On the Polarization and Origin of Auroral Kilometric Radiation

DONALD A. GURNETT AND JAMES LAUER GREEN

Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242

Observations of radio emissions by the Hawkeye 1 satellite at low altitudes over the southern hemisphere have now provided measurements at radial distances from about 1.5 to 2.5 R_E along the auroral field lines, in the region where the intense nightside auroral kilometric radiation is believed to be generated. These measurements provide new evidence on the mode of propagation and origin of the auroral kilometric radiation. At low altitudes the auroral kilometric radiation is consistently observed to have a low-frequency cutoff at the local electron gyrofrequency f_g^-. Since the electron plasma frequency f_p^- is usually much smaller than f_g^- in the region where these observations are obtained, this cutoff corresponds closely with the propagation cutoff for the right-hand mode of propagation. These observations therefore provide a strong indication that the auroral kilometric radiation is right-hand polarized in agreement with previous conclusions made on the basis of the angular distribution of this radiation. In the local evening region, where the intense auroral kilometric radiation is believed to be generated, a few events have been detected for which no low-frequency cutoff is evident. In these cases the auroral kilometric radiation appears to merge essentially continuously into a band of intense auroral hiss which extends downward to frequencies as low as 1 kHz. These observations suggest that the generation of the whistler mode auroral hiss and the escaping auroral kilometric radiation are very closely related. Possible mechanisms which could produce strong coupling between the whistler mode and the escaping free space electromagnetic modes are discussed.

INTRODUCTION

Previous studies have shown that the most intense kilometric radio emissions from the terrestrial magnetosphere are usually generated relatively close to the earth, at radial distances ranging from about 2.0 to 3.0 R_E over the nightside auroral zones [*Gurnett*, 1974; *Kurth et al.*, 1975; *Kaiser and Stone*, 1975; *Alexander and Kaiser*, 1976]. Following the terminology of *Kurth et al.* [1975], we will refer to the intense auroral-related kilometric radio emissions from the nightside of the earth as auroral kilometric radiation. Although many spacecraft have made observations of these radio emissions, including Ogo 1 [*Dunckel et al.*, 1970], Imp 6 [*Brown*, 1973; *Gurnett*, 1974], Hawkeye 1 [*Kurth et al.*, 1975], Imp 8 [*Gurnett*, 1975], and Rae 2 [*Alexander and Kaiser*, 1976], up to the present time none have obtained measurements at low altitudes over the auroral zones where the auroral kilometric radiation is believed to be generated. Fortunately, because of changes in the orbit parameters after launch, the polar-orbiting Hawkeye 1 spacecraft, which was launched on June 3, 1974, has recently been able to provide some limited coverage of this very interesting region. The purpose of this paper is to present the initial results obtained from observations of auroral kilometric radiation at radial distances of about 2.0 R_E over the auroral zone. These measurements provide important new evidence on the mode of propagation and origin of the auroral kilometric radiation.

SPACECRAFT ORBIT AND INSTRUMENTATION

The Hawkeye 1 spacecraft is in a highly eccentric polar orbit with initial apogee and perigee geocentric radial distances of 130,856 and 6,847 km, respectively. Initially, the apogee and perigee were located almost directly over the north and south poles. Because of orbit perturbations the perigee radial distance increased substantially, reaching a maximum of about 11,000 km about 2 years after launch. The increase in the perigee altitude together with changes in the argument of perigee permits Hawkeye 1 to obtain measurements along the auroral field lines over the southern hemisphere at radial distances up to about 2.5 R_E, in the region where the auroral kilometric radiation is believed to be generated. Over the northern hemisphere the auroral field line crossings occur at radial distances greater than 4.0 R_E, beyond the region where the radiation is generated.

Since the details of the Hawkeye 1 plasma wave experiment have been described in previous papers [*Kurth et al.*, 1975; *Green et al.*, 1977], only a few brief comments are given for a review. Electric field measurements are made on Hawkeye 1 using an electric dipole antenna with a tip-to-tip length of 42.45 m. A 16-channel spectrum analyzer is used to determine the frequency spectrum of the electric field. The frequency range of the spectrum analyzer is 1.78 Hz to 178 kHz, and the dynamic range is 100 dB. Measurements of the local magnetic field strength (to compute the electron gyrofrequency) are obtained from a triaxial magnetometer. The magnetometer has four sensitivity ranges which can be selected by ground command. During the low-altitude passes over the southern hemisphere the sensitivity range of the magnetometer is usually set at $\pm 25{,}000\ \gamma$. In this range the instrumental accuracy is $\pm 125\ \gamma$ on each axis. The data used in this study include approximately 200 passes over the southern polar region from about April 1975 to July 1976. Most of these data were obtained via the French telemetry station at Terre Adélie, near the south magnetic pole.

CONTINUUM RADIATION

Three types of high-frequency radio emissions, (1) continuum radiation, (2) auroral kilometric radiation, and (3) auroral hiss, are commonly observed by Hawkeye 1 during the low-altitude passes over the southern hemisphere. Although our primary interest is in the intense auroral kilometric radiation, we first discuss the continuum radiation observations, since this radiation plays an essential role in our analysis of the local electron plasma frequency. A typical example of the continuum radiation observed by Hawkeye 1 over the southern hemisphere is illustrated in Figure 1, which shows the electric field intensities in 16 frequency channels from 1.78 Hz to 178 kHz. The intensity scale for each channel is proportional to the logarithm of the electric field strength, with a

Paper number 7A0879.
0148-0227/78/027A-0879$03.00

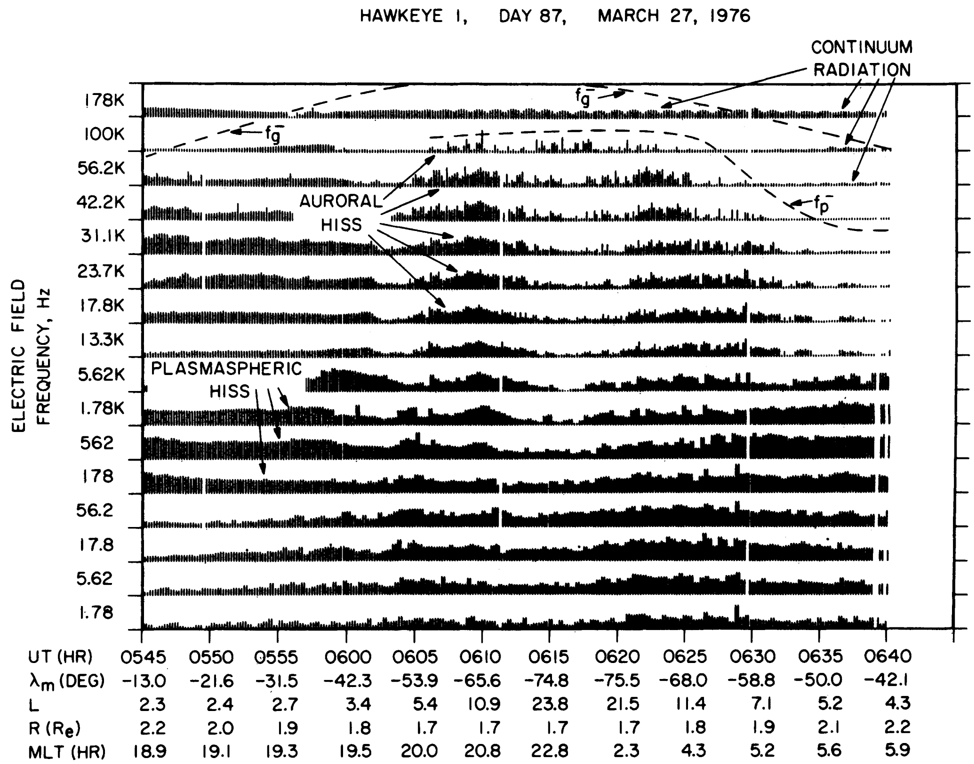

Fig. 1. A typical Hawkeye 1 pass over the southern hemisphere showing the occurrence of continuum radiation over a large region of the polar cap. The dashed line marked f_g^- is the measured electron gyrofrequency. The electron plasma frequency f_p^- is estimated on the basis of the low-frequency cutoff of the continuum radiation and the upper-frequency cutoff of the auroral hiss, which provide upper and lower bounds for the local electron plasma frequency.

range of 100 dB from the base line of one channel to the base line of the next higher channel. The identification of this radiation is based on the close similarity to a type of radiation called continuum radiation, which is commonly observed in the outer magnetosphere at frequencies above the local electron plasma frequency [*Gurnett and Shaw*, 1973; *Brown*, 1973; *Gurnett*, 1975]. The identifying characteristics of the continuum radiation are that (1) the intensity is relatively weak, typically 10^{-17}–10^{-20} W m^{-2} Hz^{-1}, (2) the spectrum extends over a broad range of frequencies with a sharp low-frequency cutoff at the local electron plasma frequency f_p^-, and (3) the intensity is nearly constant on a time scale less than a few hours and seldom varies by more than 10–15 dB. As can be seen in Figure 1, the continuum radiation detected in the 178-kHz channel is relatively weak ($\sim 1.3 \times 10^{-17}$ W m^{-2} Hz^{-1}) and has the very smooth temporal variations characteristic of this type of radiation. The periodic modulation on a time scale of about 1 min is caused by the antenna rotation. The fact that this same type of radiation can be detected essentially continuously out to large distances from the earth, in regions where the local electron gyrofrequency and plasma frequency are well below the wave frequency, provides substantial evidence that the radiation is escaping electromagnetic radiation and not a locally trapped plasma wave mode. The abrupt low-frequency cutoff of the continuum radiation spectrum in Figure 1, between the 100- and 178-kHz channels from 0600 to 0630 UT, and at slightly lower frequencies after 0630 UT, is interpreted as being due to the propagation cutoff of the left-hand polarized ordinary (*L-O*) mode at the electron plasma frequency f_p^-. This cutoff cannot be associated with the right-hand polarized extraordinary (*R-X*) mode cutoff

$$f_{R=0} = \frac{f_g^-}{2} + \left[\left(\frac{f_g^-}{2}\right)^2 + (f_p^-)^2\right]^{1/2} \quad (1)$$

since the continuum radiation extends well below the electron gyrofrequency f_g^-, indicated by the dashed line in Figure 1. As can be seen from (1), the *R-X* cutoff frequency is always above the electron gyrofrequency. Although the continuum radiation cutoff provides an upper limit to the local electron plasma frequency, additional information is needed to uniquely determine the local electron plasma frequency, since the propagation cutoff is not necessarily determined by local conditions. The presence of whistler mode auroral hiss provides an additional constraint on the local electron plasma frequency. As can be shown [*Stix*, 1962], the upper cutoff frequency of the whistler mode is determined by either the electron gyrofrequency f_g^- or the electron plasma frequency f_p^-, whichever is smaller. Since auroral hiss is detected in the 100-kHz channel from 0605 to 0625 UT and continuum radiation is present in the 178-kHz channel, the local electron plasma frequency must be between 100 and 178 kHz. By using this information a rough estimate can be made of the local electron plasma frequency, as shown by the dashed line marked f_p^- in Figure 1. The uncertainty in this determination of the local plasma frequency varies considerably, depending on the presence of the auroral hiss and the continuum radiation. In some cases, only an upper or a lower bound can be placed on the plasma frequency. In all cases the local electron plasma frequency must be below the lowest frequency for which the continuum radiation can be detected and above the highest frequency for which the auroral hiss can be detected. Since no other method exists on Hawkeye 1 for determining

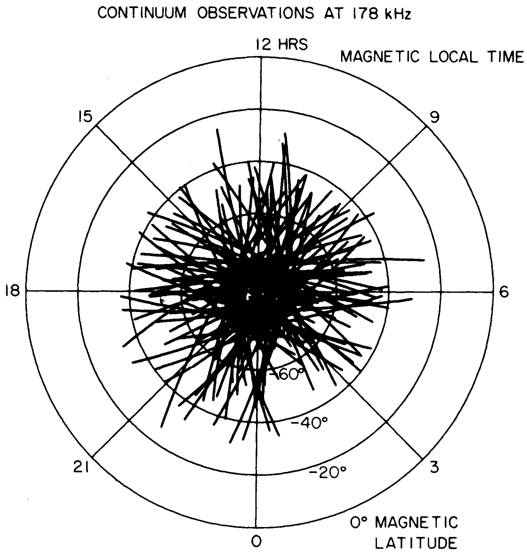

Fig. 2. The trajectories of all passes for which continuum radiation comparable to the case in Figure 1 is observed by Hawkeye 1 over the southern hemisphere at 178 kHz. The equatorward cutoff at about −40° magnetic latitude occurs as the spacecraft enters the higher-density region inside the plasmasphere with local plasma frequencies greater than 178 kHz.

the local electron density (hence electron plasma frequency), this type of analysis provides an essential tool for determining the local characteristic frequencies of the plasma. The electron densities obtained from this type of analysis, typically 50–100 el cm^{-3} at ~2.0-R_E radial distance over the polar cap, are in good quantitative agreement with extrapolations from measurements by the Alouette and Isis satellites at lower altitudes and with direct measurement from S3-3 [*Torbert et al.*, 1977].

Continuum radiation similar to that in Figure 1 is a common feature of all of the Hawkeye 1 southern hemisphere observations. Figure 2 shows a polar plot (magnetic latitude and magnetic local time) of all the times for which continuum radiation was detected by Hawkeye 1 over the southern hemisphere. This plot shows that the continuum radiation was observed nearly uniformly over the entire polar region, with essentially no significant local time dependence. The latitudinal cutoff at about 40° magnetic latitude is caused by the rapid increase in the electron density, hence electron plasma frequency, as the spacecraft enters the plasmasphere.

Since the continuum radiation extends down to frequencies below the propagation cutoff for the right-hand mode, it is concluded that a substantial fraction of this radiation is left-hand polarized. This result is in close agreement with the earlier results of *Gurnett and Shaw* [1973], which also showed a significant left-hand component extending below the $f_{R=0}$ cutoff frequency. The continuum radiation in Figure 1 also shows a substantial spin modulation. The phase of this spin modulation indicates that the electric field of these waves is oriented approximately parallel to the magnetic field. The spin modulation usually disappears as soon as the wave frequency exceeds the local electron gyrofrequency, which is approximately equal to the cutoff frequency for the right-hand polarized mode, $f_{R=0} \simeq f_g^-$, when $f_p^- \ll f_g^-$. These variations in the spin modulation, with sharp nulls for $f_p^- < f < f_{R=0}$, and a nearly isotropic distribution for $f > f_{R=0}$ are also consistent with the continuum radiation observations obtained in other regions of the magnetosphere (compare with Figure 11 from *Gurnett and Shaw* [1973]).

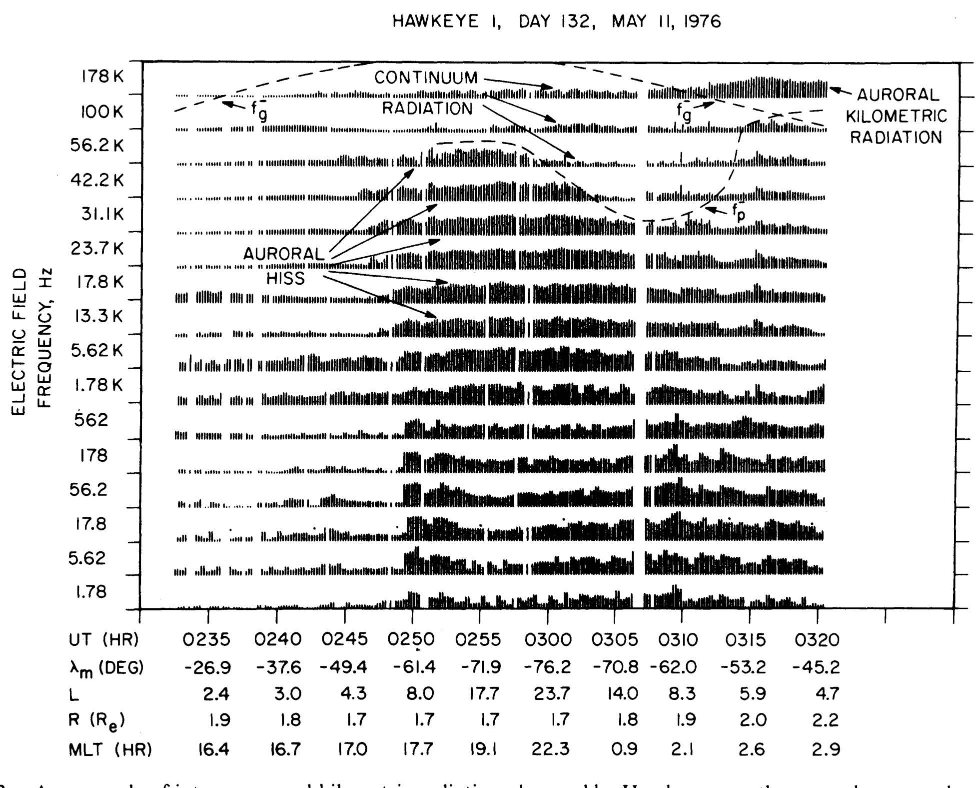

Fig. 3. An example of intense auroral kilometric radiation observed by Hawkeye over the auroral zone at about 2.0 R_E on the nightside of the earth. Note that the auroral kilometric radiation only occurs in the region where the wave frequency exceeds the local electron gyrofrequency.

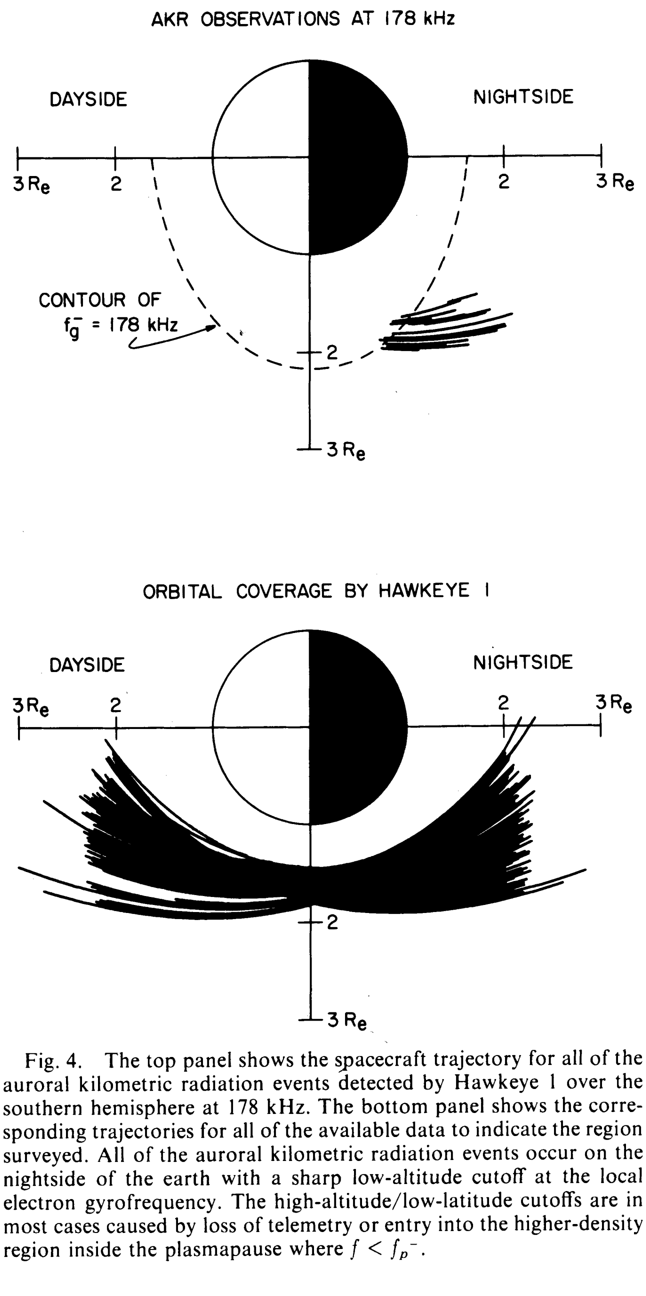

Fig. 4. The top panel shows the spacecraft trajectory for all of the auroral kilometric radiation events detected by Hawkeye 1 over the southern hemisphere at 178 kHz. The bottom panel shows the corresponding trajectories for all of the available data to indicate the region surveyed. All of the auroral kilometric radiation events occur on the nightside of the earth with a sharp low-altitude cutoff at the local electron gyrofrequency. The high-altitude/low-latitude cutoffs are in most cases caused by loss of telemetry or entry into the higher-density region inside the plasmapause where $f < f_p^-$.

AURORAL KILOMETRIC RADIATION

In addition to the relatively weak continuum radiation, intense bursts of auroral kilometric radiation are also frequently detected by Hawkeye 1 during the low-altitude passes over the southern hemisphere. An example of such an auroral kilometric radiation event is shown in Figure 3. The identification of this radiation is based on the close similarity to previous observations of auroral kilometric radiation at higher altitudes [*Gurnett*, 1974; *Kurth et al.*, 1975]. The principal identifying characteristics are the frequency range, ~100–300 kHz, the high intensity, $\sim 10^{-12}$ W m^{-2} Hz^{-1} at 178 kHz, and the large temporal fluctuations on time scales of a few minutes and longer. In contrast to the continuum radiation, which is usually observed with comparable intensities over the entire polar region, the auroral kilometric radiation is observed only on the nightside of the earth and only in regions where the wave frequency exceeds the local electron gyrofrequency. The cutoff in the auroral kilometric radiation near the electron gyrofrequency is clearly evident in Figure 3 (the electron gyrofrequency is shown by the dashed line marked f_g^-). The confinement of the auroral kilometric radiation to frequencies above the local electron gyrofrequency is, except for a few cases which are discussed later, a general feature of all of the Hawkeye 1 southern hemisphere observations. This relationship is illustrated further in Figure 4, the top panel of which shows the spacecraft trajectory for all of the auroral kilometric radiation events detected by Hawkeye 1 and the bottom panel of which shows the corresponding orbital coverage for all of the data analyzed. The spacecraft trajectories in this illustration are projected onto a plane containing the magnetic axis of the earth and the intersection of the orbital plane with the magnetic equator. The projection plane is always oriented in such a way that crossings of the magnetic equatorial plane on the dayside of the earth, from 6 to 18 hours magnetic local time, are plotted on the side marked dayside and the corresponding nightside crossings, from 18 to 6 hours magnetic local time, are on the side marked nightside. Only auroral kilometric radiation events with intensities exceeding 1.0×10^{-15} W m^{-2} Hz^{-1} are shown in the top panel. As can be seen, all of the auroral kilometric radiation events occur on the nightside of the earth. The magnetic local time dependence is illustrated in further detail by Figure 5, which shows a polar plot (magnetic latitude and local time) of the regions where the auroral kilometric radiation is observed. All of the events occur at latitudes typical of the auroral field lines. A substantial dawn-dusk asymmetry is also evident, with more events on the dawnside of the earth than in the local evening. This asymmetry disagrees with the earlier results of *Gurnett* [1974], *Kurth et al.* [1975], and *Kaiser and Stone* [1975], which place the primary source in the local evening, and is believed to be due in part to the nonuniform telemetry coverage. Because of limitations in the telemetry reception over the south pole, fewer passes were obtained in the local evening than in local morning. Also, several events in the local evening were eliminated from consideration because of difficulties in clearly dis-

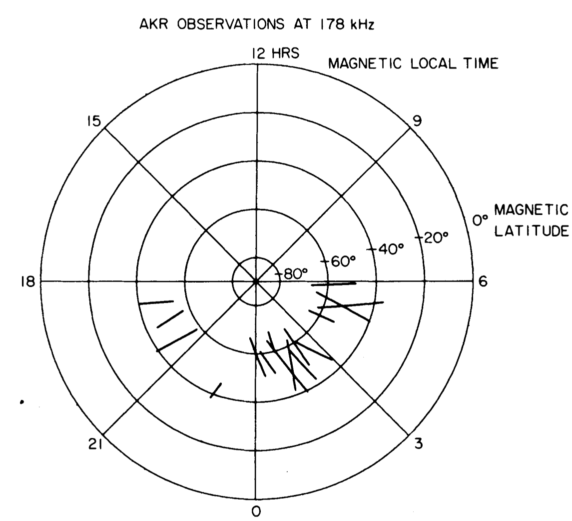

Fig. 5. The local time distribution of the events shown in Figure 4. Several events, such as those shown in Figures 7 and 8, were eliminated in the local evening region because of difficulty in distinguishing the auroral kilometric radiation from auroral hiss. The apparent high-latitude cutoff is probably strongly influenced by the trajectory, since this cutoff is primarily determined by the local electron gyrofrequency (see Figure 4). The low-latitude cutoff is caused by both telemetry loss and entry into the plasmasphere.

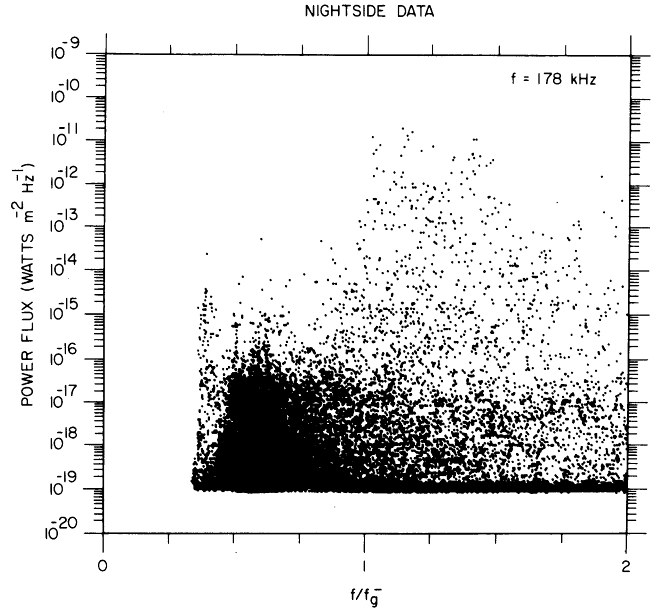

Fig. 6. A scatter diagram showing the power flux as a function of the wave frequency (178 kHz) divided by the local electron gyrofrequency. Again, passes for which the auroral hiss emissions were indistinguishable from the auroral kilometric radiation are eliminated. These data show a sharp cutoff in the auroral kilometric radiation intensity at the local electron gyrofrequency. The large number of points at intensities less than 10^{-16} W m^{-2} Hz^{-1} are caused by continuum radiation, which displays no comparable cutoff at the local electron gyrofrequency.

tinguishing the auroral kilometric radiation from auroral hiss. These events are discussed in more detail in the next section.

The spatial distribution of the auroral kilometric radiation in Figure 4 clearly shows a sharp low-altitude cutoff at a radial distance which corresponds to an electron gyrofrequency equal to the wave frequency (178 kHz). The dashed line marked 'contour of $f_g^- = 178$ kHz' is an average contour based on the measured magnetic field strengths. Although some longitudinal variations are present in the magnetic field strength, these variations do not affect the constant f_g^- contours by more than a few percent. Essentially no auroral kilometric radiation is observed at radial distances below the level where the electron gyrofrequency is equal to the wave frequency. The cutoff at the local electron gyrofrequency is illustrated in further detail by Figure 6, which shows a scatter plot of all of the available power flux measurements at 178 kHz as a function of the ratio of the wave frequency to the local electron gyrofrequency, f/f_g^-. As can be seen, all of the intense auroral kilometric radiation events occur when the local electron gyrofrequency is less than the wave frequency.

It is also of interest to compare the observed power fluxes with previous measurements at larger radial distances from the earth. From Figure 6 it is evident that the maximum power flux at low altitudes, $R \simeq 2.0\ R_E$, is approximately 10^{-11} W m^{-2} Hz^{-1}. In comparing this intensity with Figure 5 from *Gurnett* [1974] it is seen that these power fluxes are in excellent quantitative agreement with measurements at larger radial distances using a simple $1/R^2$ extrapolation. This close agreement provides substantial evidence of the near-earth origin of the intense auroral kilometric radiation, probably at radial distances less than 3.0 R_E for 178 kHz.

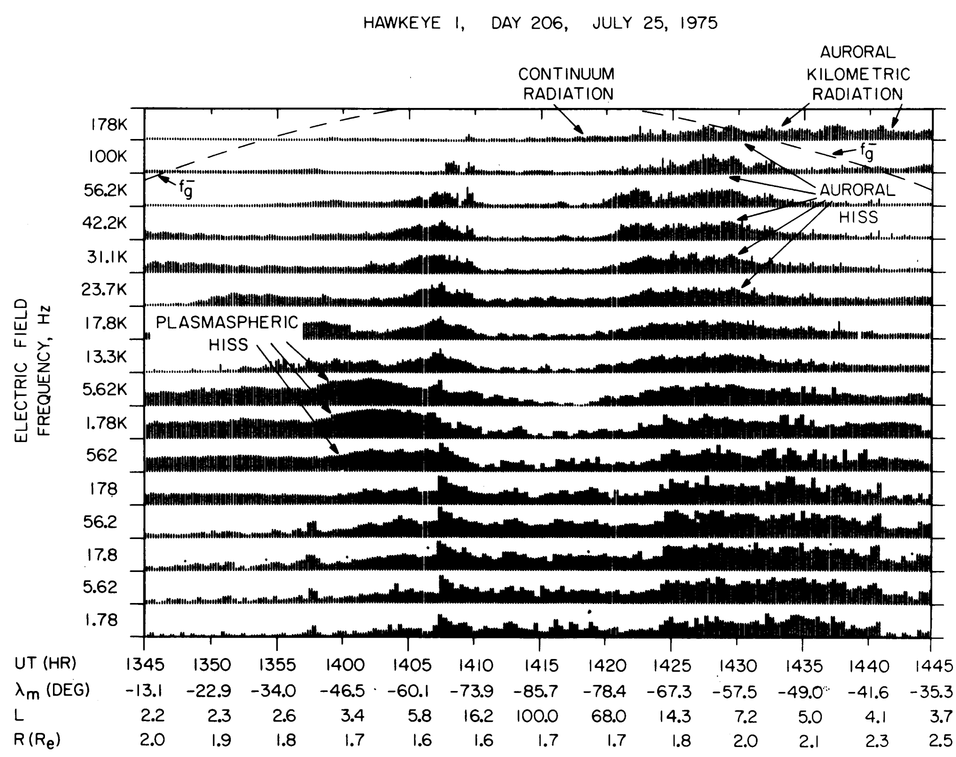

Fig. 7. An example of an event in which the auroral hiss spectrum extends essentially continuously into the auroral kilometric radiation at 178 kHz with no evidence of an evanescent (nonpropagating) region between these two types of radio emissions. Note that the radiation in the 178-kHz channel after about 1432 UT cannot be whistler mode auroral hiss, since the whistler mode cannot propagate at $f > f_g^-$. Similarly, the radiation labeled auroral hiss cannot possibly be an escaping free space mode, since this radiation extends downward to frequencies much too low (< 1 kHz) to be above the local electron plasma frequency.

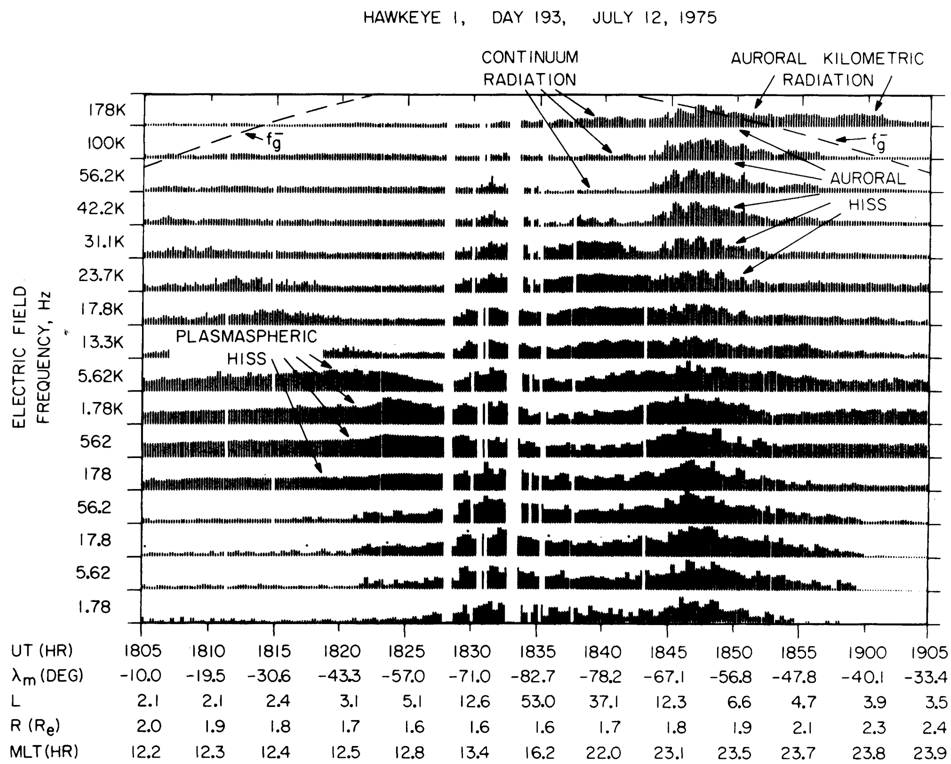

Fig. 8. Another example similar to Figure 7 illustrating the continuous extension of the auroral hiss spectrum into the auroral kilometric radiation.

Relationship Between Auroral Hiss and Auroral Kilometric Radiation

In several cases, events have been observed in the local evening which do not display the sharp low-frequency cutoff discussed in the previous section. These events have been singled out for a separate discussion, since they are unusual and appear to provide important information on the origin of the auroral kilometric radiation. Two such events are shown in Figures 7 and 8. In Figure 7 the characteristic signature of the auroral kilometric radiation is clearly evident, the radiation extending over a large region at frequencies above the electron gyrofrequency. Equatorward of the auroral zone, at about 1443 UT, a sharp low-frequency cutoff at the local electron gyrofrequency can be seen in the 100-kHz channel. However, over the auroral zone, from about 1425 to 1430 UT, the radiation appears to extend across the local electron gyrofrequency with no evidence of a sharp cutoff. In this region the auroral kilometric radiation appears to merge essentially continuously into a band of auroral hiss which extends down to frequencies as low as a few hundred hertz. The identification of this low-frequency noise as auroral hiss is based on the close similarity to previous observations of auroral hiss with low-altitude spacecraft [*Laaspere et al.*, 1971; *Gurnett and Frank*, 1972]. The main identifying characteristics of the auroral hiss are (1) the wide bandwidth, typically from a few hundred hertz to several tens of kilohertz, (2) the relatively high intensity, typically 1–10 mV m^{-1}, and (3) the occurrence in a narrow latitudinal band about 10°–15° wide over the auroral zone. The event in Figure 8 shows a similar merging of the auroral kilometric radiation spectrum with the auroral hiss spectrum. In both cases the auroral hiss and auroral kilometric radiation intensities are comparable in the region where the two spectrums appear to merge.

These events are considered unusual because according to cold plasma theory the escaping free space modes are separated from the whistler mode by an evanescent (nonpropagating) region. Since the whistler mode cannot propagate above the electron gyrofrequency and since the free space modes cannot propagate below f_p^- or $f_{R=0}$ (depending on the polarization), the broad band of radiation in Figure 7 and 8 must consist of two or more distinct plasma wave modes, even though the noise appears to extend essentially continuously from a few hundred hertz to well above the electron gyrofrequency. Unfortunately, in these cases it is usually not possible to give a reliable estimate of the local electron plasma frequency because of the absence of identifiable cutoff frequencies. However, comparison with other similar passes through the same region suggests that the plasma frequency is probably in the range 30–100 kHz.

Interpretation and Discussion

The Hawkeye 1 observations at low altitudes over the southern hemisphere have revealed several new characteristics of the intense auroral kilometric radiation generated over the earth's auroral zones. In most cases it is found that the auroral kilometric radiation has a sharply defined low-altitude cutoff at the altitude where the local electron gyrofrequency is equal to the wave frequency. A few exceptional cases occur in which a low-frequency cutoff cannot be clearly identified. In these cases the auroral kilometric radiation appears to merge essentially continuously into a band of auroral hiss which extends down to frequencies as low as a few hundred hertz. In all cases the intense (>10^{-15} W m^{-2} Hz^{-1}) auroral kilometric radiation is detected on the nightside of the earth. The maximum intensities of this radiation are consistent with source positions relatively close to the earth at radial distances of only a few

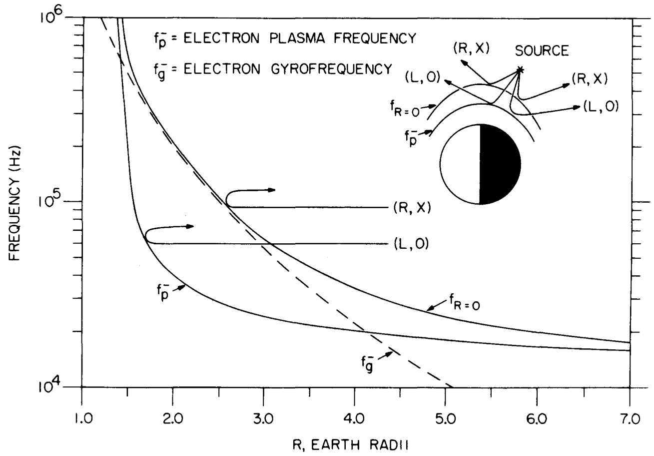

Fig. 9. A qualitative model showing the expected variations of the cutoff frequencies, f_p and $f_{R=0}$, for the left-hand (*L-O*) and right-hand (*R-X*) polarized modes of propagation as a function of radial distance. These cutoff frequencies determine the closest radial distance at which the free space electromagnetic modes can approach the earth (see the sketch of typical ray paths). If a significant downward propagating component exists, these propagation cutoffs can be used to identify the polarization of radiation emitted by a source above the ionosphere.

earth radii. Relatively weak continuum radiation emissions are also commonly detected by Hawkeye 1 over the southern polar cap. The continuum radiation usually extends downward to lower frequencies than the auroral kilometric radiation and shows no evidence of a cutoff at the local electron gyrofrequency.

To interpret these results, we first consider the possible explanations for the cutoff in the auroral kilometric radiation at the local electron gyrofrequency. Two possibilities exist. Either the cutoff is a propagation effect, or it is a characteristic of the generation mechanism. The cutoff can be most easily explained if it is a propagation effect. In all cases for which a detailed analysis can be performed, as in Figure 3, it is found that the electron plasma frequency is much smaller than the electron gyrofrequency, $f_p^- \ll f_g^-$, in the region where the cutoff is observed. Under these low-density conditions, as can be seen from (1), the propagation cutoff for the right-hand polarized mode is essentially equal to the electron gyrofrequency, $f_{R=0} \simeq f_g^-$. The correspondence of this propagation cutoff with the observed cutoff in the auroral kilometric radiation provides strong evidence that the radiation is propagating in the right-hand polarized (*R-X*) mode. This conclusion is in agreement with the earlier results of *Green et al.* [1977], which show that the right-hand mode gives the best fit to the angular distribution of the auroral kilometric radiation at large distances from the earth. A qualitative model illustrating the expected variation of the *R-X* and *L-O* cutoff frequencies with radial distance is shown in Figure 9, together with a sketch of typical ray paths near the cutoffs. The small difference between $f_{R=0}$ and f_g^- is clearly evident in the region where $f_p^- \ll f_g^-$, from about 50 to 500 kHz.

The alternative possibility, that the radiation is left-hand polarized and that the cutoff is a characteristic of the source, is much more difficult to explain and places some very stringent constraints on the generation mechanism. For the left-hand polarized mode the cutoff at f_g^- can only be explained if the radiation is emitted as an upward propagating wave at a frequency near the local electron gyrofrequency. No downward propagating component would be allowed, since this component would produce a cutoff near f_p^- (see Figure 9), similar to the continuum radiation, rather than at f_g^-. At the present time these requirements are believed to be inconsistent with all known theories for generating the auroral kilometric radiation. For example, Doppler-shifted cyclotron radiation such as proposed by *Melrose* [1976] would produce emission near f_g^- but would be in the right-hand polarized mode, since the electrons are rotating in the right-hand sense with respect to the magnetic field. Similar difficulties appear to be present in the various other mechanisms for generating the auroral kilometric radiation.

The occurrence of a few exceptional events for which the auroral kilometric radiation merges essentially continuously into a broad band of auroral hiss at lower frequencies is believed to be very important for understanding the origin of this radiation, since it appears that the spacecraft may be passing through the source region in these cases. The association of these events with the source region is necessarily somewhat subjective, since we have no way of definitely determining when the spacecraft is in the region where the radiation is being generated. However, all of these events occur over the auroral zone in the local evening, in the region where direction finding measurements [*Kurth et al.*, 1975; *Kaiser and Stone*, 1975] indicate that the most intense kilometric radiation is generated. Also, the maximum intensities observed at low altitudes are in good quantitative agreement with measurements made at larger radial distances using a simple $1/R^2$ scaling law, which indicates that the spacecraft must be in or very close to the source region.

The most general comment that can be made concerning the interpretation of these events is that the auroral kilometric radiation and auroral hiss emissions appear to be closely coupled, perhaps even generated by the same basic mechanism. At low frequencies, below f_p^- and f_g^-, it can be stated with a high degree of confidence that the auroral hiss is propagating in the whistler mode. Similarly, at high frequencies the auroral kilometric radiation must be propagating in one of the two escaping free space modes, probably in the *R-X* mode according to our earlier discussion. For propagation in a cold homogeneous plasma these modes are completely decoupled, the whistler mode being confined to the region where $f <$ min $[f_p^-, f_g^-]$ and the free space modes being confined to the regions where $f > f_p^-$ and $f > f_{R=0}$. However, the continuity of the observed spectrums across these cutoff frequencies strongly indicates that the whistler mode and the escaping free space radiation are strongly coupled. The possibilities for such mode coupling effects [see *Jones*, 1976, 1977] are so numerous and complex in the auroral plasma, with the known small-scale irregularities and hot plasma effects, that we only attempt to comment on some of the general possibilities and implications. From a viewpoint of energy flow, two general possibilities exist, depending on the direction of propagation of the auroral hiss. If the auroral hiss is propagating upward away from the earth at high altitudes, as suggested by the observations of *Gurnett and Frank* [1977], then it is possible that the auroral kilometric radiation is just auroral hiss which has escaped from the earth. This interpretation has the advantage that a well-established theory exists for generating and amplifying the auroral hiss up to high intensities [*Maggs*, 1976] but also has the difficulty that some coupling mechanism is needed to explain how the auroral hiss can propagate across the evanescent region between the whistler mode and the free space mode. If the auroral hiss is propagating downward toward the earth, as indicated by Poynting flux measurements at low altitudes [*Gurnett and Frank,* 1972], then it would appear that the auroral hiss may be directly associated with the generation of the auroral kilometric radiation, either by mode coupling of the downward propagating component of the kilometric radiation across the evanescent region or by a parametric decay process involving the simultaneous generation of both types of radiation.

These first observations in the region where the auroral kilometric radiation is believed to be generated leave many unanswered questions. Because of the difficulties in uniquely identifying the mode of propagation on the basis of the cutoff at the electron gyrofrequency, direct measurements of the polarization are still urgently needed. Measurements at slightly higher altitudes, from about 2.5 to 4.0 R_E radial distance along the auroral field lines, are also needed to completely survey the region where the radiation is believed to be generated. Continued variations in the Hawkeye 1 orbit are later expected to provide measurements in this altitude range. However, measurements with improved frequency resolution and Poynting flux determinations to establish the direction of propagation, all of which would greatly aid in the interpretation of these data, will probably not be available until the launch of the Dynamics Explorer spacecraft in 1980.

Acknowledgments. The authors wish to express their thanks to D. Jones and R. Boswell for their helpful comments and suggestions concerning the interpretation of these data. We also extend our thanks to J. A. Van Allen for the use of the Hawkeye 1 magnetic field data. The research at the University of Iowa was supported by the National Aeronautics and Space Administration through grants NGL-16-001-002 and NGL-16-001-043, through contracts NAS1-11257 and NAS1-13129 with Langley Research Center, and by the U.S. Office of Naval Research through contract N00014-76-0016.

The Editor thanks J. Alexander for his assistance in evaluating this paper.

REFERENCES

Alexander, J. K., and M. L. Kaiser, Terrestrial kilometric radiation, 1, Spatial structure studies, *J. Geophys. Res.*, *81*, 5948, 1976.

Brown, L. W., The galactic radio spectrum between 130 kHz and 2600 kHz, *Astrophys. J.*, *180*, 359, 1973.

Dunckel, N., B. Ficklin, L. Rorden, and R. A. Helliwell, Low-frequency noise observed in the distant magnetosphere with Ogo 1, *J. Geophys. Res.*, *75*, 1854, 1970.

Green, J. L., D. A. Gurnett, and S. D. Shawhan, The angular distribution of auroral kilometric radiation, *J. Geophys. Res.*, *82*, 1825, 1977.

Gurnett, D. A., The earth as a radio source: Terrestrial kilometric radiation, *J. Geophys. Res.*, *79*, 4227, 1974.

Gurnett, D. A., The earth as a radio source: The nonthermal continuum, *J. Geophys. Res.*, *80*, 2751, 1975.

Gurnett, D. A., and L. A. Frank, VLF hiss and related plasma observations in the polar magnetosphere, *J. Geophys. Res.*, *77*, 172, 1972.

Gurnett, D. A., and L. A. Frank, A region of intense plasma wave turbulence on auroral field lines, *J. Geophys. Res.*, *82*, 1031, 1977.

Gurnett, D. A., and R. R. Shaw, Electromagnetic radiation trapped in the magnetosphere above the plasma frequency, *J. Geophys. Res.*, *78*, 8136, 1973.

Jones, D., Source of terrestrial-non-thermal radiation, *Nature*, *260*, 686, 1976.

Jones, D., The second *z*-propagation window, submitted to *Nature*, 1977.

Kaiser, M. L., and R. G. Stone, Earth as an intense planetary radio source: Similarities to Jupiter and Saturn, *Science*, *189*, 285, 1975.

Kurth, W. S., M. M. Baumback, and D. A. Gurnett, Direction finding measurements of auroral kilometric radiation, *J. Geophys. Res.*, *80*, 2764, 1975.

Laaspere, T., W. C. Johnson, and L. C. Semprebon, Observations of auroral hiss, LHR noise, and other phenomena in the frequency range 20 Hz to 540 kHz on Ogo 6, *J. Geophys. Res.*, *76*, 4477, 1971.

Maggs, J. E., Coherent generation of VLF hiss, *J. Geophys. Res.*, *81*, 1707, 1976.

Melrose, D. B., An interpretation of Jupiter's decametric radiation and the terrestrial kilometric radiation as direct amplified gyroemission, *Astrophys. J.*, *207*, 651, 1976.

Stix, T. H., *The Theory of Plasma Waves*, McGraw-Hill, New York, 1962.

Torbert, R. B., F. S. Mozer, S. von Glinski, and M. Temerin, Observations of the local plasma density below 8000 km on the S3-3 satellite (abstract), *Eos Trans. AGU*, *58*, 1214, 1977.

(Received August 8, 1977;
accepted September 9, 1977.)