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Whistler Evidence of a 'Knee' in the Magnetospheric Ionization Density Profile

D. L. CARPENTER

Radio Science Laboratory, Stanford University
Stanford, California

Abstract. Study of a new whistler phenomenon shows that the magnetospheric ionization profile often exhibits a 'knee,' that is, a region at several earth radii in which the ionization density drops rapidly from a relatively normal level to a substantially depressed one. The new whistler phenomenon (called, for convenience, the 'knee whistler') is compared with ordinary whistlers and is illustrated by a number of examples recorded at middle- and high-latitude stations. It is suggested that the knee exists at all times in the magnetosphere, and that its position varies, moving inward with increasing magnetic activity. There are indications that conditions of whistler-mode propagation may be unusually favorable on the low-latitude side of the knee and that the region on the high-latitude side may be favorable for the production of triggered ionospheric noise. It is pointed out that knee whistlers account for a substantial number of the observations of deep density depressions during magnetic storms. Several questions of interpretation are raised, and the direction of future investigations is indicated.

INTRODUCTION

Recent research on a new whistler phenomenon suggests that the distribution of ionization in the magnetosphere may show a pronounced departure from smoothness. At low heights, the equatorial density profile may show normal density levels and a relatively smooth decrease with increasing height, but at a geocentric distance of several earth radii the density level may drop sharply, returning to a gradual rate of decrease only after a substantially depressed level is reached. The principal purpose of this note is to describe the new type of whistler evidence being used to investigate this 'knee' in the magnetospheric density profile.

It is difficult to find a simple name for the new type of whistler, because of its complicated frequency versus time shape; one awesome possibility is 'reversed nose whistler train.' Purely for convenience the term 'knee whistler' will be used, with the understanding that the whistler is not itself knee-shaped but is interpreted in terms of a knee in the magnetospheric ionization.

The new whistler phenomenon was first noted by Helliwell and Carpenter in 1961; it was later discussed briefly by *Carpenter* [1962*a*] in connection with studies of the magnetosphere during magnetic storms. On the basis of recent work, it is now possible to describe the knee whistler in detail and in particular to compare it with the class of whistlers usually reported and discussed in the literature.

There is great variety in the spectrums of actual whistler observations, including variety in the number of component traces of a whistler and in the observable frequency range and definition of the traces. Most of the observations reported thus far belong to some subclass of the type illustrated schematically by Figure 1*a* (spectrums) and by Figures 1*b* and 1*c* (density analysis). On the spectrographic records of this type of whistler (1*a*) the various traces or components generally do not cross one another, and there is a relatively smooth decrease in frequency at the nose f_n (frequency of minimum group delay for a trace) with increasing group delay at the nose t_n. The locus of values of (f_n, t_n) for the multicomponent whistler of Figure 1*a* is shown in Figure 1*b*. Such a distribution in (f_n, t_n) space is interpreted as representing a relatively smooth decrease in magnetospheric ionization with height [*Smith*, 1960, 1961; *Pope*, 1961] as suggested by Figure 1*c*. In this figure, N, the number density of electrons per cubic centimeter, is plotted versus geocentric distance in the geomagnetic equatorial plane. (From whistler theory it is known that the value of nose frequency for a whistler trace indicates approximately the whistler path latitude [*Smith*,

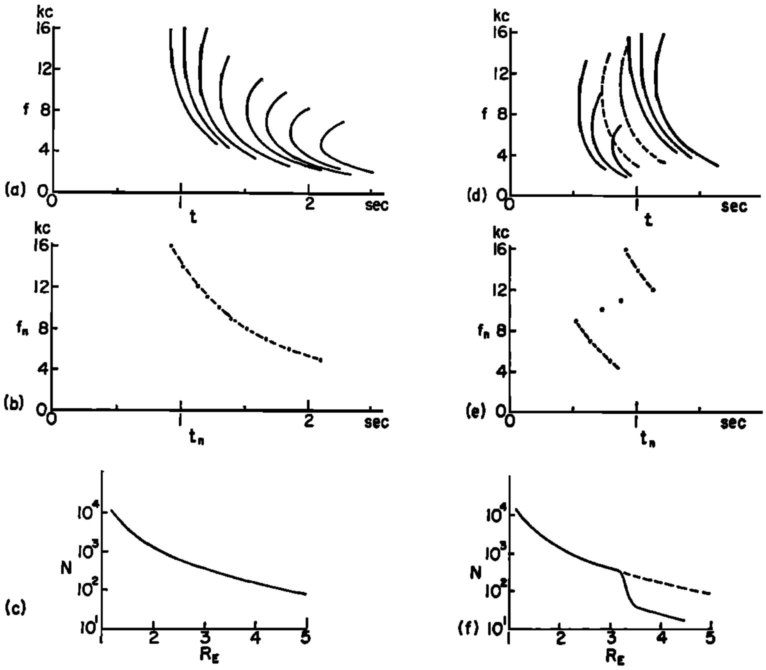

Fig. 1. Schematic comparison of spectrums and analysis for the ordinary whistler(*a, b, c*) and the knee whistler (*d, e, f*). The time scales (for *a, b, d, e*) represent time in seconds from the originating lightning flash. The curve of electron concentration versus geocentric distance in the geomagnetic equatorial plane (*c*) is an average of the results shown for December and June (near sunspot maximum) by *Smith* [1961].

1960], and the value of t_n is proportional to the square root of the scale factor of the ionization distribution along the path. The tendency of the (f_n, t_n) locus for a whistler to depart from a relatively smooth curve is then indicative of a corresponding lack of smoothness in the equatorial density profile. The knee whistler, as the following paragraphs will show, involves a particularly pronounced type of deviation from a smooth (f_n, t_n) locus.)

The Knee Whistler

The spectrums of a multicomponent knee whistler are shown schematically in Figure 1*d*. The first three traces in a descending order of nose frequency are in a normal position (cf. Figure 1*a*). The next three traces, two of which are shown dashed in Figure 1*d*, show a decrease in t_n with decreasing f_n, so that the distribution of components seems to fold back on itself. The last two traces, with the lowest values of f_n, show once again an increase in t_n with decreasing f_n, although the values of t_n are much lower than the corresponding values shown in Figure 1*a*. The locus of (f_n, t_n) values (Figure 1*e*) exhibits a relatively pronounced zigzag pattern, which, in terms of the equatorial ionization density profile, may be tentatively interpreted by the curve drawn in Figure 1*f*. This curve shows a knee separating a relatively undisturbed distribution on its inner side and a depressed density level on its outer side. In the vicinity of the knee the density gradient rises to a value of the order of ten times the average gradient when a knee is not observed.

Examples. Individual knee whistlers show considerable variation in the value of nose frequency at the knee and in the number, frequency range, and configuration of traces. Corresponding ionization density profiles show variety in the position, shape, and degree of definition of the knee. Figure 2 illustrates some of this variety by a plot of (f_n, t_n) for seven whistlers recorded during magnetically disturbed periods. The examples are assigned an identification number and are listed in Table 1, along

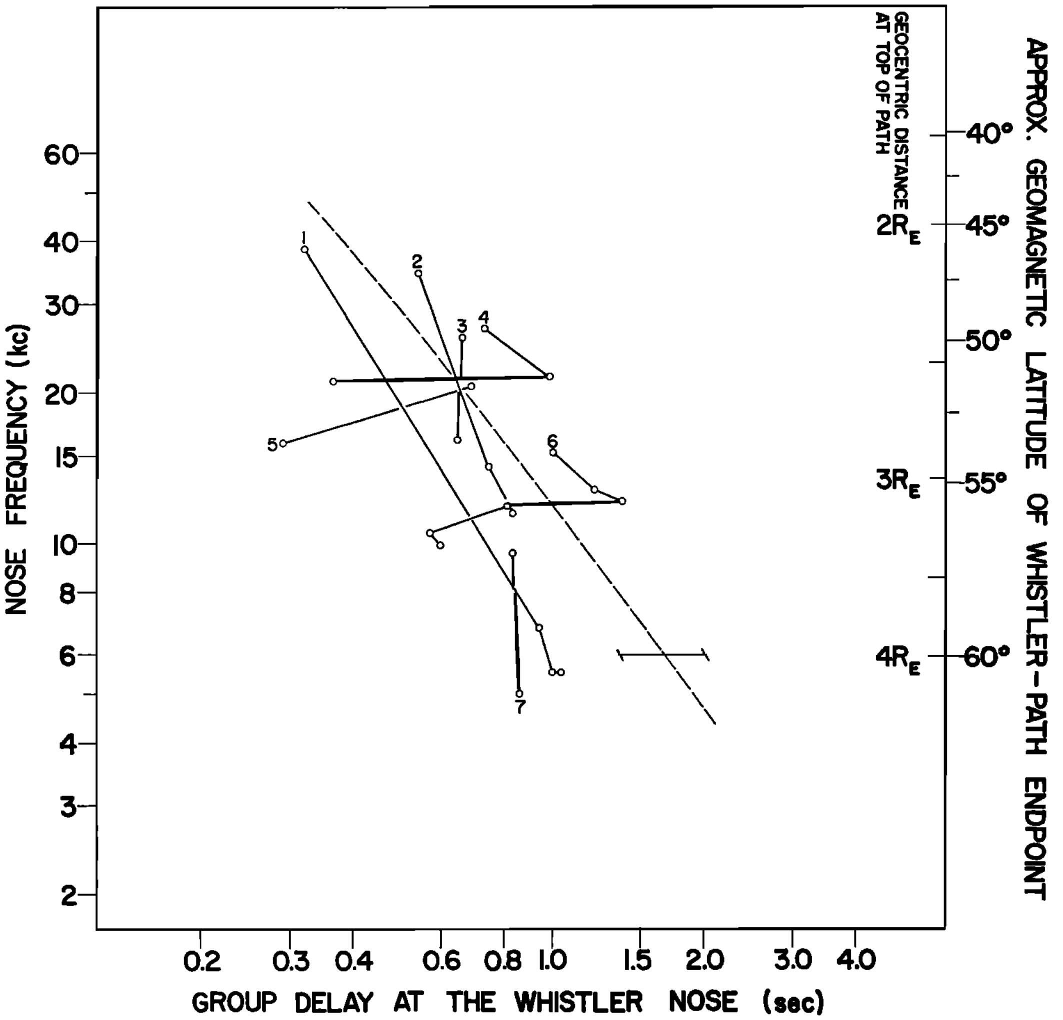

Fig. 2. Examples of knee whistler data from magnetically disturbed periods (see Table 1). The dashed reference line is characteristic of the distribution of quiet-period whistler data ($K_p \leq 5$ in the preceding 72 hours) for the January to June period of 1961.

with universal time, local time, and recording stations for each event. Data points from a single whistler are connected by straight lines, which are probably indicative of the true shape of the knee only on segments for which the data points are fairly closely spaced in the f_n direction.

Figure 2 employs logarithmic scales of f_n and t_n (in contrast to Figures 1*b* and 1*e*). The relation between nose frequency and path latitude is illustrated by including on the right-hand side scales for whistler path end-point latitude and geocentric distance at the top of the whistler path. The dashed reference line in the figure is characteristic of the distribution of 'quiet-period' whistler data ($K_p \leq 5$ in the 72 hours preceding an observation) for the January–June period of 1961 (see *Carpenter* [1962*b*]). The horizontal flag represents an estimate of the 90 per cent range of variation of all Stanford and Seattle routine observations of that period (excluding observations preceded within 72 hours by K_p levels of 8 or 9).

The seven whistlers plotted in Figure 2 show considerable variety in the extent to which a knee is defined. Examples 3 through 7 define the position of the knee rather well, in that they show a substantial departure from the normal distribution of (f_n, t_n) points over a relatively limited range of path latitudes.

Spectrograms illustrating examples 4 and 6 in Figure 2 are shown in Figure 3. Note that the nose frequency is not directly observable on these records, so that the knee-whistler spectrums may at first appear to resemble the lower-frequency part of a normal whistler (1*a*). This superficial resemblance to normal whistlers (especially true for middle-latitude whistlers) is an important reason why the knee whistler has not been recognized before.

The first four spectrograms in Figure 3 show a whistler recorded simultaneously at Stanford and Seattle on November 23, 1959 (example 6 in Figure 2). Values of (f_n, t_n) for this whistler were scaled by the extrapolation method described by *Smith and Carpenter* [1961]. An arrow in the lower margin of a record indicates the causative atmospheric and thus the time of origin (accurate to within about 30 ms) of an event. The causative atmospheric is identified by the methods discussed by *Carpenter* [1960] and by *Smith and Carpenter* [1961].

Consider the Seattle records (the first row of spectrograms, with range 0–8 kc/s, and the third row, with range 0–16 kc/s). In a normal Seattle whistler exhibiting many components the first traces in order of appearance would show relatively high values of f_n, say near 30 kc/s (geomagnetic latitude roughly 48°), and the last traces values of f_n near, say, 6 kc/s (latitude 60°). Intermediate traces, often the most intense, might show values of f_n near 14 kc/s (latitude 54°). In the example illustrated, substantial departures from this relationship occur; i.e., the first traces exhibit values of f_n lower than the values scaled for the stronger traces farther to the right, producing the pattern shown for example 6 in Figure 2. This evidence that the early traces are actually associated with the longer, higher-latitude whistler paths is supported in Figure 3 by the fact that Stanford (43.7°N geomagnetic), at a lower latitude than Seattle (53.6°N geomagnetic), does not show evidence of the early traces.

The bottom record in Figure 3 illustrates a whistler recorded at Unalaska, Alaska (50.9°N geomagnetic), on October 24, 1958 (example 4 in Figure 2). There are three principal traces, and, as often happens at middle latitudes, the traces are clustered near the knee. The value of f_n scaled for the first trace differs only slightly from the value scaled for the last component, but the corresponding values of t_n are separated by a factor of nearly 3 (which implies a density variation across the knee by about an order of magnitude). The middle and last traces exhibit values of (f_n, t_n) typical of magnetically quiet periods during October and November 1958.

TABLE 1. Knee-Whistler Observations during Magnetically Disturbed Periods

Number	Date	Time, UT	Recording Station
1	April 17, 1961	1050:10	Stanford/Seattle
2	March 15, 1958	1235:37	Stanford/Seattle
3	April 11, 1959	1835:44	Unalaska
4	Oct. 24, 1958	1236:04	Unalaska
5	Oct. 1, 1961	1250:20	Stanford
6	Nov. 23, 1959	2235:34	Seattle
7	July 20, 1959	0535:47	Byrd

The type of knee whistler spectrums often seen at high latitudes is illustrated in Figure 4. In cases of this kind, the traces on the high-latitude (low-f_n) side of the knee often show observable noses, and the distinctive structure of the knee whistler, as illustrated in Figure 1*d*, is then easily recognized.

The two whistlers illustrated in Figure 4 were recorded during a single 2-minute run at Byrd Station in the Antarctic (70.5°S geomagnetic). The recordings were made on August 10, 1961, during a period preceded by moderate to low magnetic activity. Two examples are shown as evidence that the entire configuration of the event is repeated, and is not merely a chance composite of two whistlers from separate lightning sources. Values of (f_n, t_n) were scaled for the event at 2250:40 by direct measurement and by the extrapolation techniques previously mentioned. The causative atmospherics were identified by a variety of the techniques already referenced.

The values of (f_n, t_n) for this event fall into two distinct groups, a middle-latitude group characterized by normal values of t_n, and a slightly higher-latitude group, including several

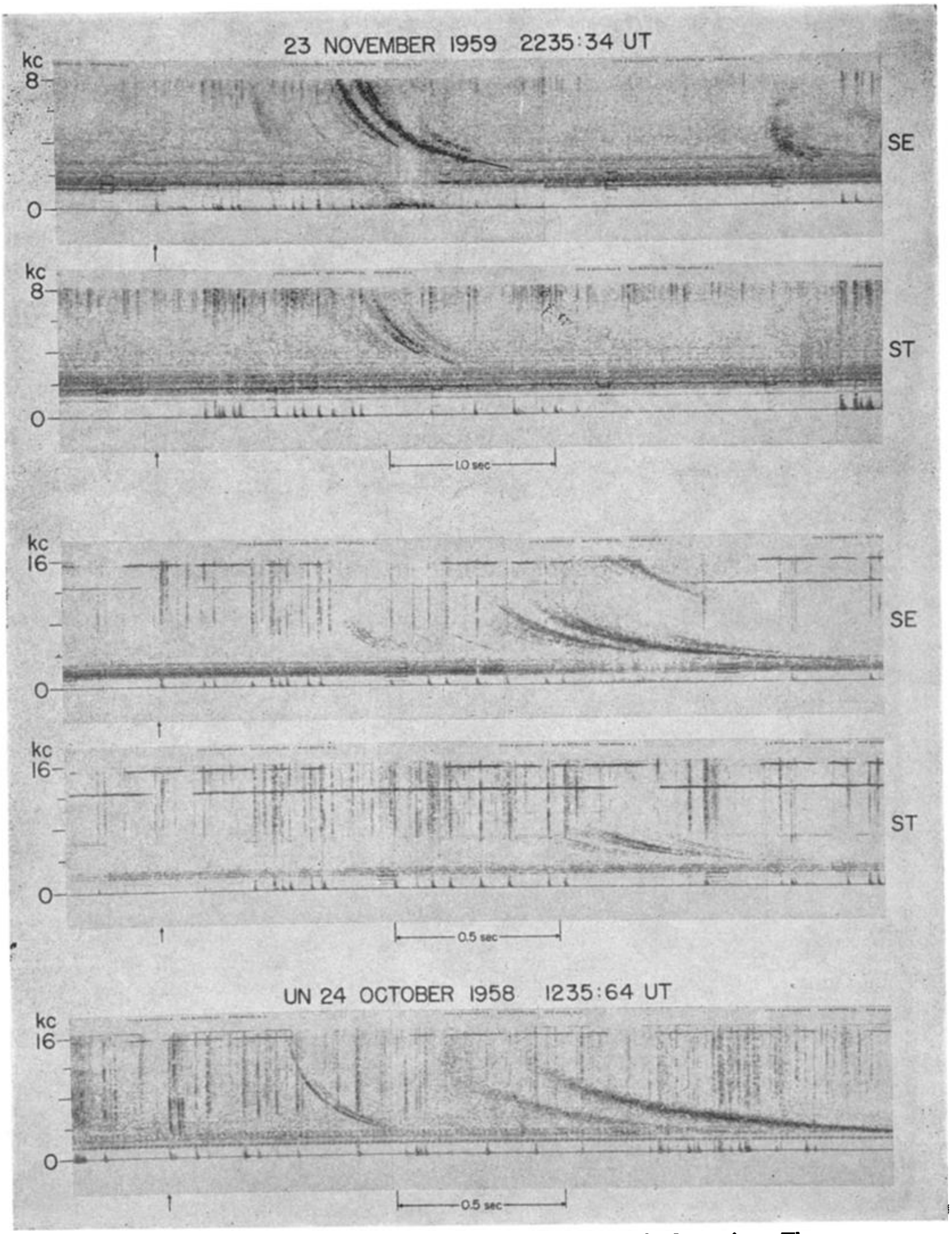

Fig. 3. Spectrograms of knee whistlers recorded at middle-latitude stations. These are examples 4 and 6 from Figure 2, showing Seattle and Stanford records for November 23, 1959, and Unalaska records for October 24, 1958. The causative atmospheric of a whistler is indicated by an arrow.

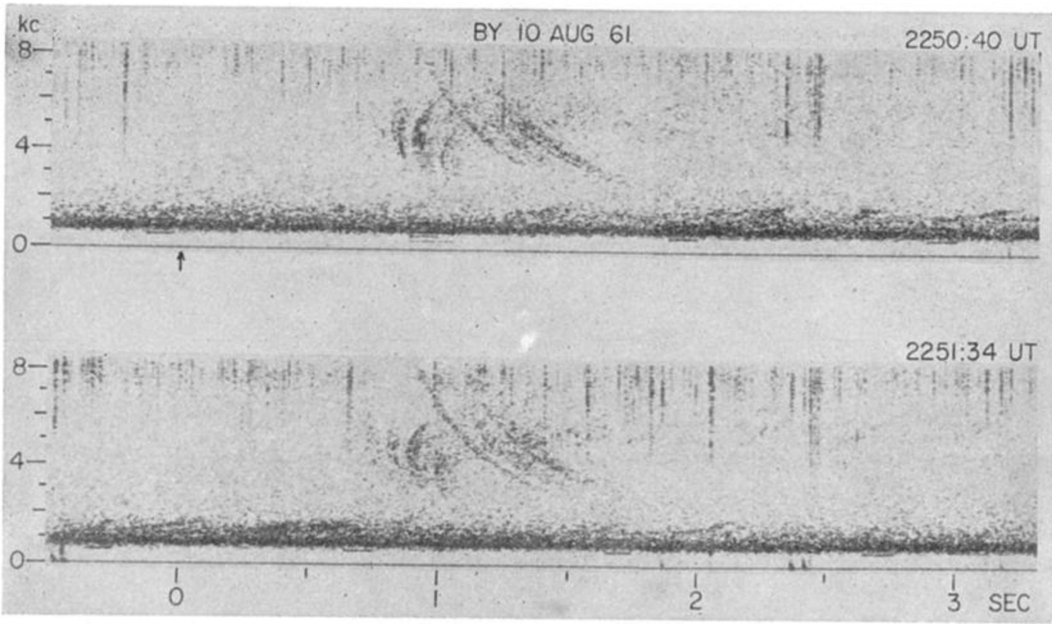

Fig. 4. Spectrograms of two knee whistlers recorded at Byrd Station in the Antarctic on August 10, 1961. The origin of the time scale is set at the position of the causative atmospherics of the whistlers.

observable noses, with unusually low values of t_n (cf. Figure 1e or 2):

(f_n, t_n)	kc/s	sec
Normal values	20.3	0.757
	16.5	0.956
Low $-t_n$ values	7.4	0.608
	4.9	0.820
	4.5	0.905
	4.4	0.852
	3.5	1.014

(Experimental error is of the order of a few per cent.)

A simple density interpretation of these data, analogous to that presented in Figure 1*f*, shows a relatively normal distribution between about 2.6 and $2.9R_E$, and a reduction from the local normal level by a factor of about 6 from 3.7 to about $5R_E$. By inference, the knee is placed between roughly 3 and 3.5 R_E.

Experimental Results

Once the knee phenomenon has been identified the investigation tends to follow two related courses: one devoted primarily to interpreting the whistler spectrums in terms of physical processes in the magnetosphere (see discussion), and the other directed toward gathering further information on the conditions under which the knee is observed. As work along these two lines is still in a preliminary stage, the following remarks on the experimental results must be understood to be tentative.

1. The evidence suggests that the knee is always present in the magnetosphere and that its position varies under certain conditions. The most detailed evidence obtained so far concerns the magnetic variation and indicates that the knee moves inward with increasing magnetic activity. During periods preceded within 72 hours by severe magnetic storms, observations of knees tend to fall between about 2.5 and $3.5R_E$. Observations of knees preceded by relatively moderate magnetic activity tend to fall in the range from 3 to $4.5R_E$. Whistler observations preceded by periods of very low magnetic activity do not usually exhibit a knee but instead show normal density levels out to some point in the range from about 5.5 to $7.5R_E$ and do not contain information on conditions beyond that point.

2. Conditions for whistler propagation on the low-latitude side of the knee may be unusually good during magnetically disturbed periods, involving whistler echo trains and VLF ionospheric noises which echo in the whistler mode.

The Seattle record at the top of Figure 3 illustrates this situation. It shows a whistler recorded at 1435 local time, a daylight hour when echoing is rare. At the far right, crossing the end of the spectrogram at about 5 kc/s, part of a three-hop echo may be seen (energy that has traversed the whistler path three times). This echo is related to the second strong trace of the whistler, which has (f_n, t_n) values of about 13 kc/s, 1.2 seconds. Further spectrographic analysis (not shown) reveals additional echoes, and it is found that the noselike burst near the right end of the record (just below the beginning of the three-hop echo of the whistler) is also followed by whistler-mode echoes. These echoes following the burst of ionospheric noise exhibit delays between successive hops identical with the corresponding delays between echoes of the whistler.

3. Triggering of chorus (a type of VLF ionospheric noise) on the high-latitude side of a knee has been observed in several of the examples studied. Note, in Figure 4, for example, that the traces on the high-latitude side of the knee trigger faint rising tones near 6 kc/s, which then continue for some time after the appearance of the whistler.

4. Knee whistlers account for a significant number of the recent observations of density depressions in the magnetosphere during magnetic storms [*Carpenter*, 1962*a*]. It is not yet possible to clarify the relation between knee whistlers and whistlers that show depressed values of electron density but contain no direct information about the existence of a knee.

Interpretation of the Knee Whistler

To date, more than twenty knee whistlers have been studied in detail and many additional examples have been analyzed on a limited basis. The results provide strong support for the descriptive picture of Figures 1*d* and 1*e*, and thus support the contention that there is a pronounced physical transition at the time and place indicated by the measurements. The task of actually describing this transition begins here.

One of the first questions encountered is whether the observed patterns of the knee whistler spectrums could be the result primarily of the distortion of the geomagnetic field by a ring current. Preliminary consideration of this question indicates that the observed data patterns cannot be recovered on such a basis [*Carpenter*, 1962*c*; *Spreiter and Briggs*, 1962], althought it cannot be concluded that ring currents or related effects play no role in the whistler picture.

An interpretation of the data in terms of a knee in the ionization is the only way in which the peculiar spectrums of knee whistlers can reasonably be explained, but the shape of the ionization knee, in particular the shape as a function of position along the field lines, is not at all clear. Does the knee correspond to a uniform density reduction all along certain field lines, involving a substantial depletion of the electron content of the tubes of force; or is the knee the result of a redistribution of ionization, in which the ionization along certain field lines is shifted toward the feet of the lines but in which the electron content of the tubes of force is not substantially changed? (In either situation a relatively pronounced knee would exist along the top of the paths near the geomagnetic equatorial plane, so that Figure 1*f* is probably useful as a representation of conditions in that region.) The choice of alternative explanations, or of some combination of them, will depend on careful examination of certain details of the records, including the frequency versus time (dispersion) behavior of the higher-latitude traces and the manner in which the value of the nose frequency varies through a succession of traces near the knee. In studying alternative explanations it will be necessary to consider such matters as the range of latitudes at which knees occur and the types of density variation with latitude at the base of the magnetosphere that seem admissible. It will also be of interest to examine questions like the effect on whistlers of regions in which the magnitude of the refractive index for whistler propagation is relatively low.

Conclusions

Study of the knee whistler shows that some type of pronounced physical transition often exists in the magnetosphere. The experimental evidence suggests that the transition is always present in the magnetosphere and that it moves inward during periods of increased magnetic activity.

There is good ground for belief that the transition involves a knee in the profile of magnetospheric ionization, separating an inner region where density levels are relatively normal and an outer region of depressed density. As an example, a pronounced knee near $3.5R_E$ would involve a reduction from about 400 electrons/cm^3 at the 'top' to about 40 electrons/cm^3 at the 'bottom' (the number 400 electrons/cm^3 is taken from *Smith* [1961]). It is not yet clear to what extent the depressed density levels outside the knee involve precipitation of electrons and to what extent redistribution of ionization along the field lines is a factor.

Continued study of the knee whistler should illuminate many areas of research, including, to mention a few, the nature of certain types of chorus, VLF propagation in the presence of large transverse gradients of ionization, and VLF propagation under conditions of unusually low ratios of plasma frequency to gyrofrequency. Once the knee is described in greater detail, occurrence data on various forms of VLF ionospheric noise may take on a new significance and be more readily explained. A crucial and probably difficult step in further work will be clarification of the relation between ordinary whistlers and knee whistlers. When this is done, our ability to describe the physical behavior of the magnetosphere will be substantially increased.

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