Statistics of pulsating auroras on the basis of all-sky TV data from five stations. I. Occurrence frequency

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The frequency of occurrence of pulsating auroras is statistically examined on the basis of all-sky TV data for 34 nights from five stations, in a range from 61.5 to 74.3° in geomagnetic latitude. The results are that: (1) occurrence probability of a pulsating aurora is 100% after 4 h in geomagnetic local time, (2) pulsating auroras occur in the morning hours along the auroral oval even when magnetic activity is as small as $0o \leq K_p \leq 1$, (3) pulsating auroras occur even in the evening when K_p increases to greater than 3−, (4) drift of pulsating auroras is westward in the evening while it is eastward in the morning hours, (5) the region of pulsating auroras splits into two zones, 64 to 68° and 61 to 63° in geomagnetic latitude, after 4 h geomagnetic local time for K_p from 2o to 3−, and the splitting also appears to exist for greater K_p as evidenced by observation other than our auroral data. These results are discussed in relation to distributions of cold plasma irregularities and energetic electrons in the magnetosphere.

On a fait une étude statistique de la fréquence d'apparition des aurores pulsantes, sur la base des données TV plein ciel obtenues au cours de 34 nuits à cinq stations situées dans un intervalle de latitude géomagnétique allant de 61,5 à 71,3°. Cette étude a donné les résultats suivants: (1) la probabilité d'apparition d'aurores pulsantes est 100% après 4 h en temps géomagnétique local; (2) il se produit des aurores pulsantes durant les heures du matin le long de l'ovale auroral même lorsque l'activité magnétique est aussi faible que $0o \leq K_p \leq 1$; (3) il se produit des aurores pulsantes même dans la soirée lorsque K_p croît au delà de 3−; (4) la dérive des aurores pulsantes se fait vers l'ouest le soir, alors qu'elle est vers l'est durant les heures du matin; (5) la région d'aurores pulsantes se sépare en deux zones, 64 à 68° et 61 à 63° de latitude géomagnétique après 4 h, temps géomagnétique local, pour K_p entre 2o et 3−, et cette séparation semble exister aussi pour des valeurs plus grandes de K_p, comme l'indiquent des observations autres que nos données aurorales. Ces résultats sont discutés en relation avec les distributions d'irrégularités de plasma froid et d'électrons de haute énergie dans la magnétosphère.

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Introduction

A pulsating aurora is likely to be a visible manifestation of the pulsating precipitation of magnetospheric electrons, and the pulsating precipitation could be the result of wave–particle interactions in the magnetosphere. Even if some pulsating auroras originate from ionospheric processes (e.g., Deehr and Romick (1) and Luhmann (2)), modulation of precipitation in pulsating auroras (e.g., Whalen *et al*. (3) and Bryant *et al*. (4)) and that in the dawn auroral zone (5) indicates a primary importance of pulsating precipitation of energetic electrons in pulsating auroras. Hence, the study of the pulsating aurora can have an essential importance in understanding the plasma state in the magnetosphere.

In spite of their importance, pulsating auroras have not been studied well enough, possibly because of the weakness in luminosity and the complexity of the displays. In particular, a statistical study of their occurrence warrants more investigation (see, for example, refs. 6 and 7 and

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references therein). Kvifte and Petersen (6) showed the occurrence probability of a pulsating aurora in a magnetic latitude range from 65 to 68° and at 75° on the basis of photometric data for the period 1967–1968 from Tromsö and Spitzbergen. Although their result showed the occurrence probability of a pulsating aurora with respect to magnetic local time, the latitude coverage was inadequate to establish the morphology. In addition, the modes of pulsating auroras could not be specified, since they used photometers. On the other hand, Royrvik and Davis (7), using TV data, managed to show statistical occurrences of several modes of pulsating auroras. However, they did not show quantitative statistics of pulsating auroras with respect to latitude and local time.

In order to establish the morphology of pulsating auroras, and to obtain the observational facts of the pulsating precipitation in pulsating auroras in relation to concurrent geomagnetic pulsations and VLF emissions, the authors have carried out four campaigns for aurora–ULF–VLF observations in Canada as one of our IMS projects since 1976. The fourth campaign was carried out for the period from Jan. 9 to Mar. 1, 1980. The central part of the campaign was located in Saskatchewan, and was coordinated with the Canadian Pulsating Aurora Campaign with the support of the National Research Council, Canada for almost the same period of time. Other stations were distributed in Manitoba, Alberta, British Columbia, and the Northwest Territories.

Only statistical results on the occurrence of pulsating auroras on the basis of all-sky TVs for the fourth campaign will be given in this paper.

Instruments and Observations

Three ISIT-TV cameras, assembled in the Geophysics Research Laboratory, University of Tokyo were distributed at Rabbit Lake, La Ronge, and Park Site. Fish-eye lenses used for these TV cameras were modified Kenko which yielded a focal/aperture ratio 2.8 for the ordinary 1″ ISIT imaging tube surface. The threshold of the imaging system is about 50 R in the auroral green line at real time speed and it can be reduced by frame integrations. Another ISIT-TV camera, one kindly supplied by Toshiba Electric Co. for this fourth campaign, was operated at Rankin Inlet. Since it was expected that the aurora over Rankin Inlet would be much weaker than that over the auroral zone stations, a modified Nikkor fish-eye lens, with focal/aperture ratio 1.4 was used. At Steen River, an SIT-TV camera was operated with a modified Nikkor fish-eye lens, with focal/aperture ratio 1.4, yielding a threshold about 500 R in auroral green line at real time speed. In addition to the five all-sky TV systems, an SIT-TV camera with a standard lens of focal length 12.5 mm with focal/aperture ratio 1.4 was operated at La Ronge in order to record the fine structures of auroras.

The observations were carried out continuously from dusk to dawn every night, except during heavily overcast periods, from January 11 to February 23, 1980. Video records of aurora were obtained on 34 out of 44 nights. The other 10 nights were either completely overcast or fully moonlit. Distribution of the auroral stations, along with the magnetic and VLF stations is shown in Fig. 1. The coordinates of the stations are given in Table 1. Statistics of the pulsating auroras given here are based on the all-sky TV observations at the five auroral stations mentioned above.

Occurrence Probability of Pulsating Auroras

In order to study the occurrence probability of pulsating auroras, all TV data from the five stations were statistically examined. In the statistics, the periods of time when the observations were made only at Rankin Inlet and/or Park Site were excluded. The reason for this is that the geomagnetic latitude of Rankin Inlet is a little too high to detect pulsating auroras at any time, and also the geomagnetic latitude of Park Site is a little too low for magnetically quiet periods of time. Since the K_p indices during the campaign were unusually low for the solar maximum, as seen in Fig. 2, this consideration of Park Site data is reasonable.

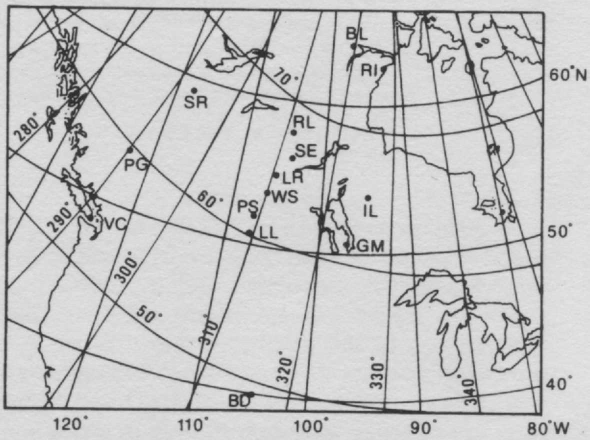

FIG. 1. Distribution of stations. BL, Baker Lake; RI, Rankin Inlet; RL, Rabbit Lake; SR, Steen River; SE, South End; IL, Island Lake; LR, La Ronge; WS, Waskesiu; GM, Gimli; PS, Park Site; LL, Lucky Lake; PG, Prince George; VC, Victoria.

TABLE 1. Coordinates of stations along with types of observations

Observation site		Geographic Lat.	Geographic Long.	Corrected geomagnetic Lat.	Corrected geomagnetic Long.	Observation types (A: Aurora, U: ULF, V: VLF)
Baker Lake	(BL)	64.2N	96.0W	75.1	320.4	U
Rankin Inlet	(RI)	62.8	92.2	74.3	328.0	A U V
Rabbit Lake	(RL)	58.2	103.7	68.1	311.9	A U V
Steen River	(SR)	59.7	117.2	66.6	293.7	A U V
South End	(SE)	56.3	103.5	66.3	312.8	U V
Island Lake	(IL)	53.9	94.7	65.5	326.5	U
La Ronge	(LR)	55.2	105.3	64.8	311.0	A U V
Waskesiu	(WS)	53.9	106.1	63.4	310.5	U V
Gimli	(GM)	50.6	97.0	61.9	323.9	U
Park Site	(PS)	52.2	107.2	61.5	309.8	A U V
Lucky Lake	(LL)	51.0	107.1	60.3	310.3	U V
Prince George	(PG)	53.9	122.9	59.6	290.9	U
Victoria	(VC)	48.3	123.6	53.7	292.6	U

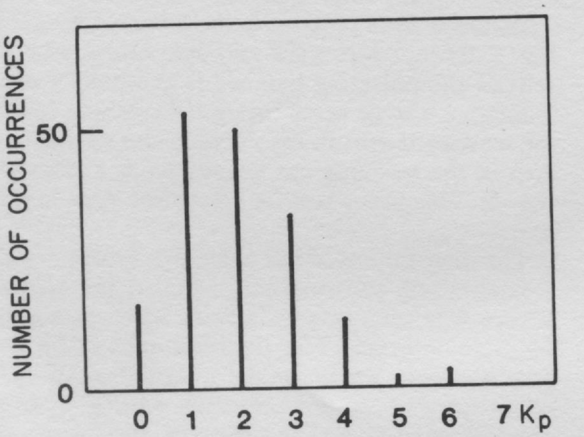

FIG. 2. Distribution of K_p indices for the periods of auroral observations, (0 to 15 h UT), from Jan. 11 to Feb. 23, 1980.

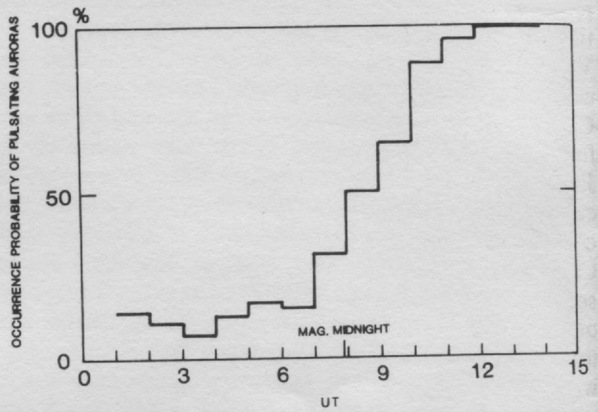

FIG. 3. Occurrence probability of pulsating auroras. Statistics are on the basis of all-sky TV cameras at Rankin Inlet, Rabbit Lake, Steen River, La Ronge, and Park Site. The ratio of the number of time intervals when a pulsating aurora was seen to that of any type of aurora, regardless of the location of pulsating auroras in an all-sky field over 10° elevation is plotted against universal time.

Thus, the periods of time when at least one TV camera of the three auroral zone stations (Rabbit Lake, Steen River, La Ronge) was operated, were divided into 1 h intervals, and each interval was examined to determine if pulsating auroras were seen at any stations in the field of view above 10° elevation. Then the ratio of the number of intervals when a pulsating aurora was seen to the number of intervals when any aurora was seen, was plotted with respect to universal time.

Figure 3 illustrates the occurrence probability of a pulsating aurora thus obtained. Since some auroras were always seen for every observation time interval from at least one of the three stations, the ratio defined above is identical to the occurrence probability of a pulsating aurora, normalized by the observation time. Note that the five stations each cover a large extent of the sky, so that even if one station is missing because of cloudy sky or other condition all pulsating auroras will be detected.

Two important facts are found in Fig. 3. One is that the occurrence probability at the magnetic midnight is about 30% and it rapidly increases to 100% about 4 h magnetic local time (1200 UT). This means that the pulsating aurora can be seen somewhere along the auroral oval every morning after 4 h magnetic local time possibly even for very quiet periods of time. This fact further means that the pulsating aurora is a usual component of auroral displays in the morning.

We must note here the night of Feb. 22, 1980. Observation was carried out until 1123 UT at Rabbit Lake, until 1400 UT at Park Site, and until 1200 UT at Rankin Inlet on that day. Although an extremely faint aurora, north of Rabbit Lake seemed to pulsate slightly during the period from

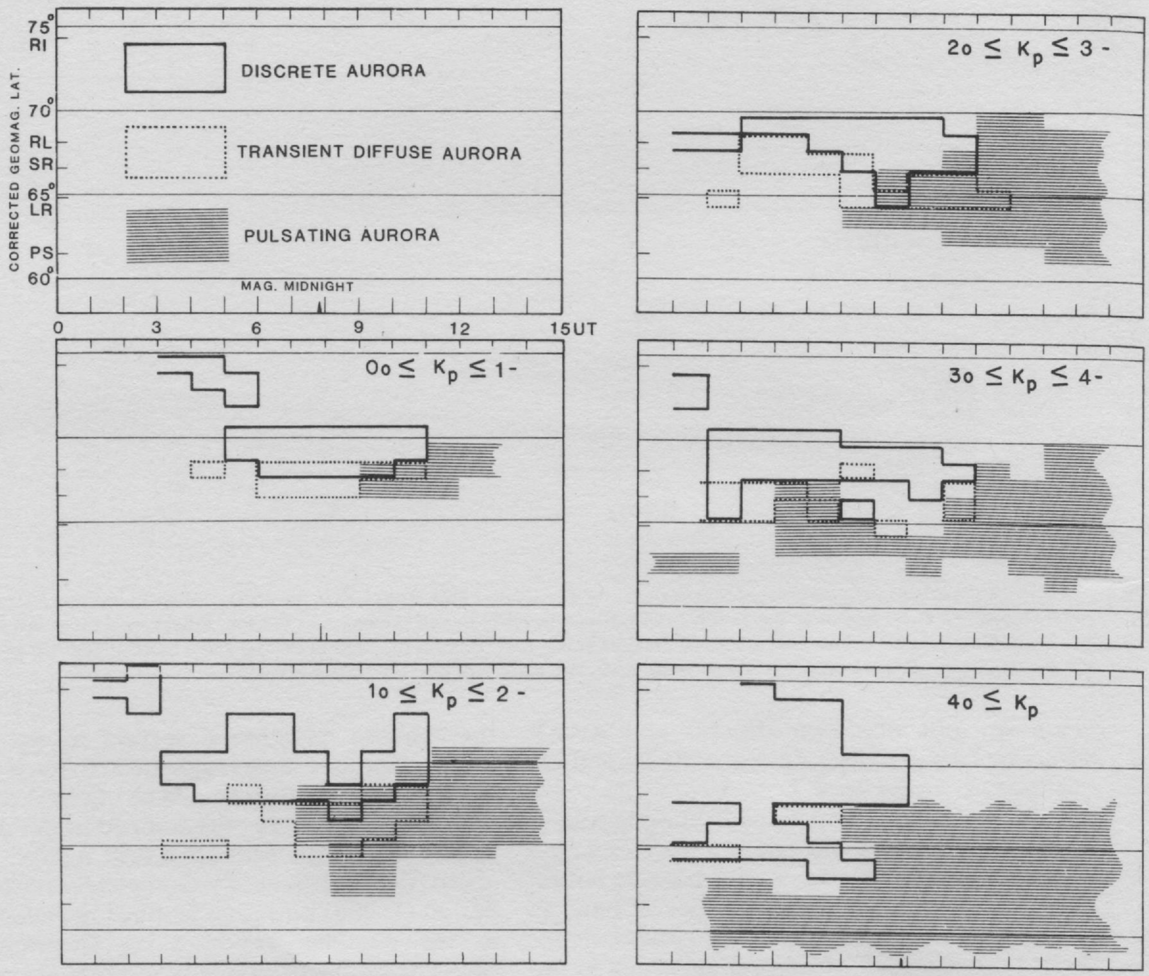

FIG. 4. Distributions of discrete auroras; diffuse, transient, nonpulsating auroras; and pulsating auroras in five ranges of K_p; $0o \leq K_p \leq 1-$, $1o \leq K_p \leq 2-$, $2o \leq K_p \leq 3-$, $3o \leq K_p \leq 4-$ and $4o \leq K_p$. Pulsating auroras occurred during activity even as low as $0o \leq K_p \leq 1-$, and occurred even in the evening hours as early as 17 h magnetic local time during activities $3o \leq K_p$.

well into evening when the activity is in the range $3o \leq K_p \leq 4-$, with the center of activity lying between 62 and 66° after 2–3 h.

It may be worth noting that the low-latitude boundary tends toward lower latitudes after midnight in the activity ranges $2o \leq K_p \leq 3-$ and $3o \leq K_p \leq 4-$. This trend corresponds to the similar shape of the low-latitude boundary of the auroral oval. In addition, the observation indicates that the pulsation zone splits into two branches. For the activity range $2o \leq K_p \leq 3-$, the pulsation zone splits into two after 4 h, one from 64 to 68° and the other from 61 to 63° in geomagnetic latitude. The splitting appears to exist for $K_p \geq 3o$ also. Though our own auroral data are inadequate to determine the splitting for the greater activities, there is supporting evidence as will be mentioned later.

The results concerning distribution of pulsating auroras are summarized in the schematic illustrations in Fig. 7. The case for $K_p \geq 3o$ is speculative as mentioned above and will be discussed more in the following section.

Conclusions and Discussions

This statistical study shows, on the basis of TV observations: (1) that a pulsating aurora can always be seen somewhere along the oval in the morning hours after 4 h magnetic local time, (2) that pulsating auroras could occur in a latitude range 66.5 to 70° after 1 h magnetic local time even for the period of time as quiet as $0o \leq K_p \leq 1-$, (3) that pulsating auroras occur in the evening hours when activity increases, $3o \leq K_p$, in the magnetic latitude range 61 to 69°, (4) that the drift of the pulsating aurora is westward in the evening while it is eastward in the morning, and (5) that the zone of pulsating auroras

0940 to 0950, it is uncertain that the form did pulsate. Since the observation ceased at 1123 UT at Rabbit Lake, the only station where any aurora was seen on that day, we can say nothing about the possibility of the pulsating aurora after 1123 UT. If there was no pulsating aurora through 1400 UT, the 100% possibility of occurrence after 1200 UT in Fig. 3 would be reduced to 95%. Figure 3 also indicates that the pulsating aurora occurs in the evening hours as early as 17 h magnetic local time (0100 UT), although its probability is not large. It will be shown later that the occurrence of pulsating auroras in the evening is a contribution from active periods of time, when K_p is greater than 3−.

Distribution of Pulsating Auroras

Next, the change in the distribution of pulsating auroras with respect to K_p was examined. In so doing, the all-sky TV data from the five stations were divided into 3 h intervals with common K_p. Then, the all-sky field of each TV image was divided into five geomagnetic latitude zones, each of width 1°: one centered over the zenith of each station and two zones north and south of the centered zone, respectively. This procedure allowed us to set up a continuous coverage from 59 to 77° in geomagnetic latitude, with 1° accuracy in the auroral locations. The regions between Rabbit Lake and La Ronge, and between La Ronge and Park Site can be almost covered by three such zones instead of five, since the width of each region is about 350 km. On the other hand, the north–south distance between Rankin Inlet and Rabbit Lake is about 600 km, a little too broad to cover by the five-zone system. Hence, we carefully examined the regions beyong the five specified zones in order to cover the region in between Rankin Inlet and Rabbit Lake.

The auroras were classified into three categories: discrete auroras; diffuse, transient, nonpulsating auroras; and pulsating auroras. Note that here the term discrete aurora has the usual meaning, but it represents a fairly active aurora, and that the diffuse, transient, nonpulsating aurora is not necessarily identical to the diffuse aurora in the evening, even though it may actually include some of the diffuse aurora. The occurrence of the three kinds of auroras, thus categorized, were examined in 1° latitude zones mentioned above and 1 h time intervals, for magnetic activity, in five ranges of K_p: 0o $\leq K_p \leq$ 1−, 1o $\leq K_p \leq$ 2−, 2o $\leq K_p \leq$ 3−, 3o $\leq K_p \leq$ 4 and 4o $\leq K_p$. Figure 4 illustrates the distribution of auroras thus obtained.

Two important facts, mentioned in the previous section, are clearly seen in Fig. 4. Namely, the pulsating aurora occurs in the morning after 1 h (or more definitely after 3 h) magnetic local time in the geomagnetic latitude range 66 to 70° even for a period of time as quiet as $K_p \leq$ 1−. The occurrence region of a pulsating aurora expands equatorwards and the occurrence time expands to the evening side as activity increases. The occurrence region expands equatorwards to 61° and the occurrence time is as early as 17 h magnetic local time as K_p becomes greater than 3−. For the periods with K_p greater than 4− the region can extend down to 59° or lower and the occurrence time would be expected to advance to well before 17 h, although the data in the campaign did not cover times before 19 h for this activity range.

Although drifts of pulsating patches are somewhat outside the context of this paper, it is worth noting the fact that the pulsating patches in the evening hours drift westward in contrast to the eastward drift of patches in the morning hours; see Fig. 5. Except during the midnight hours, when the drift of the pulsating patches is generally variable indicating a large scale rotational or shear feature, the westward drift in the evening and the eastward drift in the morning are usually clear as shown in Fig. 5. This point will be discussed later in some detail.

The distribution of the pulsating aurora in Fig. 4 is qualitative, showing only whether the pulsating aurora was seen in a 1° latitude zone during each 1 h time interval. The distribution can be more quantitatively shown as the distribution of occurrence number of the pulsating aurora. Figure 6 illustrates such distributions of the occurrence numbers. The area surrounded by a thick line represents the region where the pulsating aurora is seen for a 1 h interval, shaded areas represent the region of occurrences for two intervals, doubly shaded areas represent 3 to 4 intervals, and dark areas indicate 5 or more intervals. Although the amount of data is not large enough to produce reliable statistics, especially with respect to various K_p indices, the tendency of the occurrence is still fairly clear in Fig. 6. During quiet times, 0o $\leq K_p \leq$ 1−, the pulsating auroral activity is centered at latitude 67–68° after 3 h. As K_p increases to 1o $\leq K_p \leq$ 2−, the pulsation zone expands from 64 to 69° after 1 h. In both cases, the auroral pulsation appears to start at lower latitudes in the midnight sector and the high latitude boundary of the pulsating aurora expands polewards during the morning hours. When 2o $\leq K_p \leq$ 3−, the pulsation zone further expands southward to cover the region 62 to 67° and the pulsations tend to start a little before magnetic midnight. The occurrence time advances

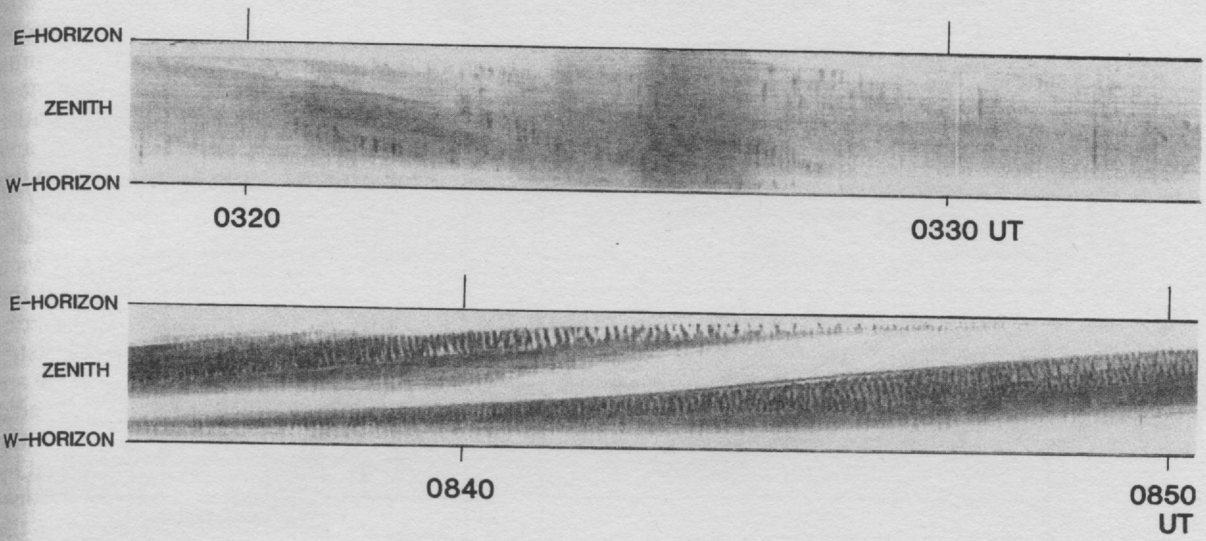

FIG. 5. Drifts of pulsating auroral patches in the E–W direction at Park Site on Feb. 16, 1980. Ordinates indicate locations of aurora along the E–W line over the zenith from horizon to horizon and the abscissa is time. Pulsating auroras are seen as vertically elongated dark dots. Sequences of the dots going down toward the right in the top panel indicate that the pulsating auroral patches drift westward, and those going up in the bottom panel show eastward drifts.

appears to split into two, 64–68° and 61–63° in magnetic latitude, after 4 h magnetic local time, for the activity range $2o \leq K_p \leq 3-$.

Result (1) indicates that the pulsating aurora is not a special phenomenon but is a very common condition of auroral displays in the morning hours. Result (2) indicates that even activities as small as $0o \leq K_p \leq 1-$, can give rise to the conditions for pulsating precipitation of auroral electrons in the dawn sectors. This fact probably means that even a very small auroral expansion can produce energetic electrons in the magnetosphere near the midnight sector. Similar statistics of pulsating auroras by Kvifte and Petersen (6), however, showed only 50 ~ 75% occurrence probability for the period with $\Sigma K \leq 20$, ($\bar{K} \leq 2.5$) in the northern sky from Tronsö. The discrepancy between our result and theirs may be due to the fact that we utilized TV data from five stations while they used photometric data from two stations. Local pulsating auroras may be missing by their photometric observations.

In result (3), some of the occurrence of the pulsating auroras in the evening for the period $3o \leq K_p$, could be explained by the westward expansion of the acceleration region in larger activities as manifested by active westward travelling surges or auroral bulges. However, most pulsating auroras in the early morning are presumbly due to energetic electrons which are injected in and/or near the magnetic midnight sector and drift eastward through the dawn/noon sectors to the evening sector. During a large magnetic activity, a quantity of energetic electrons should be injected, and some of them are likely to stay trapped in the magnetosphere during the azimuthal drift motion, circling about the Earth nearly completely. The short-period (1–30 s) pulsating features of radar auroras in the daytime, reported by McDiarmid and McNamara (8), presumably indicate the pulsating precipitation of electrons that would produce pulsating auroras if it were dark. This type of radar auroral pulsations occur more often during magnetically disturbed periods. They were found to take place at 62–64° in geomagnetic latitude. The radar was installed in Ottawa where the geomagnetic latitude is 58.9°.

The considerations in the previous paragraph and result (5), indicating the splitting of the pulsation zone, lead us to an expectation that for $K_p \geq 3o$, pulsating auroras occur well before 17 h and well after 6 h in local magnetic time, possibly to the noon meridian, in a latitude range from 59 to 66° or a little higher. Hence, the illustration for $K_p \geq 3o$ in Fig. 7. As mentioned in the previous section, it is not that the splitting in this case of $K_p \geq 3o$ resulted from our auroral observation. Our own auroral data are not sufficient to conclude the splitting. However, the same tendency in the splitting is seen in the figures by Kvifte and Petersen (6), though they mentioned nothing about the splitting. There is another piece of evidence indicating the splitting.

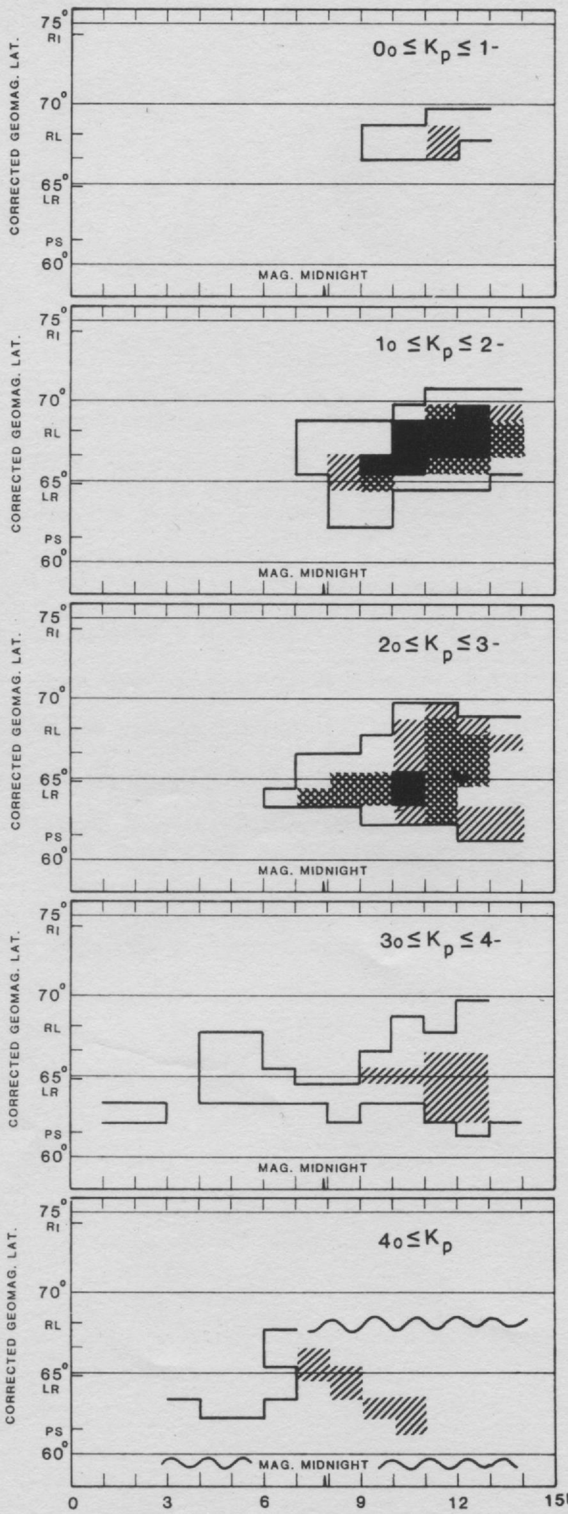

FIG. 6. Distribution of occurrence frequency of pulsating auroras in five ranges of K_p indices. The pulsating auroral region appears to split into two zones, 61–63° and 64–68° in geomagnetic latitude, after 4 h magnetic local time in the range 2o ≤ K_p ≤ 3−.

As reported in a separate paper (9) geomagnetic pulsations having the same charateristics as those concurrent with the dawn sector pulsating auroras occur often at 60–62° in geomagnetic latitude near the noon meridian. The daytime short-period radar auroral pulsations reported by McDiarmid and McNamara (8) occur both in the morning and in the afternoon.

The drift of the pulsating patches is usually irregular in the midnight sector. It often shows a clockwise rotational tendency, viewed along the magnetic field, especially near the Harang discontinuity. Result (4) strongly suggests that the distribution and drift of pulsating auroral patches are determined by the distribution and drift of cold plasma irregularities due to the electric field in the magnetosphere, while pulsation itself is caused by the pulsating precipitation of energetic electrons. This interpretation is based on the fact that the westward drift of the pulsating auroral patches in the evening cannot be explained in terms of magnetic drift of energetic electrons. In conjunction with result (3), result (4) appears to indicate that the pulsating precipitation occurs mostly by the encounter of energetic electrons with cold plasma irregularities, drifting by electric fields, as suggested by Oguti (10) and Johnstone (11).

The pulsating auroral region tends to be higher in latitude in the morning hours than at midnight. It probably lies equatorward of the lower latitude boundary of the discrete auroral oval during slightly active periods. As to the pulsation zone split for $K_p \geq$ 2o, the higher latitude branch appears to tend to a higher latitude during morning hours similar to that for low activities, however, the lower latitude branch appears roughly along a constant L line. These tendencies may indicate that the pulsating precipitation in the morning is due to a wide-spread source region of energetic electrons. The higher latitude branch may be due to local acceleration of electrons along the discrete auroral oval. Electrons may be accelerated less and may be lost rapidly as they drift eastward. The lower latitude branch may be ascribed to the magnetic drift to energetic electrons produced by an auroral expansion of considerable size. In lower latitudes, it can produce much more energetic electrons which are likely to survive during the course of their traverse along a constant L shell around the Earth.

Although we know that the pulsating aurora can be classified into several modes at least (e.g., Royrvik and Davis (7) and Oguti (12)), no consideration of classification was made in the statistics here. Statistics with mode information will be given in a separate paper.

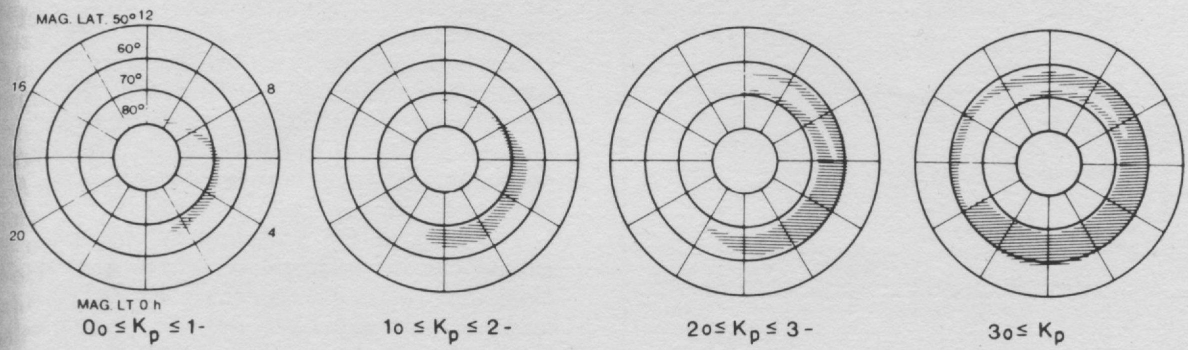

FIG. 7. Schematic illustrations of the pulsating auroral regions when $0o \leq K_p \leq 1-$, $1o \leq K_p \leq 2-$, $2o \leq K_p \leq 3-$ and $3o \leq K_p$. The appearance of pulsating auroras outside the epoch 17 h to 06 h is inferred by VLF and magnetic side-evidences.

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