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Whistler Studies of the Plasmapause in the Magnetosphere

1. Temporal Variations in the Position of the Knee and Some Evidence on Plasma Motions near the Knee

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Abstract. The position of the knee in the density of magnetospheric ionization was measured on a high time-resolution basis using whistlers recorded during July and part of August 1963. (The knee is an abrupt decrease in magnetospheric ionization density, frequently observed at field lines with an equatorial radius of about 4 R_E.) The data were obtained at Eights (64°S dipole latitude) and Byrd (70°S dipole latitude) in the Antarctic. The whistler results and results from other experiments confirm that the knee is a regular feature of the magnetosphere. For conditions of steady, moderate geomagnetic agitation ($K_p = 2$–4), the diurnal variation in geocentric equatorial range to the knee is remarkably repeatable. It is characterized by: (1) a slow inward movement of the knee on the nightside, covering about 1.5 R_E in 10 hours; (2) a slight outward movement on the dayside covering about 0.5 R_E; and (3) a rapid outward shift in the late afternoon covering about 1 R_E in 1 hour. During periods of changing magnetic activity, the knee position changes with at most a few hours' delay, moving inward with increasing magnetic activity. The results from Eights and Byrd may be generalized to describe a three-dimensional model of thermal ionization in the magnetosphere involving a dense ($\sim$100 el/cm^3) inner region and a tenuous ($\sim$1 el/cm^3) outer region separated by a sharp field-aligned boundary, the plasmapause. During the postmidnight hours, the inward motion of the knee involves a corresponding inward motion of the ionization just inside the plasmapause. The rapid outward shift of the knee near 1800 LT does not involve an outward plasma motion, but instead involves the presence of a region of 'new' high-density ($\sim$100 el/cm^3) plasma in the equatorial range of about 4–5 R_E. Preliminary evidence shows that, at least in the period 0000–1700 LT, the ionization inside the plasmapause rotates at approximately the angular velocity of the earth.

INTRODUCTION

Until a few years ago, it was believed that the ionization density in the magnetosphere falls off relatively smoothly with increasing radial distance from the earth. In 1963, however, a report based on whistlers showed that this is not true, that in fact the equatorial profile of electron density exhibits an abrupt decrease, or 'knee,' at several earth radii [*Carpenter*, 1963]. In that report a number of the basic features of the knee were described, including its apparent permanence as a feature of the magnetosphere, its tendency to move inward during periods of increased magnetic activity, and also the major features of the equatorial electron-density profile in the vicinity of the knee.

Recent whistler research has been concerned with elaborating upon the initial description. Particular attention has been devoted to: (1) the diurnal and magnetic-disturbance variations in the position of the knee; (2) motions of magnetospheric plasma near the knee; and (3) details of electron density and total tube electron content near the knee. Research results on the knee position and on plasma motions are presented in the present paper; the results on electron density and tube content, in a companion paper [*Angerami and Carpenter,* 1966]. For convenience, the present paper will be called K-1, and the companion report K-2.

Whistler studies of the knee have recently been augmented by a variety of experimental methods, particularly as applied in satellites. These methods and the whistler technique complement one another in several striking ways. For example, whistlers provide relatively accurate estimates of electron number density on the outer portion of the field-line paths. In such regions, satellite-borne traps and analyzers present serious interpretive difficulties in the determination of absolute levels of ion density, and thus can benefit from comparison with the whistler results. Measurements based on whistlers provide particularly good detail on the variation of total tube electron content with latitude and on the equatorial profile of electron density. In contrast, traps and analyzers afford the possibility of profiles along tracks well removed from the equatorial plane. Furthermore, satellite radio techniques may provide special information on knee effects between the regular ionosphere and the position of the spacecraft. Such measurements include Doppler techniques for estimating the total columnar electron content between a ground station and the satellite, and VLF group-delay measurements, useful in estimating average electron density along the field line below the vehicle.

A particularly important property of satellite measurements is the possibility of rapidly scanning over a wide range of magnetic longitudes and, in the case of low-inclination orbits, a wide range of local time. This provides an extremely valuable complementary relation to the whistler data, which, in terms of fine detail, have so far been concentrated on a narrow range of magnetic longitudes and in the austral winter. On the other hand, the whistler method is unique in its capacity to provide high time-resolution data, and thus to clarify the details of rapid magnetic-disturbance and diurnal variations in the position of the knee.

Observations of knee effects in satellites and rockets date back to the work of Gringauz and his colleagues, who flew ion traps on Luniks 1 and 2 and noted significant decreases in ion current at several earth radii [*Gringauz et al.,* 1960]. The observations have recently been greatly widened in scope and detail through the mass-spectrometer measurements on Ogo 1 by *Taylor et al.* [1965], and through ion-trap measurements on Ogo 1 by *Whipple and Troy* [1965]. These findings strongly confirm the whistler results and also provide important extensions of the information about the knee phenomenon. Doppler measurements of slant columnar electron content on Ogo 1 are providing a special type of information on the knee [*Lawrence et al.,* 1965], and the properties of hydromagnetic emissions are beginning to be used to deduce ion densities in the tenuous region outside the large density gradient [*Wentworth,* 1965; *Dowden and Emery,* 1965]. Again, the results support the conclusions from whistlers.

The present paper is based largely on a remarkable set of data obtained in July and August of 1963 at Eights, Antarctica. The diurnal variation in the position of the knee has been studied in detail, and a striking repeatability has been found, making it possible to present a preliminary descriptive model of the distribution of thermal ionization around the earth. Several important details of the model have been identified, including magnetic-disturbance effects and certain motions of tubes of ionization in the vicinity of the knee.

In the calculations reported below, a simple centered-dipole coordinate system is employed. During periods of moderate magnetic activity the equatorial distance to the knee is typically 3.5 to 4 R_E, a distance at which the expected departures of the earth's field from a dipole are small in comparison to other effects to be described (see *Mead* [1964]). When the knee is observed near 6 R_E, the magnetic activity is low (K_p = 0–1), so that even here the simplification appears justified.

The evidence of this paper and of paper K-2 indicates that the knee is an essentially field-aligned structure. This evidence of strong geomagnetic control, combined with the fact that whistler nose frequency is sensitive to equatorial magnetic field strength, suggests the use of equatorial radius in earth radii as a parameter to characterize the meridional behavior of the knee. As an example, we shall write either 4

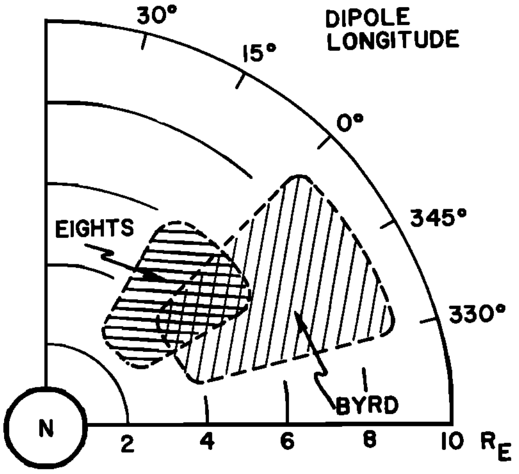

Fig. 1. Equatorial cross sections of the field-aligned sectors of the magnetosphere 'observed' from Eights and Byrd Stations in the Antarctic. The size and particularly the spread in longitude of the sectors are intended to show optimum observing conditions during the austral winter. Further study is needed to determine the longitude spread more precisely and also to present details of the high-latitude border of the Byrd sector.

R_E or $R_E = 4$ to indicate a knee with geocentric equatorial radius of 4 earth radii.

With regard to nomenclature, the word 'plasmapause' will be used when the three-dimensionality of the knee phenomenon is emphasized. In a later section of the paper the word 'plasmasphere' will be used to indicate the dense region inside the plasmapause, and 'plasma trough' to indicate the tenuous region outside.

Description of the Experiment

Most of the results reported in this paper are based on data from Eights and Byrd Station in the Antarctic, whose coordinates are, respectively: 75°S, 77°W geographic, 64°S dipole; and 80°S, 120°W geographic, 71°S dipole. Local time along the field lines connecting Eights and its conjugate, Quebec City, Canada, is about 5 hours behind universal time. For Byrd and its conjugate, Great Whale River, Canada, the corresponding lag is about 6 hours. The portions of the magnetosphere 'seen' by Eights and Byrd in the austral winter are indicated in Figure 1 as intersections with the geomagnetic equatorial plane. For Eights the range is from about 2.5 to 6 R_E; for Byrd it is roughly 3.5 to 9 R_E (this limit has not yet been studied in detail). A typical whistler does not cover the entire range, but rather a segment 1–2 R_E in extent.

The 30° longitude spread of the sectors is intended to be comparable to the 20° range of dipole latitudes known to be excited in some cases. The actual longitude spread of a single whistler appears to vary with local time, being relatively small at night, somewhat larger in daytime, and on some afternoons approaching the sector width shown in Figure 1. The larger daytime spread is not yet understood but may be partly attributable to low daytime absorption in the southern ionosphere and to a favorable daytime distribution of high-latitude lightning sources in the northern hemisphere.

The method of determining the position of the knee in the magnetosphere may be summarized by reference to Figure 2. The whistler illustrated contains six components excited by a single lightning flash, three, *a*, *b*, *c*, propagating in the high-density region inside the plasmapause; and three, *d*, *e*, *f*, in the low-density region outside. Traces *c* and *d* are identified as propagating closest to the plasmapause, and, since the field-line paths for these two components may be identified from the associated nose frequencies, the position of the knee is well defined. For the whistler illustrated, the nose frequency at the knee is about 4.5 kHz, and the corresponding geocentric equatorial range is 4.2 R_E. (For details of the method of determining path location from whistler nose frequency, see *Carpenter and Smith* [1964] or *Helliwell* [1965].)

Spectrographic records of two well-defined

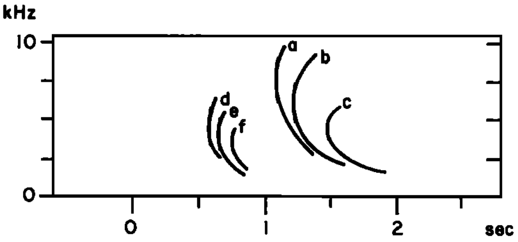

Fig. 2. Idealized frequency-versus-time characteristics of a knee whistler. Components *a*, *b*, and *c* propagate in the high-density region inside the plasmapause; components *d*, *e*, and *f*, in the low-density region outside.

knee whistlers are shown in Figure 3. These events were recorded at Eights, Antarctica, near 0750 LT on July 7, 1963. The top and middle records show one event on two frequency ranges, 0–40 kHz (top) and 0–20 kHz (middle). A second event is shown on the bottom record to demonstrate the repeatability on a scale of minutes that is characteristic of whistlers. In both whistlers there are three principal components, with nose frequencies at 25, 11, and 8 kHz. The first two components exhibit travel times characteristic of the high-density region inside the plasmapause; the third component, with travel time of 0.5 second, is identified with the low-density region. The knee is inferred to lie between 3.2 and 3.5 R_E, a range corresponding to the interval 8–11 kHz in nose frequency.

The position of the knee may be estimated in the absence of traces identifying the low-density region, because whistler components propagating outside the knee are often absorbed in the medium whereas those propagating

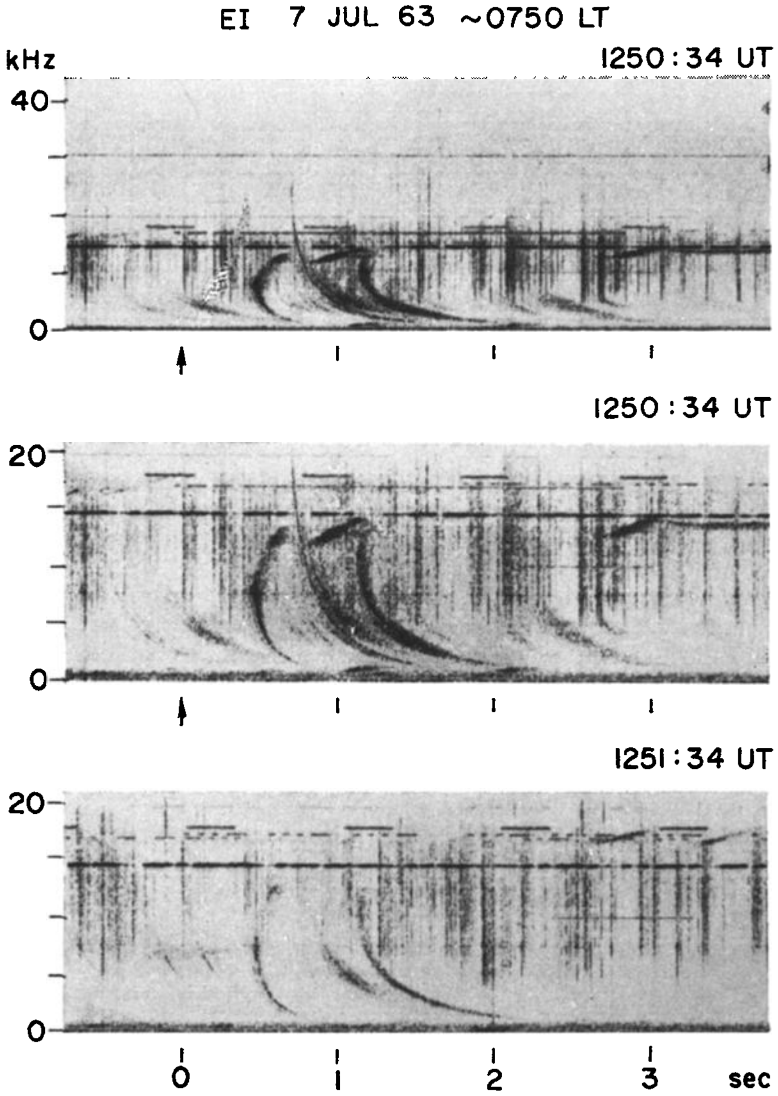

Fig. 3. Spectrograms of two knee whistlers recorded 1 minute apart at about 0750 LT on July 7, 1963, at Eights, Antarctica. The first event is shown on the upper and middle records in the frequency ranges 0–40 and 0–20 kHz, respectively.

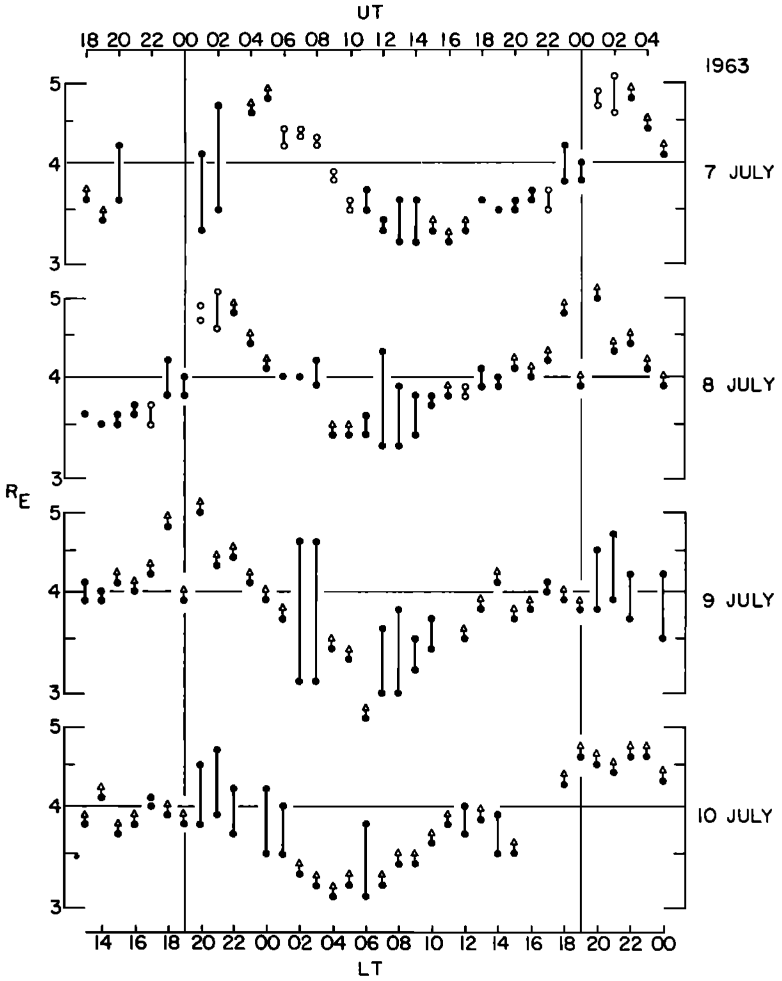

Fig. 4. Variation of the equatorial geocentric distance to the knee versus time during 4 consecutive days of relatively steady, moderate geomagnetic agitation in July 1963. The observations were made at Eights, Antarctica. Open or closed circles connected by a line signify that the knee lies somewhere between the extremes of the line. An arrow connected to a data point means that the knee must lie at an equatorial radius larger than that of the point.

just inside are often extremely well defined. When the whistler rate is high and many paths are excited, the high-latitude limit of propagation has been found to provide a good estimate of the position of the knee, particularly during the hours 0000–1800 LT. Examples will be shown in the next section.

The results described below are based primarily on data obtained at Eights Station during July and part of August 1963. The recordings include hourly 2-minute runs and continuous runs of 3 hours' duration made once a day. Fifteen of the 3-hour runs were examined, as well as several days' data from Byrd station. The total number of whistlers involved in the study was about 100,000.

Experimental Results on Temporal Variations in the Position of the Knee

One object of this section is to present new data on the persistence of the knee. The matter will be discussed after a description of the diurnal and magnetic-storm variations in the knee position.

The diurnal variation in the position of the knee. A number of weak gradual-commencement magnetic storms occurred during July 1963. Several of them exhibited protracted recovery phases in which the K_p index remained near 3 for several days in succession. For these periods, the knee data are relatively complete and provide a kind of steady-state view of the diurnal variation of the knee during periods of moderate disturbance. The pattern is illustrated in Figure 4, which shows a plot of the geocentric equatorial range of the knee versus universal time (top) and local time (bottom). The plot shows four successive universal-time days, July 7, 8, 9, and 10, 1963. To facilitate comparison of data taken near 0000 UT, each level contains data from several additional hours on the preceding and following days. An arrow connected to a data point means that the knee must have an equatorial radius larger than that of the point (case of propagation inside the knee only). Open or closed circles connected by a line signify that the knee lies somewhere between the extremes of the line (open circles indicate the overlap condition described in paper K-2). In practice it has been found that the points with arrows are useful in estimating the position of the plasmapause. This can be seen in Figure 4 by the qualitative agreement of the two types of points, particularly in the interval from about 0300 to 2000 UT.

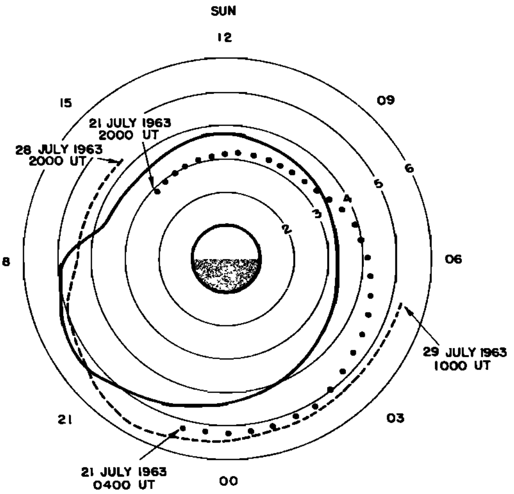

Fig. 6. Equatorial radius of the knee versus local time. The solid curve represents average behavior during periods of moderate, steady geomagnetic agitation ($K_p = 2$–4). The observations were made in July and August 1963 at Eights, Antarctica. The dots show a particular example involving increasing magnetic agitation (see Figure 8); the dashes, an example of decreasing agitation (see Figure 9).

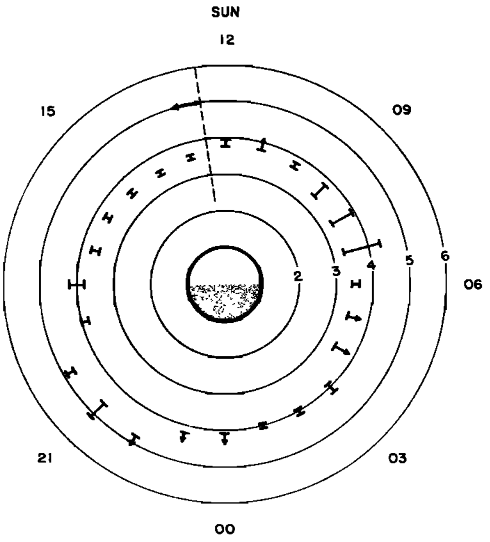

Fig. 5. Equatorial radius of the knee versus local time for the period July 7, 1800 UT, through July 8, 1700 UT (see Figure 4). The arrow and dashed line indicate the beginning of the sequence.

The remarkable features of Figure 4 are, first, the persistent, smooth behavior of the data on a single day; and second, the repeatability from day to day. These features have a counterpart in the persistence and repeatability of the profiles of electron density and tube electron content near the knee, matters discussed in some detail in paper K-2.

To clarify some of the features of Figure 4, it is convenient to use the polar plot of Figure 5, where the data points for July 7, 1800 UT, through July 8, 1700 UT, are plotted with respect to local time (see arrow and dashed line marking the beginning of the sequence). The data are consistent from hour to hour, and it is noteworthy that, in 18 of the 24 hours illustrated, both inner and outer limits on the position of the knee were determined. Note further that usually, if only the inner limit was defined, the knee may be inferred to be within 0.5 R_E of that limit.

The smoothness and repeatability of the data have made it possible to draw an estimated average curve for conditions of steady magnetic agitation with $K_p = 2\text{–}4$. The result is the solid curve in Figure 6, which again displays equatorial range versus local time. The principal features of this curve are as follows:

1. A relatively broad minimum in geocentric distance, centered roughly on 0600 LT. The minimum distance is about 3–3.5 R_E.
2. A maximum geocentric distance at about 2000 LT, the maximum being about 5–5.5 R_E.
3. Following the maximum near 2000 LT, a decrease in range with time on the nightside of the earth. The decrease is roughly 1.5 R_E over a period of the order of 10 hours in length.
4. A rapid increase in range near 1800 LT, involving a radial variation of about 1 R_E in a period of about 1 hour. In the data, this outward shift appears not as a series of incremental changes in the whistler structure but rather as a change from one basic configuration of traces to another. The two configurations representing the pre- and postshift conditions may coexist on the records for a period ranging from minutes to nearly an hour. The outward shift has been studied on continuous records representing approximately 10 days. The phenomenon occurred on all the days, although the local time of the effect varied from several hours before 1800 LT to several hours after, with roughly half the cases falling within an hour or two of 1800. An example falling near 1900 to 2000 LT is shown in Figure 5 for July 7, 1963. The effect is also illustrated in Figure 8, upper right, for July 22, 1963.
5. A gradual outward tendency across the dayside from about 0600 LT to midafternoon. The total range of this variation is of the order of 0.5 R_E, and within the period there appears to be a secondary maximum near about 1200 LT, followed by a secondary minimum near about 1400 or 1500 LT. These secondary features have not yet been studied in detail.

The solid line in Figure 6 is not intended to show how the thermal plasma near the position of the knee moves in time and space. An apparent motion of the knee might be attributed either to movement of particles into or out of tubes of force across some lower boundary near the ionosphere, or to motion of tubes of ionization transverse to the direction of the field. These questions are discussed both in K-2 and in a later section of this paper.

During July 1963, conditions corresponding to the dark curve in Figure 6 obtained on about 18 days. During the remaining days, magnetic conditions tended to be relatively quiet, and the paths describing the knee tended to move toward the poleward edge of the viewing area of Eights Station, causing the resulting information to be fragmentary. When the magnetic conditions became very quiet, however ($K_p = 0\text{–}1$), the higher-latitude position of Byrd Station became favorable for knee observations (see Figure 1). Particularly good information was available for July 3 and 29, 1963 (see Figure 9, top). From this limited quantity of data, we conclude that, with decreasing levels of magnetic agitation, the diurnal curve (of the type shown in Figure 6) moves outward and becomes more symmetric with respect to the earth. On the other hand, we infer from an earlier study of deep density depressions [*Carpenter*, 1962] that, during great storms, the pattern may be relatively more distorted than the one illustrated in Figure 6, probably reaching a geocentric distance of 2 R_E or less at some point on the nightside of the earth.

Spectrographic records showing the diurnal variation. Tracings of whistlers representing 11 different hours on August 5, 1963, are shown in Figure 7. Both the universal and local times are indicated. The whistler component propagating closest to the inside of the plasmapause is marked *i*, and the first identifiable trace propagating in the low-density region outside is marked *o*. An estimate of the equatorial radius of the knee is indicated in the right-hand margin of each record (the equals sign is used when traces are observed on both sides of the plasmapause). The corresponding nose-frequency level is shown by a horizontal mark.

To see the main features of the records, consider single events at the beginning, middle, and end of the sequence (in Figure 7, at 2050, 0950, and 1850 LT, respectively). The first and last events are very nearly the same, showing the tendency of the cycle to repeat itself on a 24-hour basis. Midway between, at 0950 LT, the trace configuration is characteristic of a knee with equatorial range about 3.3 R_E, nearer by roughly 1.5 R_E than the estimated positions at the beginning and end of the sequence.

Consider now some of the details of the

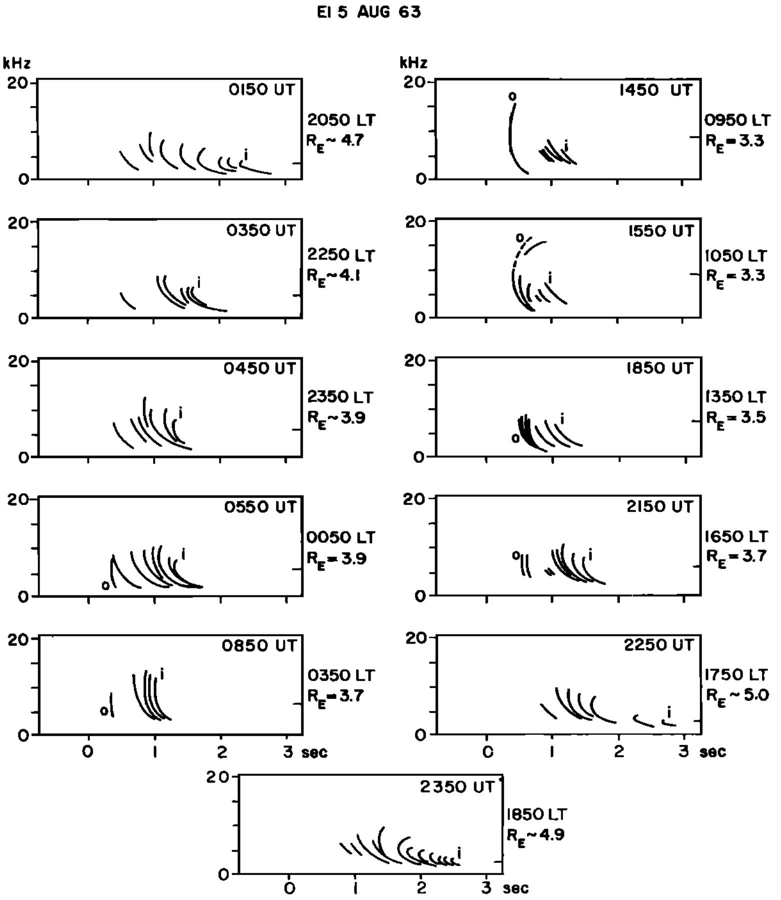

Fig. 7. Tracings of spectrograms from Eights, Antarctica, for August 5, 1963, showing an example of the diurnal variation in knee position during a period of moderate and steady geomagnetic agitation. The approximate equatorial radius of the knee is shown at the right of each record. The whistler component observed to be closest to the plasmapause on the inside is marked *i*; the component identified as closest on the outside is marked *o*.

records. On the first three spectrograms, for 2050, 2250, and 2350 LT, whistler components propagating in the outer, low-density region are not detected. As an estimate, the position of the knee is taken to be just beyond the largest R_E value represented in the whistler (trace marked *i*). The knee follows an inward trend from 2050 to 2350 LT, moving from about 4.7 R_E to about 3.9 R_E. At 0050 LT, the position is identified within narrow limits near 3.9 R_E. At 0350 LT, the information is less detailed, and the R_E value of the whistler component propagating in the outer region is used as an estimate of the knee position.

The presence of a single trace outside the knee at 0050 and 0350 LT is characteristic of nighttime records made under moderately disturbed conditions during the 1963 period studied. On such records, the presence of the abrupt decrease in density is clearly indicated, but information on electron density well outside the plasmapause is not usually available. Profiles of electron density and tube electron content for the 0050 and 0350 LT events are shown in Figures 4 and 7 of paper K-2.

At 0950, 1050, and 1350 LT, the knee is observed between 3 and 3.5 R_E. On these records the higher-frequency behavior of the components propagating in the inner region is not indicated but may be deduced with relative ease by extrapolation. The traces propagating in the low-density region are well defined and are used to identify the knee position. At 1650 LT, the position is defined within narrow limits at 3.7 R_E. Note that the knee retained its abrupt large-scale configuration for at least 16 hours, from 0050 to 1650 LT.

The rapid outward trend described earlier as taking place near 1800 LT is illustrated at the lower right in Figure 7. The knee is well defined as being within 4 R_E at 1650 LT (2150 UT), but the event at 1750 LT (2250 UT) shows clear evidence of high electron densities (high whistler travel times) to at least 5 R_E. At 1850 LT (2350 UT), a similar high-density condition is in evidence.

The magnetic-disturbance variation in the position of the knee. The magnetic-disturbance variation in knee position, involving inward movement with increasing magnetic activity, was described in a general way in an earlier report [*Carpenter,* 1963]. Additional evidence, showing knee effects near 2 R_E during great magnetic storms, was supplied in a whistler study by *Corcuff and Delaroche* [1964]. Recently, mass-spectrometer data from Ogo 1 have indicated a relation between L value at the knee and magnetic activity similar to that deduced from whistlers [*Taylor et al.,* 1965].

The Eights data now provide an opportunity to study magnetic-storm effects in some detail. Figure 8 shows a comparison of the position of the knee and the 3-hour K_p index during the universal-time period July 19 to July 22, 1963. The geocentric equatorial range of the knee is plotted in the upper half of the figure, and the K_p index, with values increasing downward, is shown below. On July 19 and 20 the knee data are somewhat incomplete, but there is evidence of a quieting effect on July 19, involving a gradual outward movement toward about 5.5 R_E as the K_p reaches levels near 1. A gradual-commencement magnetic storm began near 0000 on July 21, accompanied by a dramatic inward movement of the knee. This disturbance variation in knee position, marked D in Figure 8, is illustrated in Figure 6 by a series of dots. The distinctive feature of the disturbance variation is the tendency to move inward on the dayside of the earth, in opposition to the trend usually observed under steady-state, moderately disturbed conditions. Note that on July 22, with the beginning of the long recovery phase of the storm, the diurnal pattern resembles closely the patterns shown in Figure 4 for the period July 7–10.

Another 4-day period, July 28–31, 1963, is illustrated in Figure 9. The variation in mag-

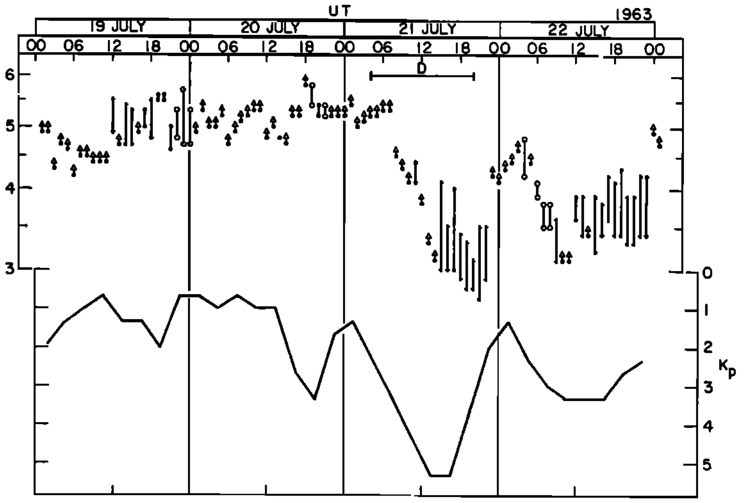

Fig. 8. Comparison of the geocentric equatorial range with the knee and the K_p index during the 4-day period July 19–22, 1963. The scale for K_p is shown with values increasing downward. The disturbance variation in the knee position, marked D on July 21, is presented on a polar plot in Figure 6.

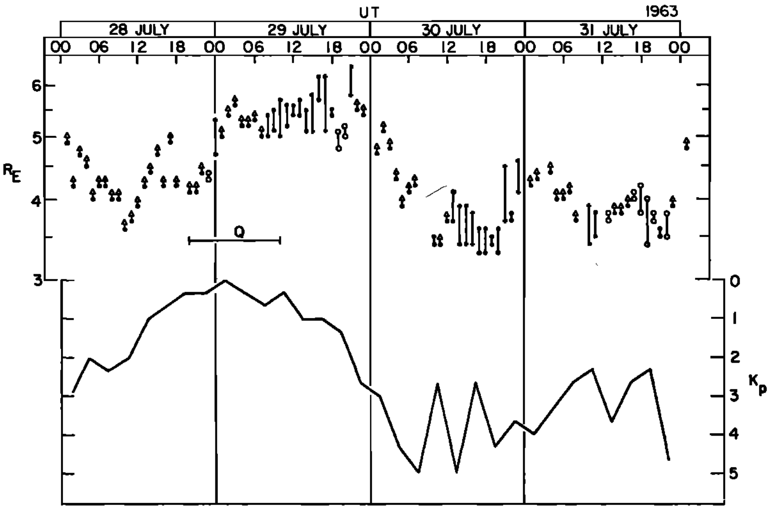

Fig. 9. Comparison of the geocentric equatorial range with the knee and the K_p index during the 4-day period July 28–31, 1963. A quieting interval in the knee behavior, marked Q on July 28–29, is shown on a polar plot in Figure 6.

netic activity during this interval was substantially similar to that for the period July 19–22 (Figure 8), and the variation in the knee position shows a corresponding similarity. The quieting effect on July 28–29 is relatively well defined, with the knee position moving outward and approaching 6 R_E late on July 29. The interval marked Q in Figure 9 is illustrated in Figure 6 by the dashed line. It is characterized by a significant outward movement on the nightside, distinctly in opposition to the trend known to exist during times of moderate but steady agitation. A gradual-commencement magnetic storm began on July 29, and the inward movement of the knee and the establishment of the typical moderate-disturbance diurnal variation are well illustrated on the latter part of July 30 and on July 31. Note on July 31 the evidence of a secondary maximum near 1800 UT (1300 LT).

On the basis of Figures 8 and 9, the phase lag between K_p and the knee movement appears to be of the order of 6 hours and is certainly much less than 24 hours. Future studies should clarify this point and should also give attention to effects associated with prolonged periods of agitation, sudden commencements, and response of the knee to disturbance as a function of local time.

Permanence of the knee. In an earlier report it was inferred that the knee is an essentially permanent feature of the magnetospheric ionization [*Carpenter*, 1963]. From the results just presented, it seems clear that the inference is correct. The evidence may be summarized as follows:

1. For the month of July 1963, approximately 100,000 whistlers were examined for information on the presence or the absence of the knee. In roughly 15,000 whistlers the position of the knee was well defined (an observation is 'defined' or 'direct' if there is simultaneous propagation on both the low- and the high-density sides of the plasmapause). In roughly 50,000 whistlers, indirect evidence of the knee was found (propagation inside the plasmapause only), and in the remaining roughly 30,000 no evidence was found to contradict the presence of a knee in the region where its presence could have been predicted from statistical considerations.

2. It was either possible to define the position of the knee or, from indirect evidence, to estimate its position within ±0.5 R_E, at least once during every 6-hour period in July 1963.

3. Under conditions of moderate magnetic activity (2 < K_p (ave) < 4) the knee position was defined in Eights data one or more times on 17 of 18 observing days. When K_p (ave) < 2, the position was defined one or more times

TABLE 1. Percentage of Observing Periods in Which the Knee Position Was Defined One or More Times

	Local Time, July 1963, Eights, Antarctica				
	00–06	06–12	12–18	18–24	00–24
18 days K_p(ave.) > 2	78%	72%	94%	44%	95%
13 days K_p(ave.) < 2	15%	38%	23%	23%	54%

on 7 of 13 days (see Table 1, third column). This variation in percentage of observations is attributed to movement of the knee toward the poleward edge of Eights' viewing area under quiet magnetic conditions.

4. The relative frequency of direct observations of the knee as a function of local-time periods and magnetic conditions is summarized in Table 1 (the knee was considered observed if it was defined in one or more of the hourly 2-minute runs during a period). For K_p(ave) > 2, the knee was defined more than 70% of the time in the periods 00–06 and 06–12 LT, and more than 90% of the time in the period 12–18 LT. The fact that the values for 00–06 and 06–12 are not above 90% is believed attributable to factors that affect whistler propagation, and not to an absence of the knee in the distribution of ionization. The low value for 18–24 LT may be attributed to many factors, including the turbulence and the shifting of the knee position characteristic of this period.

In the case of the 13 days for which K_p(ave) < 2, numbers for the various 6-hour periods are near about 30%. This is once again the effect of the poleward movement of the knee position during quiet conditions.

5. The earlier discussion of the diurnal and magnetic-storm variations showed that, under given planetary magnetic conditions, the position of the knee in space at a given local time is approximately determined. Furthermore, it is shown in paper K-2 that the distribution of electrons in the vicinity of the knee tends to reproduce itself when the same magnetic and local-time conditions are repeated.

6. Important independent evidence on the permanence of the knee has recently been obtained from several sources, including the Ogo 1 satellite. As an example from Ogo 1, the mass-spectrometer measurements reported by *Taylor et al.* [1965] showed repeated measurements of a knee effect through the period October 1964 through March 1965. These measurements provide a valuable complement to the present research, which is based primarily on the July–August period of 1963.

EXPERIMENTAL RESULTS ON THE MOVEMENTS OF MAGNETOSPHERIC PLASMA NEAR THE POSITION OF THE KNEE

It is possible that whistlers will provide a powerful means of studying the transport properties of the magnetosphere. The method has its inspiration in the unambiguous evidence that whistlers observed on the ground propagate on discrete field-aligned paths in the magnetosphere [*Helliwell et al.* 1956; *Storey,* 1962; *Allcock,* 1962]. The physical form of these discrete paths is assumed to be field-aligned ducts of enhanced or depressed ionization [e.g., *Smith,* 1961; *Helliwell,* 1965]. In the whistler experiment, under favorable observing conditions (such as prevail at Eights and Byrd Stations during the austral winter), well-defined whistlers may be excited every few seconds. Each whistler contains a number of well-defined components, each of which tends to be repeated with virtually unchanged dispersion properties in successive events. From the frequency-versus-time properties of these components, the corresponding path equatorial radii are identified (although the exact longitudes are not known in the absence of direction-finding information). There may be gradual changes in the dispersion characteristics, on a time scale much longer than the mean interval between events. By careful measurement of these dispersion changes, it is then possible to 'track' the various ducts involved and to detect certain types of path movements. Our preliminary working hypothesis is that movement of a discrete path represents movement of the associated tube of ionization.

The preliminary results described below are reported here because of their close relation to the knee phenomenon. Data from two periods, 0000–0300 and 1500–2000 LT, have been examined. Again, the magnetic condition is one of moderate but steady agitation.

Plasma movements 0000–0300 LT. When the knee is observed to move inward during the

3 or 4 hours after midnight, the thermal ionization just inside the plasmapause appears to move in a similar fashion, undergoing compression as opposed to erosion. A small amount of precipitation may be associated with the compression and with regular diffusion processes across the lower boundary of the whistler medium, but the principal observed effect is inward convection of the tubes of ionization on both sides of the knee.

An example of this phenomenon is shown in Figure 10, which illustrates the period 0000–0320 LT on July 7, 1963. At the upper left is a whistler containing a cluster of traces and also an isolated component with a nose frequency of 3.7 kHz and a travel time at the nose of 2.2 seconds. This event was recorded during the interval 0000–0010 LT. The series of truncated records extending to the right shows the isolated component as it appeared in 19 later events spaced roughly 10 minutes apart. The records have been cropped to focus attention on the gradual shift in nose frequency from 3.7 kHz at 0000 LT (arrow at left) to 4.7 kHz at 0310 LT (arrow at right). In a dipole field, this corresponds to a shift from 4.6 to 4.2 R_E. To illustrate the corresponding change in travel time at the nose, whistlers recorded at about 0150 and 0310 LT are mounted at the left, below the 0000 LT event. A comparison of the three records shows that the travel time at the nose varied from 2.2 seconds at 0000 LT to 2.0 seconds at 0150 LT, and finally to 1.9 seconds at 0310 LT. The variation in nose frequency and travel time (f_n, t_n) is summarized at the lower right by a tracing of the nose traces for 0000 and 0310 LT. The fact that the temporal variation in (f_n, t_n) follows approximately the locus of (f_n, t_n) described by the traces of a single multicomponent whistler propagating inside the knee (cf. Figure 2) implies that, during the period of inward motion described, the total content of the tube of ionization did not change by more than a few per cent. This content relation can be seen in paper K-2 by considering the reference whistler (Figure 1 in K-2) and its profile of tube electron content with latitude (Figure 3 in K-2).

The nose trace illustrated in Figure 10 was found to be propagating just inside the knee. Traces propagating in the lower-density region outside the knee followed a less well defined but similar pattern of rising nose frequency and decreasing travel time.

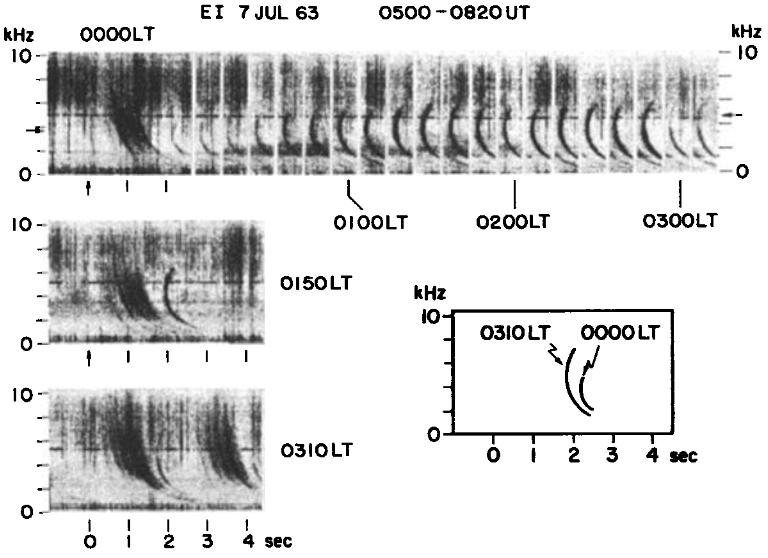

Fig. 10. Spectrograms showing a gradual variation in the frequency-versus-time properties of a whistler component during the interval 0000–0320 LT (0500–0820 UT) on July 7, 1963. The observations were made at Eights, Antarctica. Note that, in addition to illustrating a gradual change in whistler properties, the sequence of truncated records on the top line also shows the growth and decay of a band of noise near 3 kHz.

Various types of inward movement of plasma on the nightside have been predicted in theoretical studies in which the combined effects of the earth's rotation and of some type of high-latitude circulation are considered [*Axford and Hines,* 1961; *Hines,* 1964; *Maeda,* 1964; *DeWitt and Akasofu,* 1964; *Taylor and Hones,* 1965; *Fejer,* 1965]. This initial qualitative agreement encourages the hope that whistler studies can provide detailed maps of plasma movements, and thus permit estimates of large-scale electric fields in the magnetosphere.

Plasma movements near 1800 LT. The rapid outward shift of the knee near 1800 LT does not involve a corresponding movement of the plasma just inside the knee. Instead, the bulge in the curve of Figure 6 is caused by the presence near 1800 LT of a region of relatively high-density plasma beyond 4 R_E. As Eights' field of view moves hour by hour toward the dusk meridian, the knee is regularly observed at about the same geocentric range (R_E = 3.5–4). For several hours the whistler components propagating inside the knee show unchanged dispersion properties, and from this we infer that the associated tubes of ionization rotate with the earth at an approximately constant geocentric range. Quite abruptly, near 1800 LT, the whistlers indicate a region of high-density ($\sim$100 el/cm^3) plasma extending from the old position of the knee out roughly 1 R_E beyond (see also Figure 12). Because of the distribution of paths over a range of longitudes (cf. Figure 1), there may be a period from minutes to as much as an hour during which the station simultaneously sees paths representing both high and low density at the same equatorial radius. Then the low-density paths between 4 and 5 R_E disappear, and any further evidence of the knee is restricted to the vicinity of 5 R_E. It is not yet clear what happens to the low-density paths in terms of motions of ionization. It is clear, however, that the paths just inside the earlier position of the knee continue to move in a circular pattern (arrow *c* in Figure 12), not drifting outward to conform to the knee contour. The 'bulge' appears as a region of 'new' plasma, populated by new paths.

The presence of new paths is suggested by the last two records in Figure 7, which show a series of traces with high travel times at nose frequencies below 7 kHz. These traces are 'new,' and are not the result of a gradual transition from a family of traces with nose frequencies above the 7-kHz level.

The abrupt transition near 1800 LT suggests that the dense plasma appearing suddenly in the view of the station is carried to the region of observation at 4–5 R_E from the tail or flanks of the magnetosphere. The flow may involve a kind of stagnation point, in which the high-latitude inward flow encounters the opposing effect of the earth's rotation. Various types of inward flow from the tail or flanks of the magnetosphere have been predicted theoretically [*Axford and Hines,* 1961; *Dungey,* 1961, 1962; *Axford et al.,* 1965; *Taylor and Hones,* 1965].

Evidence of the corotation of the ionization inside the knee. An important preliminary objective of the new whistler method is to seek evidence of corotation of the inner magnetosphere with the earth (see, in this connection [*Hines,* 1964; *King-Hele,* 1964; *Hines,* 1965]). The limited evidence reviewed thus far suggests that the plasma inside the knee moves in a roughly circular corotating pattern (at least from 0000 to about 1700 LT, under conditions of steady, moderate geomagnetic agitation). For example, on July 10, 1963, paths clustered at three different equatorial radii inside the knee were identified before midnight local time. These three propagation regions were then identified on hourly records for 19 hours in succession. Assuming a ±1 hour longitude uncertainty, we infer from the 19-hour sequence that the paths moved with an average angular velocity Ω such that $0.9\Omega_E < \Omega < 1.1\Omega_E$, where Ω_E is the angular velocity of the earth. The frequency-time properties of the three whistler components changed from 0000 to 1700 LT roughly according to the solid curve in Figure 6, showing what appeared to be an initial nightside compression and a later gradual expansion. The participation in the radial motion by three path groups isolated from one another in space suggests strongly that drift motions associated with large-scale electric fields are being observed.

DISCUSSION

Generalization of the local-time measurements at Eights to all longitudes. The results described in the earlier sections represent regular samplings of the magnetosphere within a restricted range of longitudes centered approximately on the prime geomagnetic meridian (see Figure 1). The question then arises whether similar results would be obtained through recordings at other longitudes. There is a variety of evidence to support such an expectation.

1. Examples of the knee have been detected by the whistler method at various times over an approximately 180° range of longitude, ranging from west dipole longitude 110° [*Carpenter,* 1963] to east 80° longitude [*Corcuff and Delaroche,* 1964]. *Corcuff* [1965] reports a knee observation ($R_E \sim 2.5$) at Poitiers on October 25, 1958, about 8 hours after a corresponding observation by the author at Unalaska, some 180° in longitude from Poitiers.

2. The ion-trap measurements on Luniks 1 and 2 showed similar knee effects near the dawn and evening meridians [*Gringauz et al.,* 1960].

3. Recent measurements on Ogo 1 by means of a mass spectrometer have shown pronounced knee effects over a wide (>200°) range of longitudes [*Taylor et al.,* 1965].

4. Satellite measurements of variations in electron density with latitude at a fixed local time show trough effects in the ionosphere that are possibly related to the knee phenomenon. These observations have shown little variation with longitude [*Sharp,* 1966; *Brace and Reddy,* 1965].

On the basis of this evidence, we infer that the knee as observed at Eights displays similar characteristics at all other longitudes, and that the local-time variations illustrated in Figure 6 can be interpreted as the longitudinal variations in a three-dimensional boundary, which we call the 'plasmapause.' This view is doubtless oversimplified in many respects, but it seems appropriate as a basis for further investigation.

Relation of the magnetospheric knee to ionospheric profiles. The knee in the magnetosphere appears to have its counterpart in the profile with latitude of the nightside ionosphere. On the nightside, a variety of ionospheric troughs or depressions are observed at various altitudes, ranging from the peak of the *F* layer to 1000 km [*Muldrew,* 1965; *Sharp,* 1966] (J. O. Thomas, L. Colin, M. J. Rycroft, and K. L. Chan, part 3 of 'Topside Sounder Studies,' in preparation, 1965). A detailed correlation of the magnetospheric knee and these ionospheric effects has not yet been made, but the latitudes of observation suggest that both types of phenomena occur in roughly the same latitude range and have a similar magnetic variation, that is, an equatorward movement during periods of increasing magnetic activity. On the dayside, the two phenomena behave in a strikingly different manner, the magnetospheric knee tending to remain for many hours at roughly its nighttime position, while any large ionospheric depressions tend to be restricted to substantially higher latitudes. Qualitatively it seems difficult to describe or explain the knee entirely in terms of ionospheric mechanisms, both because of the apparent lack of correlation of position on the dayside and because of the relatively more abrupt nature of the phenomenon in the magnetosphere as compared with the shape of the ionospheric depressions (see paper K-2).

CONCLUSIONS

Preliminary model of the distribution of thermal ionization in the magnetosphere. On the basis of the results described above, we offer a preliminary model of the distribution of thermal ionization in the magnetosphere. If an observer in space could see the thermal ionization in the magnetosphere and observe its movements, the earth would appear to be encircled by a dense, doughnutlike cloud of ionization, with a sharp field-aligned boundary, the plasmapause, at an equatorial radius of 4 R_E. The cloud would appear to rotate with the earth, showing regions of compression and expansion, as well as a zone of confused motions between the 1700 LT and midnight meridians. On the dayside, the surface of the cloud might appear fluted, although this aspect remains in the area of conjecture (see paper K-2). If the observations were made during a period of moderate but steady geomagnetic agitation, the shape of the boundary would not change significantly in time; but if the magnetic activity were to increase, the plasmapause would appear to shrink inward and become relatively more asymmetric with respect to the earth. During very quiet periods the doughnut would appear to expand to equatorial radii of 6–7 R_E and assume a more circular configuration.

Some details of the model are presented in Figures 11 and 12, which show, respectively, a meridian cross section near 1400 LT and a cross

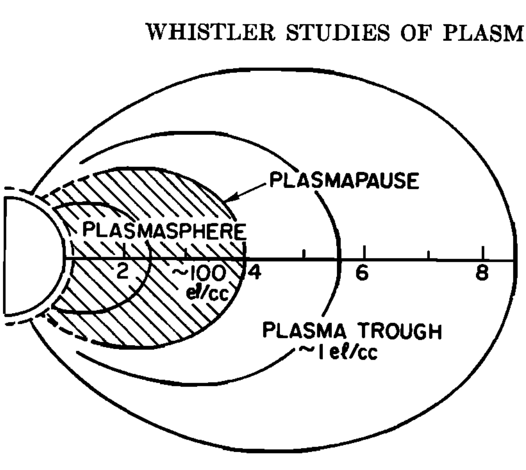

Fig. 11. Idealized meridian cross section of the magnetosphere near 1400 LT. The shaded region shows the location of the high-density plasma inside the plasmapause. The dashed part of the boundary shows the low-altitude region in which the structure of the knee is not well known. The magnetic condition represented is one of moderate but steady agitation ($K_p = 2$–4).

section in the geomagnetic equatorial plane. A condition of steady, moderate geomagnetic agitation is assumed. In Figure 11, the shaded area indicates the high-density region or 'plasmasphere' (~100 el/cm^3 near the boundary); the region outside is designated the 'plasma trough' (~1 el/cm^3). If the ionization density outside the magnetosphere in the magnetosheath is of the order of 4 ions/cm^3 as reported by *Wolfe et al.* [1966], it may be inferred that there is a kind of 'boundary knee' near the magnetopause, at which the number density increases from the low values now found to exist outside the knee (see also Figure 12). Thus, at least on much of the dayside, the region outside the plasmapause may be visualized as a kind of trough of low electron density of the order of 6 R_E wide.

The sharp boundary at 4 R_E (Figure 11) extends well down the field lines from the equatorial plane. The presence of such a boundary over this wide range may be inferred both from the total content measurements described in paper K-2 and from the recent direct measurements of knee effects by *Taylor et al.* [1965] and *Whipple and Troy* [1965]. The dashed portion of the boundary is intended to show the low-altitude region in which the structure of the knee is not well known. In this region there must be a transition from a sharp knee to a profile, which, at least in the daytime, may vary only slightly with increasing latitude (at 1000 km, say).

The equatorial view of the magnetosphere model is shown in Figure 12. In this figure, crosses outline the part of the plasma trough for which a substantial amount of information has been obtained. On the nightside, the data have so far been limited to a fairly narrow strip just outside the plasmapause; on the dayside, particularly in midafternoon, information has been obtained throughout a wide region extending close to the magnetosphere boundary. The extent of the available information outside the knee may tentatively be considered a measure of lack of turbulence near and outside the knee. In such terms, the midafternoon region, marked *Q* in Figure 12, is the quietest part of the outer magnetosphere.

The portion of the plasmapause between about 1800 and 2400 LT is shown dashed in order to call attention to several points. A relatively large number of knee observations have been made in this 6-hour period, but the shape and detailed behavior of the plasmapause are less well known here than during the period

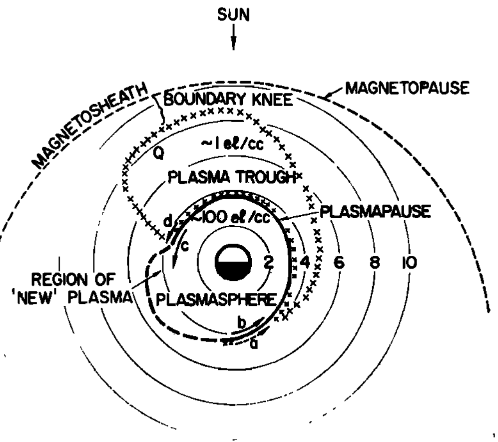

Fig. 12. Preliminary model in equatorial cross section of the distribution of thermal ionization in the magnetosphere. The model is based on data from the period July–August 1963 and represents conditions of moderate, steady geomagnetic agitation ($K_p = 2$–4). The crosses bounding the region marked 'plasma trough' indicate the region within which a significant number of observations have been made; they are not intended to represent an observed physical boundary.

0000–1800 LT. Most of the radial variation in the plasmapause takes place during the approximately 6-hour evening period. It is here that the apparent stagnation point in the plasma flow appears, and it is during this period that the inward compressional phase of the nightside movement begins. For these and other reasons we associate the period from about 1700 to 2400 LT with a steady-state input of energy from the tail or flanks of the magnetosphere. A substantial input of energy at this time is suggested by the evidence that 'new' plasma is observed near 1800 LT, plasma that does not appear to flow from the dayside of the magnetosphere.

The principal known features of the circulation patterns of the plasma are indicated in Figure 12 by arrows. On the nightside, arrows *a* and *b* show the compression effect observed in the first few hours after midnight. (Arrow *a* is shown dashed to indicate that its support in the data is as yet only fragmentary.) In the equatorial plane, the inward velocity component of the plasma moving according to arrow *b* is about 300 m/sec. Arrows *c* and *d* show schematically the complex behavior near 1800 LT when, within a period of the order of an hour, the position of the knee is observed to shift outward by a distance of the order of 1 R_E. Once again we emphasize that there is no observed outward movement of tubes of ionization in the direction of the dashed line. Instead, the plasma inside the knee continues to move in a roughly circular fashion as shown by arrow *c*. The plasma outside the knee ceases to support propagation observable at the ground station (end of arrow *d*), and no information is yet available on the further motion of this material in the near vicinity of the outward bulge. The bulge, about 1 or 1.5 R_E across, is formed by high-density plasma ($\sim$100 el/cm^3), which is believed to have moved inward from the tail or flanks of the magnetosphere.

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