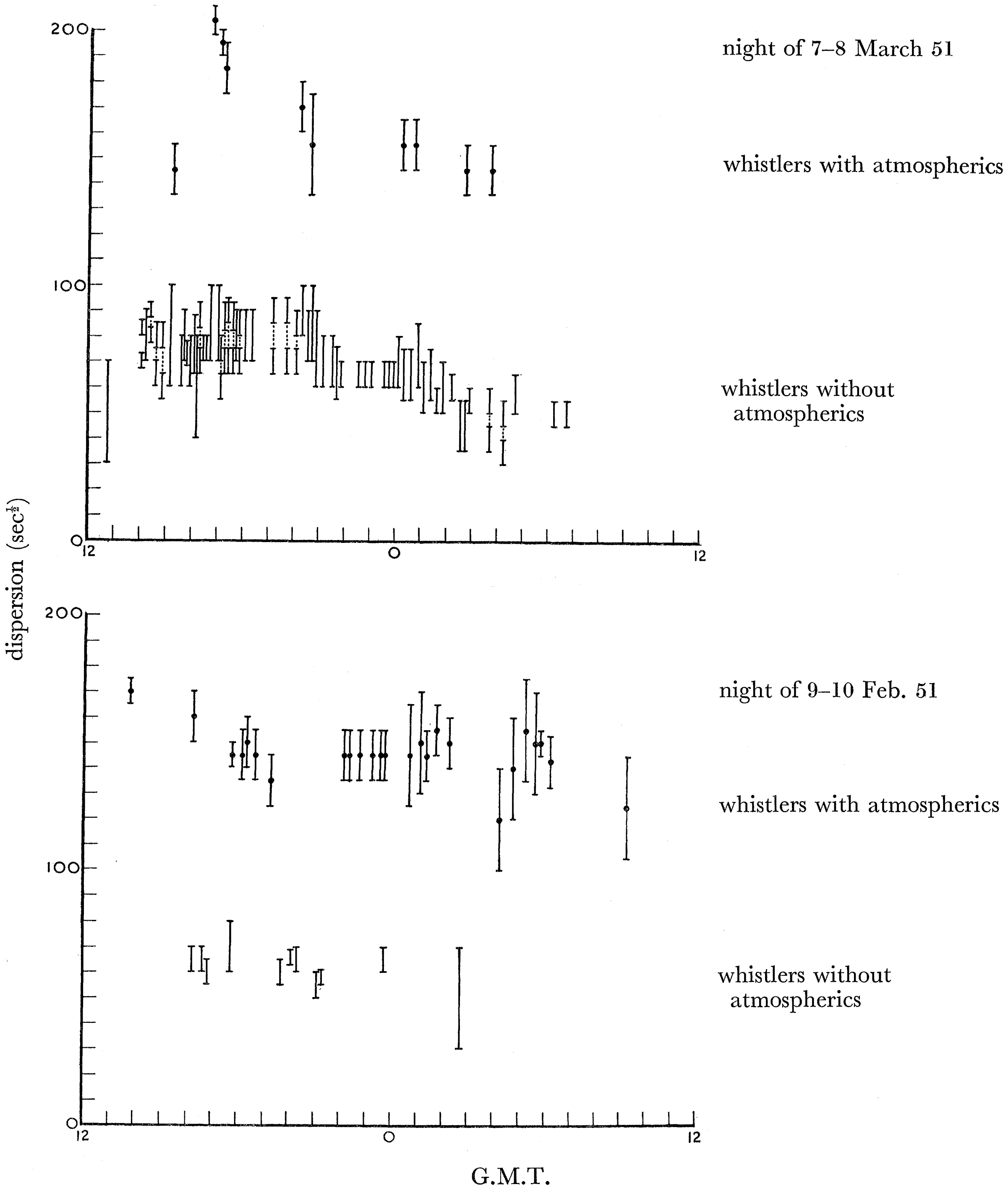


FIGURE 5. Measurements, through two nights, of the dispersions of the whistlers.

First, figure 4 shows an analysis of a rare event in which a whistler which followed a click, and one which did not, occurred almost simultaneously. The click in this particular instance was rather complex, the whole disturbance lasting for a time indicated by the horizontal line at the origin of the time axis; the $f^{-\frac{1}{2}}$ against t graph for the second of the two whistlers traces its origin to this atmospheric, but that of the first whistler intersects the time axis at another point which does not correspond to any outstanding atmospheric on the record.

This shows that the two whistlers were independent. It is evident that the first whistler is much less dispersed than the second, and the actual figures are 54 and 124 $s^{\frac{1}{2}}$.

Figure 5 shows two complete sets of dispersion measurements taken through two periods of 24 h on which both types of whistlers were present. Each vertical line represents a frequency analysis of a whistler and indicates the approximate range of dispersion which it covered. A pair of full lines joined by a dotted line signifies a whistler pair (see below). The two types are seen to fall into two separate groups, and again the whistlers which followed clicks prove to be about twice as much dispersed as those with no clicks.

On the basis of this difference of dispersion, the whistlers with and without atmospheric clicks will from now on be distinguished as 'long' and 'short' whistlers respectively.

7. Multiple whistlers

It is quite usual to hear several whistlers arrive in a group, with sufficient time between the group and the next whistler to make it clear that this is not just a chance association. The majority of these multiple whistlers are found to fall into three distinct classes, which may be designated 'whistler trains', 'multiple-flash' type groups, and 'whistler pairs'.

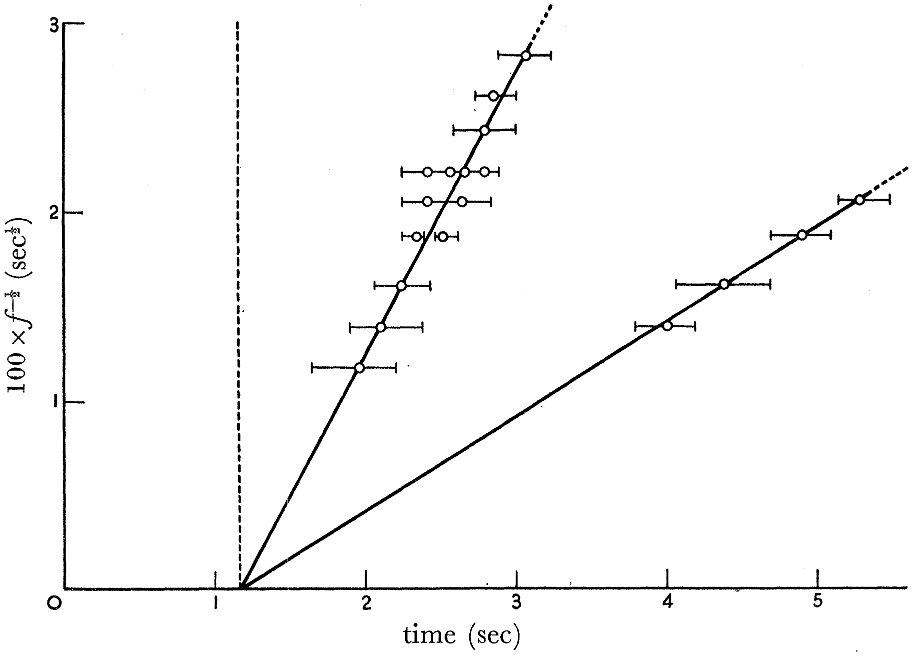


Figure 6. Short whistler with triply dispersed 'echo'.

The first of these consists of a whistler and one or more 'echoes' following each other at equal intervals, each component whistler of the train being weaker and more dispersed than the one preceding it. When the straight line plots of $f^{-\frac{1}{2}}$ against t for the successive 'echoes' were extrapolated back they intersected the time axis nearly at the same point, and if there was an atmospheric click before the train it was as usual found to have occurred at this instant.

An important difference was noted between the trains which did and those which did not follow clicks. If the train followed a click the dispersions of the successive whistlers increased in the ratios 1:2:3:4, etc., but if there was no click the ratios proved instead to be 1:3:5:7, etc. An example of the first type of whistler train has already been given in figure 3; here the mean dispersion of the first whistler was 144 $s^{\frac{1}{2}}$, that of the second 292 $s^{\frac{1}{2}}$, and their ratio 2·0 (3). An analysis of one of the second type of train, in which the first whistler was a short whistler, is shown in figure 6. Since no click was heard the origin of time is arbitrary. Here the dispersion of the first whistler was 67 $s^{\frac{1}{2}}$, of the second 201 $s^{\frac{1}{2}}$, and the ratio 3·0 (0).

Whistler trains are quite common; whenever the whistlers are loud they are usually followed by one or two 'echoes', and a normal sort of value for the decrement from the first whistler to the second is about 10 db. More rarely there occur long trains in which the decrement is much smaller. This low decrement is found only over a band about 1 kc/s wide centred on a frequency between 3 and 4 kc/s, so that after about the second echo only these components of the whistlers remain audible. The decrement at these frequencies is found to be less than would occur if the waves of the whistlers were spreading out according to the inverse square law, indicating that some form of focusing action is taking place. It also shows that little of their path can be in the lower absorbing regions of the ionosphere.

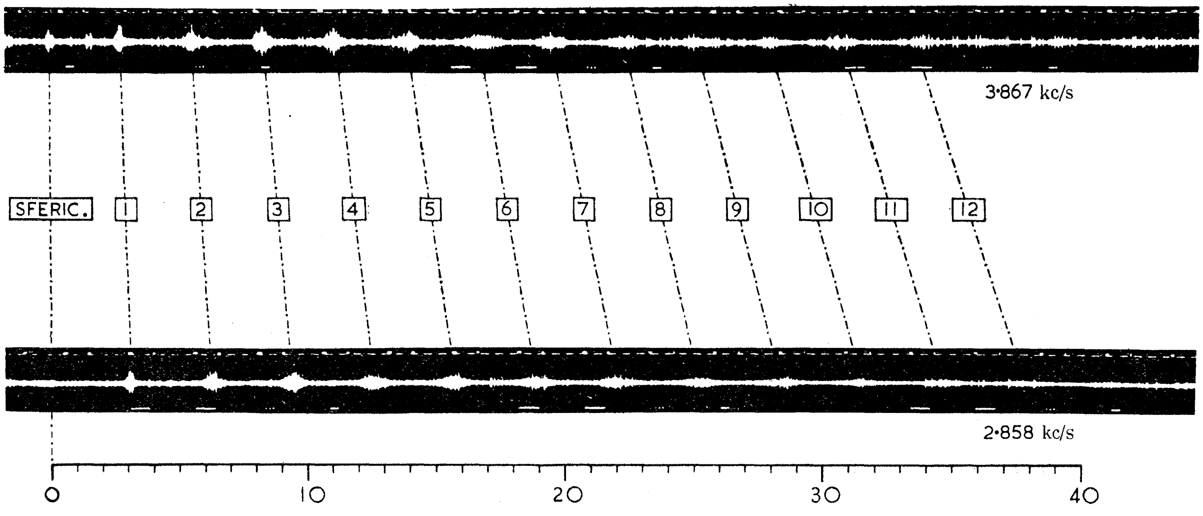
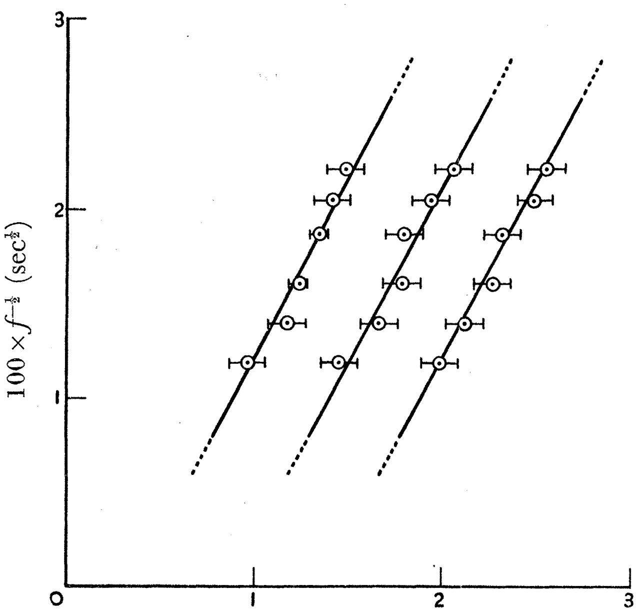


FIGURE 7. Analysis of a long train of whistlers.

An analysis of a long train following an atmospheric click is given in figure 7. These records were obtained by passing the train through the narrow-band filters of the wave analyzer and recording the envelope of the output on an oscillograph. The general width of the trace in the absence of a whistler is due to the background of normal atmospherics, while the whistlers themselves produce a broadening of the trace. About a dozen separate whistlers can be counted; note that their spacing is less at the higher of the two frequencies. On the remaining channels of the analyzer only a few echoes were distinguishable.

In this train, as in most, there is a steady decay of amplitude from one whistler to the next, but occasionally long trains are observed in which the first few whistlers actually increase in amplitude, though the later ones again decrease. If the low decrement of the long trains is indeed due to focusing, this occurrence might be caused by the successive whistlers being focused at slightly different points on the earth's surface, the natural decay of the amplitude of the first few whistlers being overridden by the approach of the point of focus towards the observer. As soon as it had passed over and begun to recede the effect of the motion of the focus would add to the decrement, and indeed these long trains appear to terminate more abruptly than usual. Trains of this kind were observed by Burton & Boardman (1933), who also noticed that they commonly had a sharp ending.

The 'multiple-flash' type of whistler group consists of up to about half a dozen short whistlers following each other in quick, often irregular, succession, with rarely more than about $\frac{1}{2}$ s between them, and all usually of much the same amplitude. On a frequency analysis, an example of which is given in figure 8, they are found also to have the same dispersion, and because they arrive at different times it is assumed that each whistler must have come from a separate lightning stroke. The natural explanation of the whole group is that it was produced from a multiple flash.



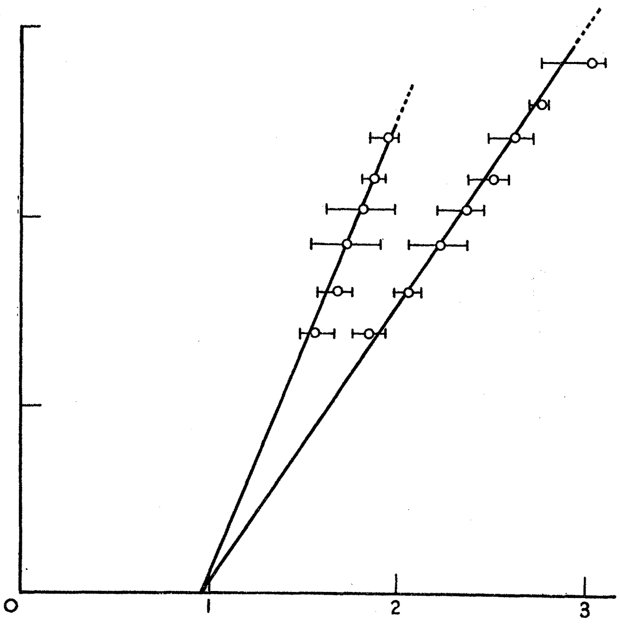


FIGURE 8. Multiple-flash type group of short whistlers.

FIGURE 9. Whistler pair.

The third type of multiple whistler is the whistler pair, consisting of two whistlers close together. It differs from the multiple-flash type in that the analysis shows both whistlers to have come from the same lightning flash, and it is not a whistler train because in these it is usual for the second whistler to be much weaker than the first, but in a pair the two component whistlers are normally of comparable amplitude and either may be the louder. Moreover, it is found that the second whistler of the pair, though more dispersed than the first, is not twice as dispersed; in the pairs analyzed in the present work the ratio of the dispersions of the two whistlers ranged from 1·4 up to 2·0. An example is shown in figure 9. The dispersion of the first whistler is $42\,\mathrm{s}^{\frac{1}{2}}$, that of the second whistler $68\,\mathrm{s}^{\frac{1}{2}}$, and their ratio 1·6 (2). Groups of more than two whistlers with non-integral dispersion ratios have not so far been observed.

Pairing is most conspicuous on short whistlers, for in a paired long whistler the two components tend to coalesce; these have nevertheless been heard. Whistler pairs were first noted and distinguished from whistler trains by Burton & Boardman (1933). Their mode of origin is not yet understood.

Of the three types of multiple whistler described above, the trains and the multiple-flash type groups are about equally common, while the whistler pairs are rather less so. More complicated types of multiple whistler have occasionally been recorded, but they have so far always proved to be resolvable into combinations of these three basic types.

8. Systematic variations in the properties of whistlers

A series of measurements was made of the rate of occurrence of the short and the long whistlers and of their dispersions throughout two winter months (February, March) and one summer month (July) of 1951. Since these measurements only cover three months of the year they provide only a partial picture of any seasonal variations, and in this they are supplemented by a large quantity of material kindly made available for analysis by Mr K. W. Tremellen of Marconi's Wireless Telegraph Co., Chelmsford. This consists of a series of observations of the occurrence of whistlers taken continuously for the seventeen months from August 1944 to December 1945, apart from some gaps due to apparatus failure.

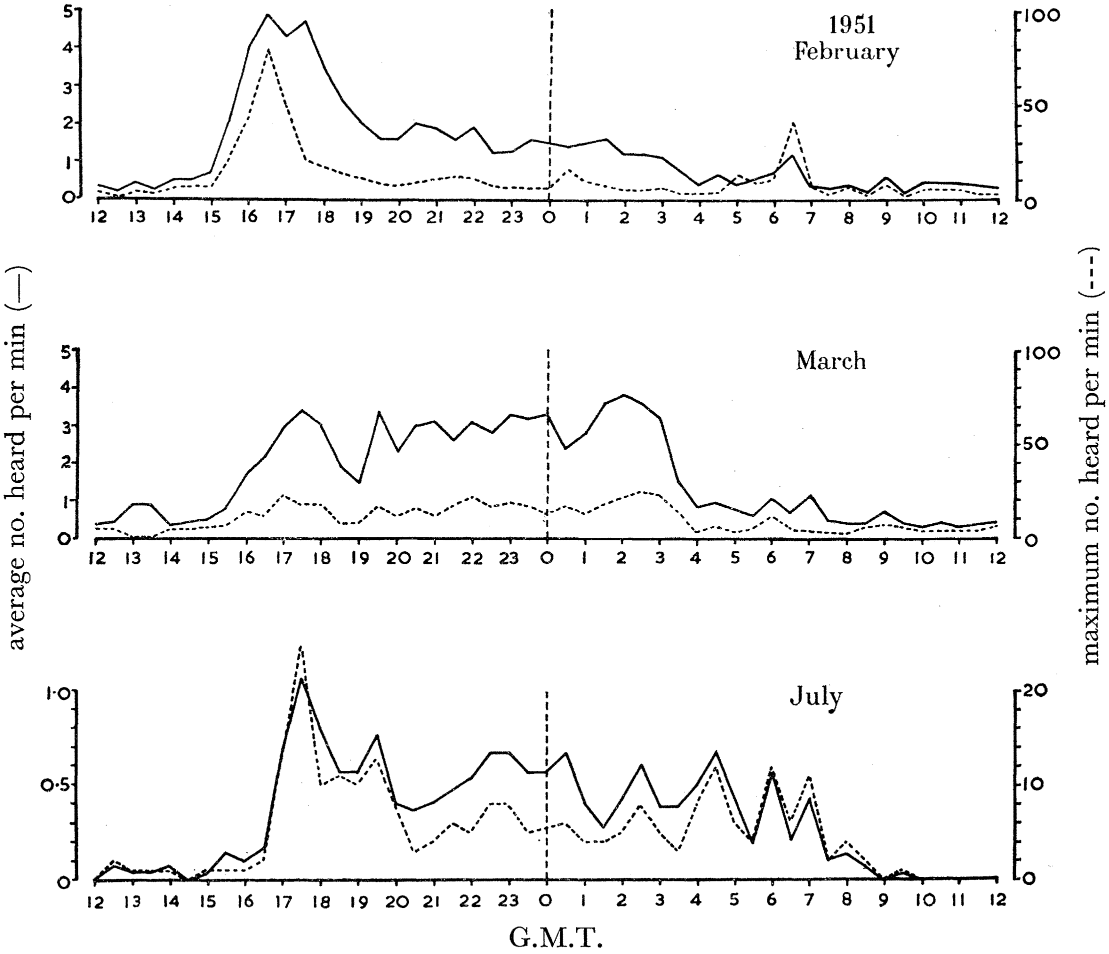


Figure 10. Daily variation of occurrence of short whistlers.

(a) *Relation between whistlers and magnetic activity*

The occurrence of whistlers varies widely from day to day. On some days they may be heard continuously at the rate of one every few seconds for the whole of the twenty-four hours, while on others none may be heard. These variations exhibit a significant association with magnetic activity. Analysis of the records taken by the Marconi workers showed that, over a period of 390 days, the coefficient of correlation between an index of whistler activity and the *K*-figure of magnetic disturbance (measured at Great Baddow) was 0·40 ± 0·06. This correlation is not so strong as that originally suggested by Eckersley (1928). A careful inspection of the records suggests that it chiefly arose from periods which were free from magnetic activity for a considerable time, when the incidence of whistlers was also much reduced, while during disturbed periods there was little or no association between the day-to-day fluctuations of the *K*-figure and whistler activity.

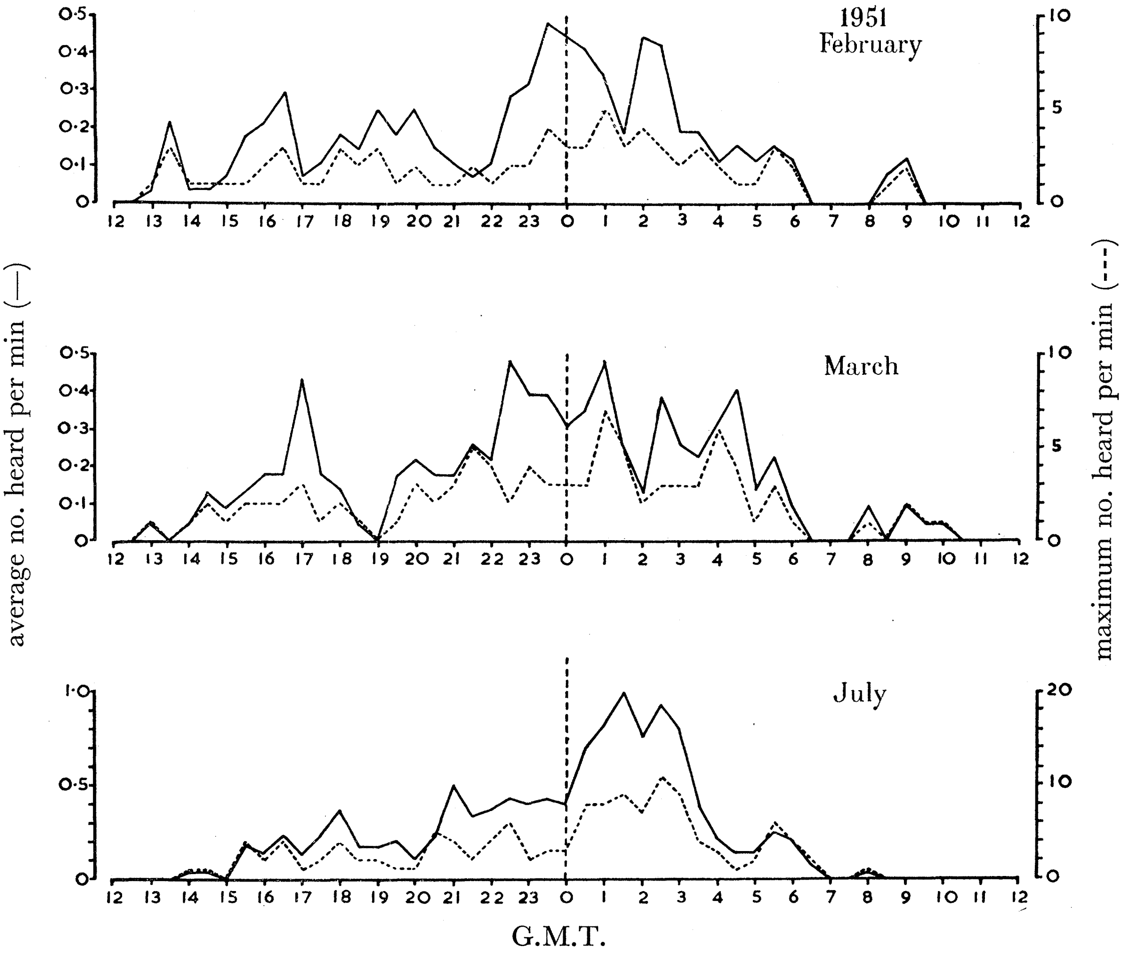


FIGURE 11. Daily variation of occurrence of long whistlers.

(*b*) *Diurnal variation of rate of occurrence*

Throughout a single day the rate of occurrence of whistlers commonly varies in an irregular and arbitrary fashion, but when the daily records are averaged over a period of a month or so a fairly consistent pattern emerges. The results are different for short and for long whistlers. Figures 10 and 11 show, for short and long whistlers respectively, and for each of the three months of observation the mean (full line, left-hand scale) and peak (dotted line, right-hand scale) values of the rate of occurrence, plotted at intervals of half an hour. Note the changes of scale between winter and summer.

There are two features common to most of the curves. First, whistlers occur more frequently (and incidentally are louder) during the night than the day, and secondly the daily variation is not symmetrical about midnight but instead rather more are heard during the late afternoon and evening than in the corresponding hours of the early morning.

(*c*) *Annual variation of rate of occurrence*

Burton & Boardman (1933) concluded that the total rate of occurrence of whistlers had little systematic variation with time of year, and this is confirmed in the Marconi records. When, however, the long and the short whistlers are counted separately they are found to have definite variations with the seasons which are opposite in sense, the former increasing from winter to summer and the latter decreasing. The figures recorded at Cambridge in 1951 were the following:

	average number heard per minute		
	February	March	July
long whistlers	0·155 ± 0·011	0·170 ± 0·13	0·240 ± 0·013
short whistlers	1·36 ± 0·03	1·70 ± 0·04	0·345 ± 0·015

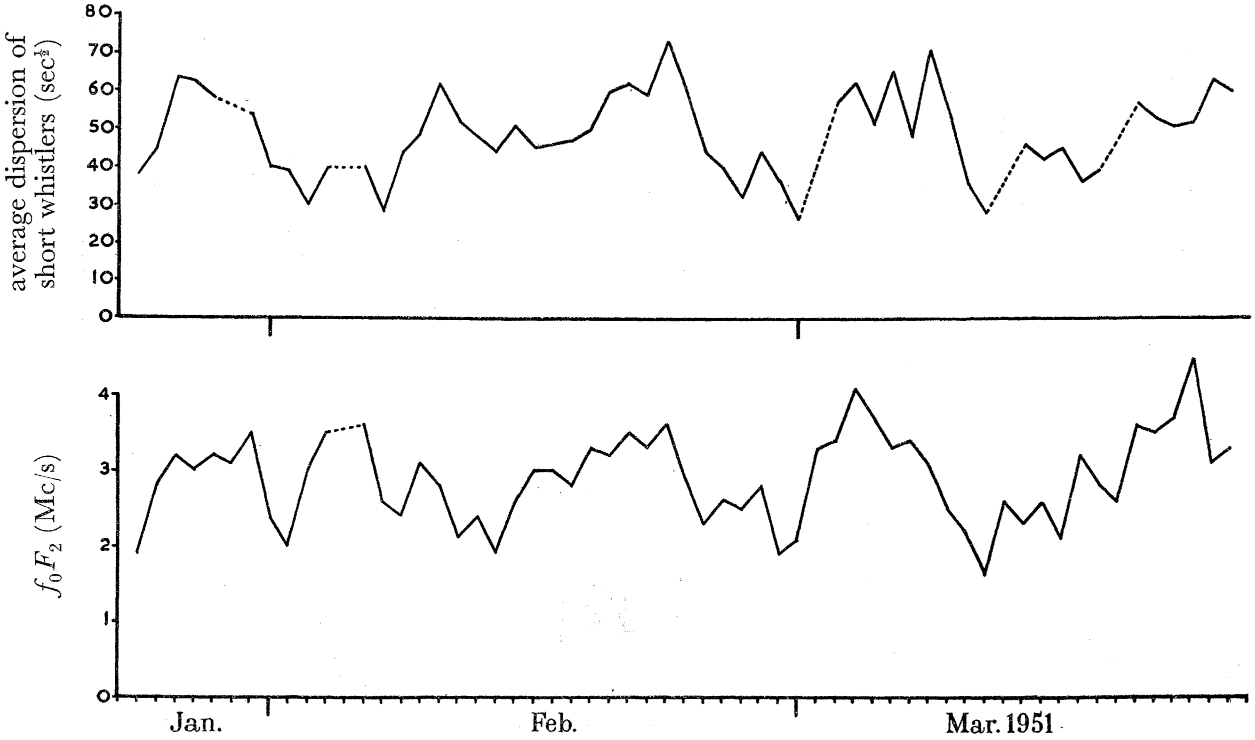


FIGURE 12. Day-to-day variation of the dispersion, showing correlation with F_2 critical frequency.

(*d*) *Variations of the dispersion*

The dispersions of the short whistlers which were observed in the course of the present work ranged from about 20 to $120\,\mathrm{s}^{\frac{1}{2}}$, and those of the long whistlers from about 40 to $250\,\mathrm{s}^{\frac{1}{2}}$. At any one time, however, different whistlers of the same type tended to have much the same dispersion, and this dispersion showed remarkably little systematic variation with time of day. The records of figure 5 are fairly typical, though perhaps the upper of the two is more variable than usual. In particular, there is no conspicuous change over dawn or sunset when the ionization densities in the lower ionosphere are altering rapidly. This being so, it is justifiable to take the average of the dispersions of any whistlers analyzed as a representative figure for each night. The variation of the nightly average dispersion of the short whistlers has been plotted out in figure 12 for a period of two months in 1951. The dotted lines indicate nights when no whistlers were analyzed, either because none were heard or because the equipment broke down.

A positive correlation has been found between these nightly dispersion figures and the critical frequency of the F_2 layer, which is graphed in the lower half of the figure. (This is the average of the critical frequencies for five hours centred on midnight, measured at Slough.) The coefficient of correlation between the two records is $0{\cdot}4 \pm 0{\cdot}2$, the error being estimated on the assumption that the number of statistically independent pairs of values is one-quarter of the actual number.

The measurements, though at present rather meagre, suggest that there is little or no variation of the dispersion with the seasons. They are summarized below:

	average dispersion in $(\text{sec})^{\frac{1}{2}}$	
month	short whistlers	long whistlers
February	46 (28 nights)	120 (19 nights)
March	50 (21 nights)	115 (12 nights)
July	53 (9 nights)	144 (11 nights)

9. SUMMARY

At this point it seems appropriate to make a summary of the chief properties of the whistlers, before proceeding to the second part of the paper where we advance a theory of their origin.

Whistlers are atmospherics which are observed in the audio-frequency band of the radio spectrum, where they appear as whistling tones of descending pitch. They are found to fall into two distinct classes, termed 'long' and 'short' whistlers. The long whistlers are observed to follow 'click' type atmospherics with a few seconds delay, while the short whistlers are not preceded by atmospherics. The atmospherics accompanying the long whistlers are produced by lightning strokes which take place within a distance of about 2000 km from the point of observation; the further the stroke the weaker is the resulting whistler. For both types of whistler the frequency (f) is related to the time (t) in such a way that the graph of $f^{-\frac{1}{2}}$ against t is linear. The $f^{-\frac{1}{2}}$ against t graph for a long whistler intersects the time axis at the instant of the associated atmospheric. The reciprocal of the slope of the $f^{-\frac{1}{2}}$ against t curve is called the *dispersion* of the whistler. When the long and the short whistlers are observed at the same time the former always have about twice as large a dispersion as the latter. There have been observations of 'whistler trains' consisting of several whistlers following one another in regular sequence; if a train followed an atmospheric the dispersions of its successive component whistlers were found to increase in the ratios 1:2:3:4, etc., but if there was no atmospheric the ratios were 1:3:5:7, etc.

The rate of occurrence of both types is greater by night than by day, but their dispersion is more or less independent of time of day. Long whistlers occur more frequently in summer than in winter, while the reverse is true for short whistlers. The day-to-day variations of total whistler activity exhibit a small but definite positive correlation with magnetic disturbance. The variations of the dispersion correlate with those of the critical frequency of the F_2 layer.

PART 2. A THEORY OF WHISTLING ATMOSPHERICS

10. Preliminary remarks

The main facts of observation concerning the whistling atmospherics have been described in the first part of this paper, and are summarized above in its final paragraph. We have now to consider the problem of their origin.

Previously a theory of whistlers had been developed by Eckersley (1935) following a suggestion of Barkhausen (1930). This theory was chiefly based on the observation of whistlers following impulsive atmospherics, and proposed that the whistlers were produced from the atmospherics by dispersion. Eckersley showed that at frequencies below the gyro-frequency radio waves could be propagated freely through the ionosphere in the extra-ordinary mode (provided that the Lorentz term in the equations of propagation was zero), and that at audible frequencies the group velocity of the waves increased rapidly with increasing frequency, so that over a long path the different frequency components of a pulse would become separated out in the manner suggested. The theory predicted that the frequency of the tone should decrease with increasing time according to the law

$$f^{-\frac{1}{2}} \propto t,$$

where t is the time after the original atmospheric click, and this was confirmed in the case of a single analysis of a whistler which had been published by Burton & Boardman (1933). Thus although the quantitative experimental evidence was scanty, what there was supported the view that whistlers were produced by dispersion of impulsive atmospherics over a path through the ionosphere. There was no knowledge of the nature of the sources of these atmospherics or of their position, nor was it known where the dispersing path went.

The theory to be described is a simple extension of that of Eckersley. We now know that the atmospherics which precede the long whistlers are produced by relatively local lightning flashes (§4). The problem is therefore to trace the paths through the ionosphere of the waves radiated by a local lightning flash, to discover how they are returned to their point of origin, and to show that the returned waves have the observed characteristics of the long whistlers. In particular, we are required to account for the manner in which the loudness of the whistler depends on the distance of the stroke. We must then explain the existence of the short whistlers and the ways in which they differ from the long whistlers.

Accordingly, we first study the general problem of the propagation of low-frequency radio waves through an ionized medium in the presence of a magnetic field, paying particular attention to the dispersive and anisotropic properties of the medium. The results are then applied to the study of the paths of low-frequency wave packets through the ionosphere. The origin and properties of whistlers are then discussed, and an explanation of the differences between long and short whistlers is put forward. Finally, an attempt is made to deduce from the observed properties of the whistlers information concerning the state of the outer ionosphere.

11. The propagation of low-frequency wave packets

The properties of radio waves travelling through an ionized medium in the presence of a magnetic field are commonly described by expressions giving the refractive index μ as a function of the parameters of the wave (its frequency and direction of propagation) and the parameters of the medium (the electron density and magnetic field strength). Now this is the wave refractive index, corresponding to the velocity of propagation u of the wave fronts of a single infinite plane wave, but in the problem in hand we are concerned not with the propagation of plane waves of a single frequency in a single direction but with that of pulses or packets of waves. If the medium is dispersive, the phase velocity varying with frequency, the packet will travel through it with a *group velocity* v (*group refractive index* μ') which differs from the phase velocity in magnitude. Likewise if the medium is anisotropic the packet will travel in a direction, the *ray direction*, which is in general inclined to the wave normal. The expression relating the wave and group velocities is well known, and the relationship between the wave normal and ray directions is equally simple. If we call the angle between the magnetic field direction and the normal θ, and that between the normal and the ray α (reckoned positive if the normal lies between the field and the ray) the relationship is (Bremmer 1949)

$$\begin{aligned}\tan\alpha &= \frac{1}{u}\frac{\partial u}{\partial\theta}\\ &= -\frac{1}{2\mu^2}\left(\frac{\partial}{\partial\theta}\right)\mu^2.\end{aligned} \tag{1}$$

The ray direction always lies in the plane containing the direction of the magnetic field and the wave normal.

In a medium which is both dispersive and anisotropic the wave packet travels in the ray direction with a velocity, here to be called the *group-ray velocity* V (*group-ray refractive index* M'), whose component in the direction of the wave normal is equal to the group velocity. The relationship between the magnitudes of these velocities is therefore

$$\left.\begin{aligned}V &= v\sec\alpha,\\ M' &= \mu\cos\alpha.\end{aligned}\right\} \tag{2}$$

We now proceed to evaluate these quantities for low-frequency radio waves in the ionosphere.

(*a*) *Wave refractive index*

The magneto-ionic theory of Appleton (1932) and Hartree (1931) gives expressions for the propagation constants (refractive index, absorption coefficient, polarization) of radio waves travelling through an ionized medium in the presence of a steady magnetic field, giving them as functions of the following variables:

the wave frequency	f
the electron density	N
the magnetic field strength	H
the angle between the wave normal and the direction of the field	θ
the collision frequency	ν

and of the constants,

the charge of an electron	e
the mass of an electron	m
the electric permittivity of free space	ϵ_0
the magnetic permittivity of free space	μ_0

or more simply as functions of certain derived quantities, now defined. Set first

wave angular frequency $p = 2\pi f$

critical angular frequency of medium $p_0^2 = (2\pi f_0)^2 = \dfrac{4\pi Ne^2}{\epsilon_0 m}$

gyro angular frequency $p_H = 2\pi f_H = \dfrac{\mu_0 He}{m}$

and thence define $x = \dfrac{p_0^2}{p^2} = \dfrac{f_0^2}{f^2}$,

$$y = \frac{p_H}{p} = \frac{f_H}{f}, \quad y_L = y\cos\theta, \quad y_T = y\sin\theta,$$

$$z = \frac{\nu}{p} = \frac{\nu}{2\pi f}.$$

The table below shows the approximate ranges of values which some of these variables take in the case of the propagation of a whistler through the ionosphere:

variable	range of values
f	0·5 to 10 kc/s
f_0	0 to 10 Mc/s
f_H	1·5 to 0·1 Mc/s
x	0 to 4×10^8
y	10 to 3000
x/y	0 to 10^5.

It will be noted that the last three variables attain values much larger than those normally met with in ionospheric work. This fact will shortly enable us to make a number of simplifying approximations in the formulae for the refractive index.

Now according to our theory most of the path of a whistler is at very great heights where collisions are so rare that their effect on the refractive indices can be neglected. They are only of importance below a height of about 80 km, and although this part of the ionosphere doubtless produces considerable attenuation of the whistlers during the daytime, it makes no appreciable contribution to their dispersion. We shall therefore assume that $\nu = 0$ in the magneto-ionic equations. Even so the general expression for the refractive index is still rather complicated, but fortunately there is a simple approximation to it, known as the quasi-longitudinal (Q.L.) approximation, which at low frequencies holds good at all levels and for all directions of propagation except those very close to the transverse direction (Booker 1935). The Q.L. formula for the refractive index of the extraordinary mode, in which the whistlers are assumed to be propagated, is

$$\mu^2 = 1 - \frac{x}{1-y_L}$$

$$\simeq 1 + \frac{x}{y_L} \quad \text{if} \quad y_L \gg 1 \tag{3}$$

$$\simeq \frac{x}{y_L} = \frac{f_0^2}{f f_H \cos\theta} \quad \text{if} \quad \frac{x}{y} \gg 1. \tag{4}$$

It will be observed that we have omitted the Lorentz polarization term from the equations. If this term were finite it would alter the refractive indices considerably and in such a way that low-frequency radio waves would be unable to travel freely through the ionosphere, and therefore whistlers could not occur at all. Hence the existence of whistlers appears to provide evidence that the Lorentz term is zero, at any rate up to the highest frequency heard which in the present work was about 10 kc/s. This, as mentioned earlier, was first pointed out by Eckersley.

We have also ignored any possible effects on the refractive index of the movements of the molecular ions in the field of the wave. This matter has been studied by Goubau (1935), and the result of applying his analysis to the present case is to confirm that unless the ratio of the number density of the ions to that of the electrons were very large these effects would be negligible.

(*b*) *Group refractive index*

The group refractive index can be derived from the wave refractive index in the usual way, and the result is

$$\mu' \simeq \left(1+\frac{1}{2}\frac{x}{y_L}\right)\Big/\sqrt{\left(1+\frac{x}{y_L}\right)} \tag{5}$$

$$= \frac{1}{2}\sqrt{\left(1+\frac{x}{y_L}\right)}+\frac{1}{2\sqrt{(1+x/y_L)}}$$

$$\simeq \frac{1}{2}\sqrt{\frac{x}{y_L}} \simeq \tfrac{1}{2}\mu \quad \text{if} \quad x/y \gg 1. \tag{6}$$

This very useful approximation holds good for large x/y, that is, whenever the group refractive index itself is large. If x/y is small the values which it indicates are too low, but so long as conditions are Q.L. the absolute error is never more than unity.

(*c*) *Relationship between wave normal and ray directions*

Similarly, by substituting the expressions for the wave refractive index into equation (1) we obtain the angle between the ray and the wave normal:

$$\tan\alpha \simeq -\frac{1}{2}\frac{x/y_L}{1+x/y_L}\tan\theta \quad (y \gg 1), \tag{7}$$

$$\simeq -\tfrac{1}{2}\tan\theta \quad \text{if} \quad x/y \gg 1. \tag{8}$$

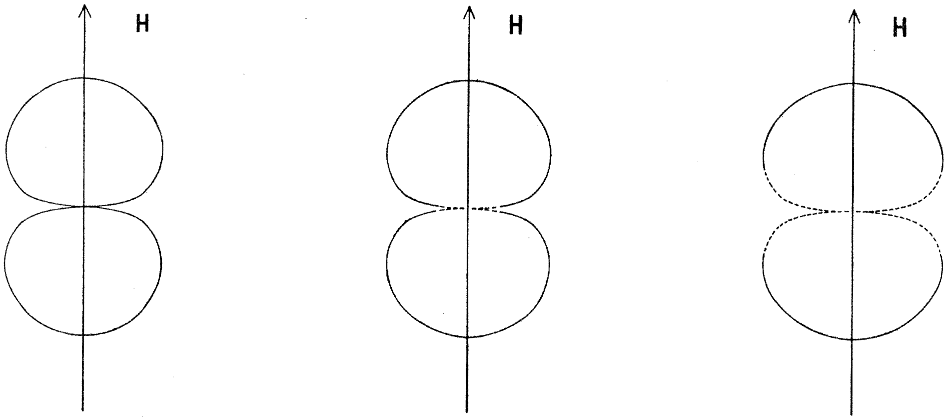
The minus sign implies that the ray direction always lies between the normal and the direction of the field.

It is customary to portray the properties of an anisotropic medium by means of certain characteristic surfaces, termed the wave surface and the ray surface. The former is a three-dimensional polar plot of wave velocity against wave normal direction, and the shape of this surface for very low frequency waves in the ionosphere is shown in figure 13. It has been worked out for the cases $x/y = \infty$, 5 and 1. The surface is a solid of revolution with the magnetic field direction as its axis of symmetry, and the figures show sections through a plane containing this direction. The dashed portions of the curves are those where the Q.L. approximation does not apply.

More important for our purpose is the ray surface, which correspondingly is a three-dimensional plot of ray velocity against ray direction. In figure 14 are shown the ray surfaces which correspond to the wave surfaces of figure 13. Their most striking feature is the remarkable way in which the rays are bunched around the direction of the field. For large x/y the possible ray directions are entirely limited to a cone of semi-angle

$$(\theta+\alpha)_{\text{max.}} = \tan^{-1}\sqrt{\tfrac{1}{8}} = 19^\circ\,29'$$

about the field direction. When x/y is small the possible divergence of the rays is rather greater, but it can be seen that the surface for $x/y = 5$ is practically indistinguishable from that for $x/y = \infty$, and even when $x/y = 1$ the rays are still restricted to quite a narrow cone. Thus whatever the normal direction of the waves within it (and this, of course, is not restricted in any way) a very low frequency wave packet can only travel through the ionosphere more or less along the lines of magnetic force.



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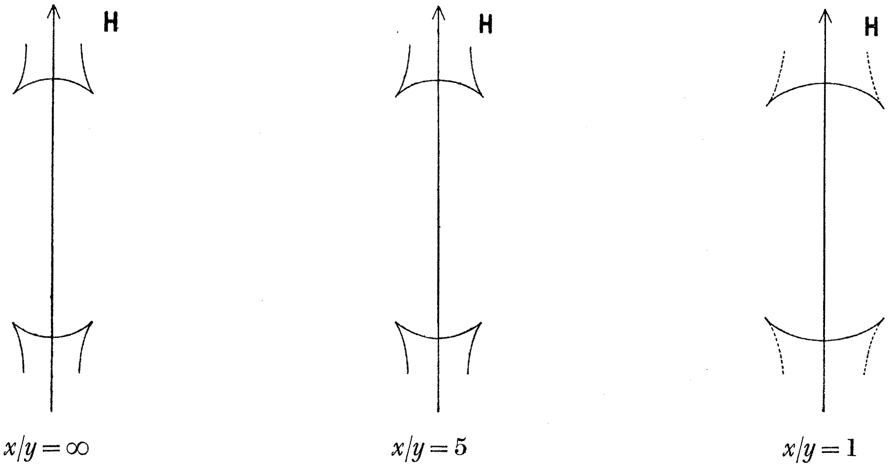

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FIGURE 13. (above). Magneto-ionic wave surfaces at very low frequency.

FIGURE 14 (below). The corresponding ray surfaces.

(*d*) *Group-ray refractive index*

By combining the expressions for μ' and for α we arrive finally at the group-ray refractive index M'. It depends both on frequency and on wave normal or ray direction and is given by

$$M' \simeq \frac{1+\frac{1}{2}x/y_L}{\sqrt{(1+\frac{1}{2}x/y_L)}}\cos\alpha \quad (y \gg 1), \tag{9}$$

with α given by equation (7). Or if also $x/y \gg 1$,

$$M' \simeq \frac{1}{2}\sqrt{\frac{x}{y}}\left[\frac{\cos\alpha}{\sqrt{\cos\theta}}\right], \tag{10}$$

with α given by equation (8).

The term in the brackets contains the angular variation of M', and this factor is plotted as a function of wave normal direction θ in figure 15. It can be seen that over a wide range of θ the variations of numerator and denominator more or less compensate one another, and that in fact their ratio is within 8 % of unity for values of θ up to 70°:

$$M' \simeq \frac{1}{2}\sqrt{\frac{x}{y}} = \frac{1}{2}\frac{f_0}{\sqrt{(ff_H)}} \quad \text{for} \quad \theta < 70^\circ. \tag{11}$$

This result, that the group-ray refractive index is practically independent of wave normal direction, is important and simplifies some of the later arguments.

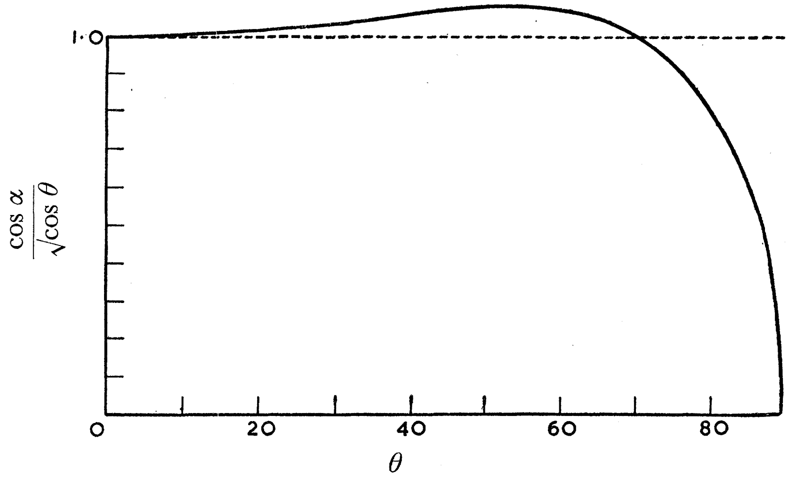

FIGURE 15. Dependence of group-ray refractive index on wave normal direction ($x/y = \infty$).

12. THE PATH OF A LOW-FREQUENCY WAVE PACKET

We have now to consider how the low-frequency components of the wave packet radiated by a lightning flash would enter the ionosphere and how they would travel within it.

Within the ionosphere the refractive indices for audio-frequency waves in the extraordinary mode are very large indeed. For a wave with its normal parallel to the magnetic field the following are some typical values:

wave frequency	local critical frequency	refractive index
10 kc/s	1 Mc/s (E-layer, say)	10
1·6 kc/s	10 Mc/s (F-layer, say)	250

For other directions of propagation the refractive indices are greater. It follows that although the waves are incident upon the base of the ionosphere with a wide range of wave normal directions, as soon as they enter it all the normals are refracted into a narrow cone about the vertical direction. The ray direction, however, is close to the direction of the field (§11c), and, indeed, in the limit of large ionization densities can never depart from it by more than about 20°. Hence the path taken by the wave packet through the ionosphere must follow the magnetic lines of force quite closely. Moreover, the relationship between the ray and wave normal directions is such that the rays are bunched to an even greater extent than the normals. For from (8) we find the change in ray direction $(\theta+\alpha)$ per unit change of wave normal direction (θ) to be

$$\frac{\mathrm{d}}{\mathrm{d}\theta}(\theta+\alpha)=1-\frac{2}{1+3\cos^2\theta}. \tag{12}$$

The magnitude of this quantity is less than $\frac{1}{2}$ for all values of θ up to 70°, and it is zero for $\theta=54^\circ\,44'$ when the inclination of the ray to the field is a maximum. It is clear, therefore, that the refraction and the anisotropy together produce a very marked beaming of the rays. The effect is greater at lower frequencies, because the refractive index is larger.

Although the precise path of the wave packet cannot be determined unless the electron density is known at all heights, it is nevertheless possible to show that the ray path is independent of frequency. For the calculation of the path involves only the law of refraction, the anisotropy law of the medium, and the geometry of the earth's magnetic field. The law of refraction is most simply expressed in terms of the wave normals, and is as follows:

$$\frac{\mathrm{d}\tau}{\mathrm{d}n}=-\frac{1}{\mu}\frac{\partial\mu}{\partial w}$$

where τ is the angle between the wave normal and any fixed direction in the plane containing also the normal to the local planes of stratification (the plane of incidence), dn is an element of length along the wave normal, dw an element in a direction perpendicular to the wave normal in the plane of incidence, and μ is the wave refractive index which is, of course, itself a function of direction. Now this equation can also be written in the form

$$\frac{\mathrm{d}\tau}{\mathrm{d}n}=-\frac{\partial}{\partial w}(\log\mu),$$

and the anisotropy law for the medium (1) can be written likewise,

$$\tan\alpha=-\frac{\partial}{\partial\theta}(\log\mu).$$

Both equations involve derivatives of the logarithm of the wave refractive index, and clearly if these derivatives are independent of frequency, so also will be the ray paths. The condition for independence is that the refractive index shall be expressible as the product of a function of frequency alone with a function of wave normal direction and the local properties of the medium (i.e. f_0, f_H). This condition is satisfied by the approximate equation (6) for the refractive index in the extraordinary mode at very low frequency.

It follows that if two pulses of waves with different centre frequencies are launched into the ionosphere at the same point and in the same direction, they will thereafter travel along the same path, albeit at different speeds.

Summarizing, we conclude that the paths through the ionosphere of the low-frequency components of the wave packet radiated by a lightning flash will exhibit certain general features. First, all the rays will follow the lines of force of the earth's magnetic field fairly closely. Secondly, the path of the central ray, i.e. the ray incident vertically at the base of the ionosphere, will be the same for all frequencies. Lastly, due to the joint effects of refraction at the base of the ionosphere and the anisotropy of the medium, the lateral spreading of the rays about the path of the central ray will be small; the spreading will be least for the lowest frequencies.

13. The origin of whistlers

(a) *Mode of production*

It is suggested that whistlers are waves from lightning flashes which have entered the ionosphere in the extraordinary magneto-ionic mode and travelled outwards along the lines of force of the earth's magnetic field. It is further suggested that the electron density in the outer ionosphere remains great enough to support this mode of propagation even up to the level above the equator, at a height of about two earth radii, where a line of force which intersects the earth's surface in England reaches its highest point. The wave packet is in this case unable to escape from the ionosphere but will be guided along the line of force right up to that point. It then continues down the line of force in the other hemisphere and arrives at the earth as a dispersed wave train which is recognized as a whistler. The mechanisms discussed above prevent undue spreading of the waves, so that their intensity at the point where they return to the ground is considerable.

It is suggested that the short whistlers heard in Cambridge originate in lightning flashes which occur at the opposite end of a line of magnetic force, somewhere in the southern hemisphere. The clicks corresponding to the direct radiation which travels in the space between the ground and the ionosphere, following the curve of the earth, are heavily attenuated even at night time, and so are too weak to be detected (Budden 1951). This accounts for the fact that short whistlers are not preceded by clicks.

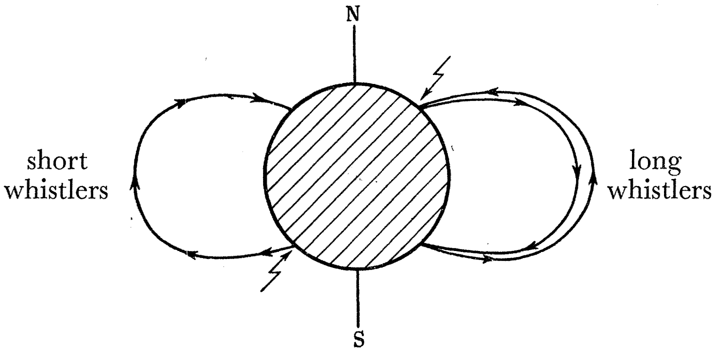

Figure 16. Suggested paths of the two types of whistler.

It is also suggested that long whistlers are heard in Cambridge when waves originating in a local lightning flash travel along the magnetic lines of force and are reflected back again after reaching the earth at the other end. The process responsible for the concentration of the energy is effective both on the outward and the return journey, so the resulting whistler is only detectable fairly near to the position of the original flash. Conversely, at a fixed point of observation long whistlers can only be received from lightning flashes that take place within a certain radius. Experiment (§4) has shown this distance to be about 2000 km.

Multiple reflexions of either type of whistler back and forth along the same line of force would explain the whistler trains, and the process of energy concentration would allow the later members of the train to have detectable intensities.

The suggested mechanisms for producing the two types of whistler are illustrated schematically in figure 16. The forked arrow indicates the position of the lightning flash.

(*b*) *Variation of frequency*

The time of arrival at the observer, measured from the instant of the lightning stroke, of the group of waves comprising frequencies in the neighbourhood of some frequency f, is given by

$$t(f) = \frac{1}{c}\int M'(f)\,\mathrm{d}s,$$

where the integral is taken along the ray path of which $\mathrm{d}s$ is an element, and c is the velocity of light. If we assume that everywhere along the path the ionization is sufficiently dense for the condition $x/y \gg 1$ to be fulfilled, then the approximate expression (11) can be substituted for the group-ray refractive index $M'(f)$ and the frequency/time law of the whistler found to be

$$t(f) = \frac{1}{c}\int \frac{1}{2}\sqrt{\frac{x}{y}}\left[\frac{\cos\alpha}{\sqrt{(\cos\theta)}}\right]\mathrm{d}s$$

$$= \left[\frac{1}{2c}\int \frac{f_0}{\sqrt{f_H}}\frac{\cos\alpha}{\sqrt{(\cos\theta)}}\,\mathrm{d}s\right]\times f^{-\frac{1}{2}},$$

$$f^{-\frac{1}{2}} = \frac{1}{D}\times t(f). \tag{13}$$

So a plot of $f^{-\frac{1}{2}}$ against time t should be a straight line which intersects the time axis at the instant of the original atmospheric. The varying conditions along the path enter only into the slope of the plot which is given by

$$D = \frac{\delta t}{\delta(f)^{-\frac{1}{2}}} = \frac{1}{2c}\int \frac{f_0}{\sqrt{f_H}}\frac{\cos\alpha}{\sqrt{(\cos\theta)}}\,\mathrm{d}s \tag{14}$$

$$\simeq \frac{1}{2c}\int \frac{f_0}{\sqrt{f_H}}\,\mathrm{d}s \quad \text{if} \quad \theta < 70^\circ \text{ everywhere.} \tag{15}$$

The quantity D is called the *dispersion* of the whistler.

If the condition that $x/y \gg 1$ were not fulfilled along the whole of the path the frequency/time law would be slightly modified. First, if parts of the path were unionized and therefore non-dispersive the $f^{-\frac{1}{2}}$ against t graph for the whistler would intersect the time axis at an instant later than that of the atmospheric, the difference between the two times being the time taken by light to traverse a distance equal to the combined lengths of these parts. Secondly, if along much of the path there were weak ionization with $x/y \approx 1$, then one can show by use of the fuller expression (9) for the group-ray refractive index that the effect would be to produce a slight downward curvature of the $f^{-\frac{1}{2}}$ against t graph at the high-frequency end. In fact, however, it can be seen from the table in § 2 *a*, which shows the range of x/y encountered in the ionosphere, that the condition is likely to be well satisfied along much of the whistler path.

Whistlers, as stated earlier (§ 5), are found to obey the linear $f^{-\frac{1}{2}}$ against t law, and thus the dispersion theory of their origin is confirmed. The fact that the whistlers are not pure tones can be explained by assuming that their waves travel from source to observer not by a single path but by a range of paths, each producing a different dispersion.

The intercepts of the $f^{-\frac{1}{2}}$ against t graphs of the long whistlers on the time axis were always found to coincide with the times of occurrence of their preceding atmospheric clicks, but unfortunately this result cannot be regarded as confirming that their path is dispersive along the whole of its length, since the probable errors of the estimated positions of the intercepts correspond to considerable distances at the velocity of light.

(c) *The differences between long and short whistlers and their associated whistler trains*

According to our theory the ionospheric path of the long whistlers is twice that of the short whistlers, so that they should be twice as much dispersed. This is what is observed (§6).

Whistler trains following the two types of whistler would be expected to have different characteristics. If the train were produced from a lightning stroke at this end of the line of force, the first whistler heard would have made altogether two journeys over the equator, the second two further journeys, and so on. Hence one would expect the dispersions of the successive whistlers to be in the ratios 2:4:6:8, etc. If, however, the stroke occurred at the opposite end the first whistler of the train would be a short whistler, having made only one traverse of the path, the next would make altogether three traverses, and so on. In this case, therefore, one would expect the ratios to be 1:3:5:7, etc. As described in §7 above, both types of train have been observed and the dispersions are indeed in these ratios.

The variations of the occurrence of the two types of whistler (figures 10 and 11) seem capable of simple explanation in this way. Thus the fact that fewer whistlers are heard during the day than the night is ascribed to the action of absorption in the lower ionosphere, and the asymmetry of the daily variation records about midnight to the circumstance that thunderstorm activity is greatest in the late afternoon. Likewise the increase in the numbers of the long whistlers from winter to summer agrees with the known seasonal variation of thunderstorm activity, while the accompanying decrease in the numbers of short whistlers is explained by the fact that the seasons alternate in the two hemispheres. We defer discussion of the effect of magnetic activity on the incidence of whistlers, here noting only that since thunderstorms and magnetic activity are not related the effect must be one on the conditions of propagation over the whistler path.

14. THE OUTER IONOSPHERE

The dispersion of a whistler is deducible from equation (15) if the magnetic field and the electron density are known at all points along its path. According to our assumption the wave packet travels along a line of magnetic force, so that both the path and the magnitude of the field are known. If the electron density is taken to be that for an F_2 layer with a Chapman distribution of electrons and a maximum electron density of $10^5\,\mathrm{cm}^{-3}$, a typical night time value, the calculated dispersion is about $2\,\mathrm{s}^{\frac{1}{2}}$. The observed value, however, is about $60\,\mathrm{s}^{\frac{1}{2}}$ (§8*d*).

If the present theory is to be held it therefore appears that we must assume that there is very much more ionization above the maximum of the F_2 layer than has previously been supposed. Furthermore, since its density is nowhere greater than that in the F_2 layer it must necessarily extend up to very great heights where the density of the atmosphere was previously thought to be negligible. This constitutes a serious objection to the present theory, but so many other facts appear to be explicable in terms of it that it seems worth while to examine how such extra ionization could perhaps arise and to consider its consequences.

The simplest way of explaining the presence of a large number of electrons at great heights is to suppose that they are produced from ionization of an atmosphere which extends, in sufficient density, to these heights. It can be shown that in order to produce the observed results in this way the temperature of the outer ionosphere would have to be at least 7200° K.* Arguments based on the rate of escape of gases from the upper atmosphere (Spitzer 1948), and also on its thermal equilibrium (Bates 1951), suggest that this temperature is probably too high.

An alternative explanation would be that the electrons are not produced by ionization of the atmosphere but are continually falling into it from outside, together presumably with an equal number of positive ions. It is suggested that the source of this ionization is the sun, and that it is some of the material, believed to be principally ionized hydrogen, which is ejected at times of disturbance and is responsible for magnetic storms and the Aurora. In this way it seems possible to reconcile the large observed value of the dispersion with the temperatures commonly accepted for the F_2 layer and above.

This suggestion has the further merit of explaining the connexion between the occurrence of whistlers and magnetic storms. During a storm the presence of the incoming ionization makes propagation possible over the whole of the whistler path, but during magnetically quiet periods the normal ionosphere does not extend up to sufficiently great heights to support the propagation of a whistler right up to and over the equator, and instead the waves escape.

On the contrary view that the upper reaches of the ionosphere are in gravitational equilibrium, this correlation would have to be explained as the effect of an increase of the temperature of these regions accompanying a storm, blowing the atmosphere and the ionization up to great heights. Since such a temperature rise is already believed to occur and to be responsible for the lowering of F_2 critical frequency which is often noted during a storm (Appleton & Ingram 1935), this possibility must be considered.

We can in fact distinguish between the two alternatives by examining the day-to-day variation of the dispersion of the whistlers. If the ionization at great heights had arrived there by displacement from the F_2 layer below, then one would expect that the increased dispersion would be accompanied by a lowering of the critical frequency. If, on the other hand, the ionization were coming in from outside one might expect a slight positive correlation between the two, since this flux of ionization might make an appreciable contribution to the electron density in the layer. In fact, the correlation is positive (§8*d*).

On the whole, then, the evidence supports the view that the ionization through which the whistlers travel is of extra-terrestrial origin. It must be admitted, however, that the electron densities required at great heights are uncomfortably large.

This work has formed part of a programme of radio research conducted at the Cavendish Laboratory with the support of the Department of Scientific and Industrial Research, to which body I am also indebted for a maintenance allowance.

I would like to express my gratitude to Mr K. W. Tremellen for giving me the benefit in discussion and correspondence of his earlier experience in this field. My thanks are also due

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* The argument involved considering how fully the atmosphere in these regions could possibly be ionized, bearing in mind the fact that pulse echoes are not observed from above the F_2 layer, and then calculating as a function of the assumed temperature the dispersion which such a distribution of ionization would produce. Full account was taken of the effect of diffusion in limiting the degree of ionization at high levels, and of the variation with height of the acceleration of gravity and the magnetic field strength.

to the Director and staff of the 'Sferic' organization of the Air Ministry Meteorological Office for their co-operation in the work of locating the sources of the atmospheric clicks which gave rise to whistlers, and to Mr P. W. A. Bowe who assisted by photographing their wave-forms. To the remainder of my colleagues in the laboratory, and in particular to Mr S. Falloon, I am indebted for much helpful advice and criticism.

Note added (11 *February* 1953). An independent estimate of the density of electrons at very great heights has now been provided by some observations, described by H. Siedentopf at the recent Assembly of the International Astronomical Union, on the zodiacal light. This phenomenon is believed to be caused by the scattering of solar radiation from a disk-shaped cloud of tenuous material which surrounds the sun and is extended in the plane of the ecliptic. From measurements of the intensity and polarization of the scattered light Siedentopf finds values for the density of free electrons in the cloud at different distances from the sun, and these greatly exceed previous estimates. At the distance of the earth's orbit the electron density is approximately 600 cm^{-3}. It is understood that this work is to be published shortly in the *Zeitschrift für Astrophysik*.

For comparison, we adopt a simple model for the distribution of electron density above the F_2 layer maximum by assuming that the dispersion produced in a whistling atmospheric per unit distance travelled (equation (14) above) is constant along its path. In this case the density at the highest point of the trajectory, at a height of about two earth radii, is found to be approximately 400 cm^{-3}. It is considered that the agreement in order of magnitude between this and the preceding figure lends support to the views advanced in this paper.

Appendix. Other atmospherics on audio-frequencies

Although the majority of whistlers are of the type described in the body of this paper, other curious audio-frequency atmospherics have been noticed from time to time. These are not so common or so uniform in nature as those already discussed, and it has not been possible to describe them quantitatively. It may, however, be of interest to give a qualitative description of what may sometimes be heard. The more common types included

(*a*) a noise which has been called the 'dawn chorus',
(*b*) a steady hiss,
(*c*) isolated rising whistles.

The three types are all associated with magnetic activity and seem to be related. Sometimes two of them occur together, at other times there is a gradual transition from one type to another.

The sound of the 'dawn chorus' may be likened to that of a rookery heard from a distance. It consists of a multitude of rising whistles against a background of a warbling sound which may be mixed with varying amounts of toneless hissing. It has a pronounced daily variation of intensity with a maximum around 6 a.m., and its occurrence correlates strongly with magnetic storms; on undisturbed nights it usually does not appear at all, while on the night of a storm it may be heard continuously for five or six hours of the early morning.

The steady hiss is most frequently heard as an accompaniment to the 'dawn chorus' in the early morning, though it may also appear on its own at any hour. On one occasion

Eckersley (unpublished) picked up this tone, at a frequency of about 5 kc/s, on a receiver connected to a pair of large direction-finding loops and observed that it was coming from a northerly direction.

The isolated rising whistles have been heard relatively rarely in the present work, about three times a month on the average, most of these occasions being in the afternoon or early evening. Burton & Boardman (1933) reported them as being much more common than this, which may perhaps be because their work was chiefly done around sunspot maximum. Each consists of a short burst of tone of rapidly varying pitch. At the start of the tone the frequency is usually between 2 and 4 kc/s, then it quickly rises and disappears above the upper limit of hearing. The variation of the frequency with time is much faster than that of a whistler.

Normally the rising whistles are not associated with any other kind of atmospheric, yet sometimes they are observed to follow clicks either very rapidly or with a delay of one or two seconds. Furthermore, they sometimes appear in conjunction with whistlers. If at a time of general rising whistle activity there should be a whistler this will usually be followed by a rising whistle, the one blending into the other so as to give the impression that the frequency variation of the whistler had changed direction. These are the 'reversing tones' described by Burton & Boardman (1933), and some excellent sound spectrograms of them have been published by Potter (1951). These show that the frequency of the whistler falls at first in the usual way and then suddenly, at a point between $1\frac{1}{2}$ and $2\frac{1}{2}$ kc/s, it reverses, rises rapidly, and disappears out of the top of the band in $\frac{1}{4}$ to $\frac{1}{2}$ s. In two of the spectrograms the rising whistle starts from the lowest frequency observed in the parent whistler, but in a third there are, during the rising whistle, faint signs of the whistler continuing downwards. The spectrograms of the rising whistles appear to be rather more diffuse than those of the whistlers, which incidentally were all short whistlers.

The reversing tones are not always as regular as this; sometimes several rising whistles detach themselves from the main whistlers at different points down the scale.

Whistlers which occur during a display of 'dawn chorus' are also liable to be followed by rising whistles. On other occasions they appear to produce a momentary enhancement of the chorus itself.

Sometimes also one hears rising whistles which are followed after a delay of a second or so by relatively slow descending whistles. A record of one event of this type was taken, and in the analysis it was found that the plot for the descending whistle was more or less straight and cut the time axis at the instant of the rising whistle. Its slope corresponded to a dispersion of about 150 $s^{\frac{1}{2}}$, which is that of a normal long whistler. Apparently, therefore, the rising whistle was the primary phenomenon and the descending whistle was produced from it by dispersion in the same way as long whistlers are produced from impulsive atmospherics.

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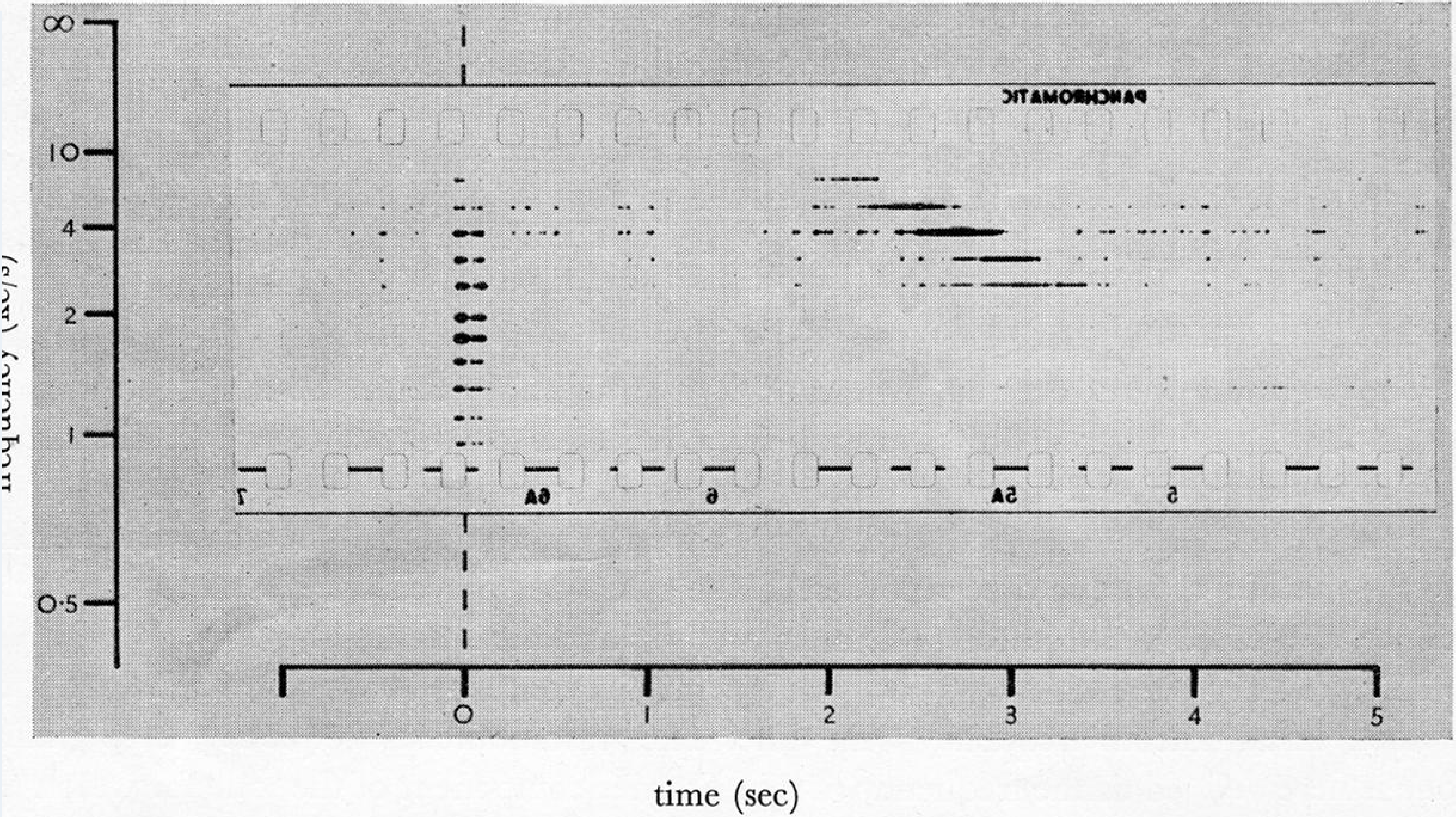

Figure 1. Sound spectrograph record of a whistler following an atmospheric click.