Abstract. Certain discrete, intense wave signals attributed to auroral kilometric radiation (AKR) were observed with ISEE-1 while it was within the plasmaspheric shadow zone for direct propagation. It is believed that wave ducting by thin depletions of the plasma density aligned with the magnetic field accounts for such signals, and that their discrete nature is caused by the satellite intercepting individual ducts. These ducts, which were also observed as coincident decreases of the upper-hybrid resonance frequency, appeared to be twenty-percent depletions roughly one hundred kilometers across. The AKR, which is emitted approximately perpendicular to the magnetic field, apparently entered these ducts equatorward of the source after the waves had been refracted parallel to the duct axis. A diffuse background was also observed which is consistent with the leakage from similar ducts at lower L-values. These observations establish the existence of ducted AKR, its signature on the satellite wave spectrograms, and new evidence for depletion ducts within the plasmasphere.

INTRODUCTION
A duct consists of an elongated region of enhanced refractive index which is capable of guiding waves by total internal reflection. As with the optical fibers used to guide light waves, the natural ducts which occur in the Earth's plasmasphere can sometimes guide radio waves over great distances and produce exceptionally strong signals at remote locations. If the duct is also curved and extends into a shadow zone, it can produce wave signals at locations inaccessible to line-of-sight propagation. The ISEE-1 satellite observations to be presented below are of this sort, suggesting that auroral kilometric radiation (abbreviated AKR) can be guided along plasma depletion ducts parallel to the geomagnetic field and reach the equatorial regions which are otherwise inaccessible.

Ducting was originally proposed more than fifty years ago to explain long-delayed radio echoes [Pederson, 1969], and this still remains a viable explanation [Muldrew, 1979; Villard et al., 1980]. Meanwhile, the existence of plasma-density depletion ducts aligned with the magnetic field was established in the ionosphere [Calvert et al., 1968] and plasmasphere [Muldrew, 1983; Loftus et al., 1986] using the topside sounder rockets and satellites. Concurrently, it was found that similar enhancement ducts were required to explain the lightning whistlers observed on the ground [Helliwell, 1965; Carpenter, 1988] and some of those observed in space [Smith and Angerami, 1968].

The difference between depletion and enhancement ducts stems from the different behavior of the refractive index for the waves involved. For the extraordinary and ordinary waves guided by depletion ducts, the refractive index is convex along the magnetic axis and its magnitude decreases with increasing plasma density. It can be shown that this is sufficient for ducting by a density minimum. For the pertinent whistler waves (below half the cyclotron frequency) the refractive index is also convex, but it increases with density, and hence ducting requires a density maximum.

The whistler observations thus far have established the existence of enhancement ducts throughout the plasmasphere and out to beyond eight earth radii in the magnetosphere [Carpenter, 1983; 1981]. However, because of the low altitude of the topside-sounder satellites and the need for lower frequencies than can be launched within the ionosphere, it was not possible to examine conjugate depletion ducts beyond L-values of about 2.8 in the plasmasphere [Loftus et al., 1968]. Up to this limit, the depletion ducts were found to be a ubiquitous feature, more or less uniformly distributed and occupying about one percent of the volume. At higher latitudes, and especially in the auroral zone, local ionospheric ducts were commonly observed, but it could not be established whether they extended to much greater altitudes. Although it consists of a single case, the new ISEE-1 observations reported here extend the range of observable depletion ducts out to four earth radii and demonstrate that they are capable of guiding the extraordinary-mode waves of auroral kilometric radiation.

Although the previous studies of depletion ducts all relied upon the ducted echoes produced by topside sounders, the new observations depend instead upon the natural signals of AKR. Such signals have received considerable attention [Gurnett, 1974; Kurth et al., 1975; Green et al., 1977; Kaiser and Alexander, 1977; Gurnett and Green, 1978; Kaiser et al., 1978; Benson and Calvert, 1979; Gallagher and Gurnett, 1979; Calvert, 1981a; 1981b], from which the following picture of the AKR source has evolved: AKR consists of extraordinary-mode waves at frequencies of 50-70 kilohertz which originate in the auroral zone near 70° invariant magnetic latitude. It is produced just above wave cutoff (both in frequency and spatially) and hence, because of the low source plasma density, at frequencies quite near the local cyclotron frequency. This implies that the source at different frequencies is distributed in geocentric altitude between 1.3 and 3.3 earth radii. Although the AKR is emitted approximately perpendicular to the magnetic field, the local wave refraction distributes it into a range of upward directions so that, from a distance, it appears to radiate from a point or line. Most pertinent for the current purposes is that AKR constitutes a natural wave source at locations sufficiently well known to permit the interpretation of the signals received by ISEE-1 and attributed to ducting.

OBSERVATIONS
The upper panel of figure 1 is a spectrogram produced using the ISEE-1 wave receiver [Gurnett et al., 1978]. It shows the stronger wave signals as darker areas, with approximately six percent frequency resolution and 38 seconds time resolution, for a fifty minute period beginning at 0300 UT on 28 June 1979. The satellite was traveling inward at the time, from a geocentric distance (R/RL) of 4.59 to 2.58, at a southern magnetic latitude (MLAT) which varied from 10.3° to 23.0°, and at a magnetic local time (MLT) which varied from 21.8 hours to nearly midnight. The satellite was thus in the evening sector, usually propitious for the observation of AKR, but at low magnetic latitudes and relatively close in.

The spectrogram shows the signal enhancement commonly observed near the local upper hybrid resonance frequency [Kurth et al., 1979], extending diagonally across the record from 50 kHz at 0300 UT to 240 kHz at 0350 UT. Since the cyclotron frequency was substantially lower than this (varying from 10 to 70 kHz), the enhancement represents the approximate plasma frequency, shown sketched in lower panel and labeled $f_{ci}$. It indicates that the plasma density increased from around 30 cm$^{-3}$ to over 700 cm$^{-3}$ as the satellite passed inward through a ragged plasmapause during this period.

Also shown in the lower panel of figure 1 are the pertinent AKR features which suggested ducting. These consist of intense discrete signals, usually confined to a single sweep of the receiver, extending from roughly ten percent above the plasma frequency to sometimes twice that frequency. Between
Fig. 1. An ISEE-1 spectrogram showing ducted AKR in the plasmaspheric shadow. The discrete signals are attributed to encounters with individual depletion ducts, also visible as brief decreases of the plasma frequency \( f_s \), and the diffuse background is attributed to the leakage from similar ducts at lower L-values.

0310 and 0321 UT and again at 0342 UT, these signals were strong enough to saturate the instrument and produce the artificial darkening which extends down to the 50 kHz band limit and obscures somewhat the upper-hybrid enhancements during these times. Also associated with these signals are the strong diffuse signals extending upward from twenty percent above the plasma frequency to the top of the record. Since both components are quite strong (typically exceeding \( 10^{-16} \text{ w/m}^2\text{Hz} \)) and occur up to 400 kHz, it is believed that they can be attributed to AKR. Furthermore, these signals exhibited the appearance usually associated with AKR, especially at the higher frequencies (200-400 kHz) and extending for nearly an hour before this segment was recorded.

However, if the discrete and diffuse signals in figure 1 are to be attributed to AKR, it is necessary to explain how they reached the satellite, in view of the equatorial shadow zone for AKR reported by Gurnett [1974]. This shadow zone is illustrated in figure 2, which shows the orbit of ISEE-1 and the presumed source locations for AKR at 100, 200, and 400 kilohertz. Also shown in figure 2 are the hypothetical plasma-frequency contours, deduced from figure 1 on the assumption that the plasma density was constant along dipole field lines, and the approximate ray paths for AKR at 200 kHz. These ray paths were drawn as straight lines, reflected where they encountered the contours at the appropriate angles for oblique reflection, neglecting the influence of the magnetic field. This admittedly crude construction is sufficient to establish that ISEE-1 was indeed in the shadow zone, since the neglected factors would only serve to enhance the refraction and produce a larger shadow. For instance, the expected density increase inward along the magnetic field would produce larger plasma densities at the reflection point, whereas with magnetic effects the extraordinary waves would be reflected at lesser densities. Both factors would move the reflection points closer to the source and thereby enlarge the shadow zone.

The remarkable aspect of figure 1 is thus that the signals attributed to AKR are observable in the shadow zone which is produced by plasmaspheric refraction. At the same time, those signals exhibit unusual behavior, in that they consist of discrete, frequency-limited bursts superimposed on a diffuse background. It also should be noted that the discrete signals tend to coincide with decreases of the local plasma density, as indicated by downward excursions of the upper hybrid resonance signals (e.g., the three dips near 0327 UT).

**DUCT MODEL**

An unusual propagation effect is the most plausible explanation for the observed signals. Otherwise it would be necessary
to either postulate an entirely new radiation source or to abandon our previous conclusions about the AKR source location. Alternatively, it was proposed by H. Oya (in a paper presented to the URSI General Assembly, 1981) that such signals, which are also observed with the Jikinen satellite (EXOS-B), could be explained by sudden contractions of the plasmasphere and the consequent contraction of the shadow zone. However, for the case presented here, this would require that the 50 kHz contour retreat to at least $L=3.5$ (that is, roughly to where the 200 kHz contour lies in figure 2) in order to explain the 200 kHz discrete signals at 0330 UT, and the consequent 4:1 density drop at the satellite (to $n_s < 50$ kHz) was not observed. Furthermore, it would be surprising for the plasmasphere to contract so much in less than a minute (to explain the brevity of the discrete signals) and then return exactly to its previous size.

Of the other possible propagation effects, the guidance around the plasmasphere in field-aligned depletion ducts appears most likely. The requisite plasma densities for a specular reflection high above the auroral zone or polar cap (a few hundred per cubic centimeter) have not been observed, nor is there reason to expect the upward gradients they would imply. Although the aspect-sensitive scattering of waves by field-aligned auroral irregularities is well established [see Davies, 1965], and the geometry would be appropriate for the AKR waves after their plasmaspheric reflection, scattering is unlikely to produce the discrete behavior which was observed. This discrete behavior, on the other hand, is easily explained by ducting and the satellite traversing individual ducts. On the assumption that the ducts were populated with AKR wave energy elsewhere, the discrete signals would correspond to waves still being ducted and unobservable outside of the ducts. This interpretation is clearly consistent with the observation of coincident plasma depletions and the conclusion that those depletions are the individual ducts. (This case, incidentally, is the first one ever found by the author where the duct and the ducted wave were both simultaneously detected.)

However, it is difficult to imagine the AKR waves entering ducts quite near the source, since the waves originate with large wave normal angles to the magnetic field in a region of quite low plasma density [Benson and Calvert, 1979; Calvert, 1981b], and both of these factors would tend to preclude ducting. Furthermore, if the AKR had entered such ducts it would have produced ducted signals at higher $L$-values than those observed. Instead, the AKR must have entered the duct at lower latitudes, where the ambient plasma density was greater and the wave refraction was sufficient to bend the wave normals parallel to the magnetic field. This phenomenon, of remote duct entry after refraction to parallelism, was well established in the topside-sounder duct studies [Calvert et al., 1962; Muldrew, 1969], where it was designated "combination-mode." It accounts for much of the spread-F (i.e., the "frequency-spreading") observed with both topside sounders and ground ionosondes [Calvert and Schmid, 1964; Fitteway and Cohen, 1961], and it appears to be a quite common radio effect in irregular magnetoplasmas.

The remote, combination-mode entry of AKR into the plasmaspheric ducts is illustrated schematically in figure 3. The ray paths at 200 and 100 kHz are shown entering the same duct, the latter having to approach the duct at a steeper angle to penetrate to the same level. At lower frequencies the waves would eventually be unable to reach the duct and this, plus the expected outward decrease of plasma density, explains why the discrete ducted signals in figure 1 begin somewhat above the local plasma frequency. At higher frequencies the refraction will eventually become insufficient to achieve parallelism, and this accounts for the upper limit to such signals.

The ducting explanation could also account for the diffuse background signals in figure 1. The AKR which illuminates the plasmasphere presumably populates many of the ducts in the magnetic meridian with some wave energy, and those lying deeper in the plasmasphere with the waves at higher frequencies. Since those ducts extend into regions of lower plasma density and magnetic field strength, and hence into regions of less efficient ducting, they may be expected to release part of the ducted energy by leakage, as is illustrated in figure 3 at 400 kHz. The accumulated leakage from all the ducts at lower $L$-values would, of course, combine to produce a smooth background signal, largely unaffected by the local plasma conditions. On the other hand, it would be difficult to distinguish this from a diffuse background produced by auroral scatter, and the former is favored primarily because it leads to a common explanation for both features.

If the discrete signals correspond to duct encounters, then their duration should indicate the duct width. Since the discrete signals tend to occupy single sweeps of the instrument, this width must be comparable to or less than the orbital distance covered during the 32 seconds required for a sweep. This distance was approximately 180 kilometers (150 km radially and 100 km in longitude). On the other hand, the signal samples were acquired sequentially during a sweep, from 50 to 400 kHz, and the discrete signals existed for an appreciable fraction of this period, varying from one-tenth to one-half (see figure 1). This implies a width of at least 20-90 km. It was therefore estimated that the duct width was roughly 100 kilometers. It is also possible to estimate the duct depth from the local density depletions associated with the discrete signals and

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**Fig. 2.** An illustration of how the equatorial shadow for AKR at 200 kHz is produced at the orbit of ISEE-1. The plasma frequency contours ($f_n$) were extrapolated along the appropriate dipole field lines and the ray paths from the assumed source location were drawn with the appropriate reflection angles, neglecting magnetic effects.

**Fig. 3.** A schematic illustration of ducted AKR, showing the waves between 100 and 200 kHz entering a duct equatorward of the source to produce a discrete encounter signal at ISEE-1, and those at 400 kHz leaking from a different duct to produce the diffuse background.
interpreted as the individual duct encounters. Since the fractional variation of plasma density is approximately twice that of the plasma frequency, the ten percent dips in figure 1 suggest that the duct depletions were roughly twenty percent.

CONCLUSIONS
An ISEE-1 spectrogram was analyzed, for which the satellite was in the plasmaspheric shadow zone for auroral kilometric radiation. Nonetheless, AKR signals were received as discrete, intense, band-limited bursts superimposed on a diffuse background, and it is proposed that the wave ducting in magnetic-field-aligned density depletions can account for this behavior. Although the AKR waves are unlikely to become ducted near the source, since the background density is quite low and the wave angles are wrong, they could have entered ducts in the plasmasphere a few thousand kilometers equatorward of the source, where the density was greater and the wave normals could have been refracted parallel to the magnetic field. The intense bursts are then explained by the satellite traversing individual ducts, and the diffuse background is explained by the leakage from similar ducts at lower L-values. The individual ducts were also visible on the spectrogram as brief, coincident decreases of the upper hybrid enhancement frequency, which indicated density depletions of roughly twenty percent. Finally, the duration of the discrete ducted AKR signals on the spectrograms indicated that the width of the ducts was around one hundred kilometers.

This observation is also a striking example of how ducting may affect the pattern of waves received in a magnetoplasma by producing strong signals at unexpected locations. It establishes the existence of depletion ducts in the outer plasmasphere, where they had not been detected previously. It further demonstrates that AKR may become ducted and it establishes the spectrogram signature which is produced by ducted AKR, namely, discrete intense encounter signals superimposed on a diffuse leakage background. The knowledge of that signature will undoubtedly benefit future studies to search for depletion ducts elsewhere and determine their frequency of occurrence.

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REFERENCES


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