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The Polarization of Escaping Terrestrial Continuum Radiation

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Plasma wave measurements from the DE 1 (Dynamics Explorer 1) spacecraft are used to determine the polarization of an escaping terrestrial continuum radiation event that occurred on March 2, 1982. The source of the radiation was determined by direction finding to be located near the magnetic equator on the nightside of the Earth at a radial distance of about 2.8–3.5 R_E. The radiation was emitted in two meridional beams, one north and the other south of the magnetic equator. Polarization measurements using the two orthogonal electric antennas on DE 1 show that the radiation is right-hand polarized with respect to an outward directed *E* plane normal in the northern hemisphere and left-hand polarized in the southern hemisphere. Comparisons with the local magnetic field show that both the northern and southern hemisphere beams are propagating in the *L-O* mode at the spacecraft. The mode of propagation has also been confirmed using measurements of the *E* plane normal angle and ellipse ratio. Because the angle between the magnetic field and the *E* plane normal rotates through perpendicular as the radiation propagated from the source to the spacecraft, mode coupling effects must be evaluated when considering the mode of propagation in the source. Estimates of the spatial gradients over the $\sim$1-R_E distance between the source and the spacecraft indicate that the radiation has not reached the region of limiting polarization. Therefore the mode of propagation must be the same at the source and at the spacecraft: i.e., the *L-O* mode. These observations support the linear conversion model of Jones in which the radiation is produced by coupling from intense upper hybrid resonance emissions near the plasmapause. This conversion mechanism predicts that continuum radiation generated in the vicinity of the plasmapause should be emitted primarily in the *L-O* mode. Remote-sensing analyses based on Jones' model yield source locations in agreement with those derived by the direction-finding method.

INTRODUCTION

For many years it has been known that an unusual type of low-intensity radio emission is generated in the vicinity of the Earth's plasmapause at frequencies from about 30 to 100 kHz. This radio emission was first reported by *Brown* [1973] and later studied in detail by *Gurnett* [1975] and *Gurnett and Frank* [1976], who called the radiation escaping continuum radiation. The term "continuum" was used because it was thought that the radiation is similar to a quasi-continuous broadband emission called continuum radiation that is trapped in the low-density magnetospheric cavity at frequencies below the solar wind plasma frequency [*Gurnett and Shaw*, 1973]. The term "escaping" was used because the radiation usually occurs at frequencies above the solar wind plasma frequency, $\sim$30 kHz, where the radiation can freely escape from the Earth. The broadband character of the radiation was later called into question by *Kurth et al.* [1981], who showed that the spectrum is not always continuous, but instead consists of many narrow-band components. Although the frequency spectrum shows considerable narrow-band structure, the temporal variations are usually smooth and continuous with fluctuations typically on time scales of tens of minutes or longer.

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Strong evidence now exists that the escaping continuum radiation is produced as a by-product of intense electrostatic upper hybrid resonance (UHR) waves that occur near the magnetic equator [*Gurnett*, 1975; *Gurnett and Frank*, 1976; *Christiansen et al.*, 1978; *Rönnmark et al.*, 1978; *Gough et al.*, 1979; *Kurth et al.*, 1981]. Several theories, both linear and nonlinear, have been advanced to explain the conversion of the locally generated UHR waves into escaping electromagnetic radiation. For a review of the conversion mechanisms, see *Melrose* [1981] and *Barbosa* [1982]. The leading linear conversion mechanism was proposed by *Jones* [1976] and has been refined by a series of papers [*Jones*, 1980, 1981*a*, *b*, 1982], in which specific predictions are made regarding the beaming of the radiation and the mode of propagation. Jones also prefers to call this radiation terrestrial myriametric radiation (TMR), on the grounds that the wavelength is in the 10-km range and the spectrum is not continuous. In Jones' model the upper hybrid (*Z* mode) waves are converted to escaping left-hand polarized ordinary (*L-O*) mode waves via a mode conversion process called the "radio window" [*Budden*, 1961]. The nonlinear mechanisms typically involve an interaction between two or more electrostatic waves. For example, the high-frequency UHR waves can interact with a low-frequency mode such as a lower hybrid wave or an ion cyclotron wave, to produce radiation at the sum of the frequencies of the two modes.

The linear conversion mechanism of Jones provides two predictions that can be easily tested. First, the radiation is expected to be beamed outward in two meridional beams at angles of $\gamma = \pm\arctan(f_c/f_p)^{1/2}$ with respect to the magnetic equator, where f_p and f_c are the electron plasma frequency and cyclotron frequency. Second, for a source located near the plasmapause the radiation should be generated primarily in the left-hand polarized, ordinary (*L-O*) mode. The first prediction was investigated by *Jones et al.* [1987] with good agreement between theory and observations. The main purpose of this paper is to use data from the Dynamics Explorer 1 (DE 1) spacecraft to investigate the second prediction, which is that the radiation is generated in the *L-O* mode.

The DE 1 spacecraft, which is in an eccentric polar orbit with perigee and apogee geocentric radial distances of 1.09 and 4.65 R_E, is in an ideal orbit to study the escaping continuum radiation, since it provides frequent passes through the equatorial region just outside the plasmapause. Three methods are used to determine the mode of propagation. The first relies on direct polarization measurements, the second uses measurments of the plane of rotation of the electric field (the *E* plane), and the third involves measurements of the ellipticity of the electric field. The results from each of these techniques are presented in the following sections.

POLARIZATION MEASUREMENTS

Two orthogonal electric antennas are used on DE 1 to provide polarization measurements. These antennas consist of a short 9.0-m tip-to-tip electric dipole (E_z) mounted parallel to the spin axis and a long 200-m tip-to-tip electric dipole (E_x) mounted perpendicular to the spin axis. In the normal mode of operation the spin axis is oriented perpendicular to the orbital plane. The relative phase and amplitude of the signals from the two antennas are measured by a sweep frequency correlator that provides one frequency scan from 2 Hz to 400 kHz every 32 s. For a description of the DE 1 plasma wave instrumentation, see *Shawhan et al.* [1982], and for a description of the procedure used to analyze the polarization, see *Calvert* [1985].

Because the argument of perigee advances at a rate of 108° per year, opportunities for studying the escaping continuum radiation occur every 1.67 years, when the apogee is near the equator. During the period for which we have data, from August 1981 to December 1983, about a dozen fairly intense continuum radiation "storms" have been identified in the DE 1 data. These storms typically last for 1–2 days and involve signal intensities up to 20 dB above the receiver noise level. Although we have several events available for study, the polarization has proved to be extremely difficult to measure. The reason is that in most cases the intensities are too low to be detected by the relatively short E_z antenna. Because of its shorter length, the E_z antenna is a factor of 35 dB less sensitive than the E_x antenna. After a careful search, only one event has been found with E_z intensities sufficiently high to provide reliable polarization measurements. This event occurred on March 2, 1982.

A spectrogram of the continuum radiation event that occurred on March 2, 1982, is shown in the top panel of Plate 1. The continuum radiation in this case consists of two distinct bands. The first band, which extends from about 70 to 120 kHz, starts at about 1500 UT and ends at about 1540 UT, just before the northbound magnetic equator crossing, which occurs at 1543 UT. The second band, which extends from about 55 to 80 kHz, starts at about 1545 UT, shortly after the equator crossing, and ends at about 1605 UT. The intense burst of noise extending across all frequencies from 1542 to 1545 UT is caused by intense electrostatic emissions at the upper hybrid frequency and near half-harmonics of the electron cyclotron frequency. These intense emissions cause nonlinear distortion in the receiver, thereby producing the broad band of noise on the spectrogram. The band of impulsive noise extending from 1450 to 1545 UT with a sharp upper cutoff at about 55 kHz is also caused by receiver distortion effects. In this case the noise is caused by intense whistler mode emissions at lower frequencies. The receiver distortion effects all appear somewhat exaggerated because the intensity scale has been expanded to show the very weak continuum radiation.

A spectrogram showing the polarization of the March 2, 1982, event is included in the bottom panel of Plate 1. The polarization is determined by measuring the relative phase of the signals from the two antennas when the E_x antenna rotates to within $\pm 60°$ of perpendicular to the local vertical. Since the E_z antenna always responds to the east-west field and the E_x antenna at this phase of the rotation responds primarily to the north-south field, the phase gives the sense of rotation of the electric field in the local horizontal plane. The coding on the spectrogram is such that red represents left-hand rotation with respect to the radius vector **R**, from the center of the Earth to the spacecraft and green represents right-hand rotation. As can be seen, the polarization of the continuum radiation in the southern hemisphere is red, indicating left-hand rotation with respect to **R**, and the polarization in the northern hemisphere is green, indicating right-hand rotation with respect to **R**.

In addition to the polarization, the electric field measurements can also be processed to give information on the direction of arrival. Direction of arrival measurements rely on the fact that in the absence of plasma effects (i.e., free space conditions) the wave vector is perpendicular to the plane of rotation of the electric field (the *E* plane). For the moment we will assume that free space conditions apply. The effect of the plasma on the tilt of the *E* plane with respect to the wave vector will be discussed later. Two methods can be used to determine the orientation of the *E* plane. For source locations near the meridian plane, which is what one expects on the basis of Jones' model, the direction of arrival can be simply obtained from the spin modulation of the E_x antenna signal. The fitting procedure used to obtain the direction of arrival in this case is described by *Kurth et al.* [1975]. For source locations away from the meridian plane the direction of arrival can be obtained in two dimensions using the more elaborate fitting procedure described by *Calvert* [1985], which uses the relative phase between the E_z and E_x signals. We will use both of these techniques to analyze the March 2, 1982, event.

The directions of arrival obtained from an analysis of the E_x spin modulation are shown in Figure 1. The spacecraft trajectory in this diagram is plotted in magnetic latitude and geocentric radial distance coordinates. The line drawn from each dot represents the direction of arrival averaged over a 5-min interval centered on the dot. A frequency range of 71.4–113.7 kHz was used for analyzing data from the southern hemisphere, and 62.4–89.8 kHz was used for the northern hemisphere. As can be seen, the radiation appears to originate from near the magnetic equatorial plane. In the southern hemisphere the source appears to be at a radial distance of about 3.0 R_E, and in the northern hemisphere the source appears to

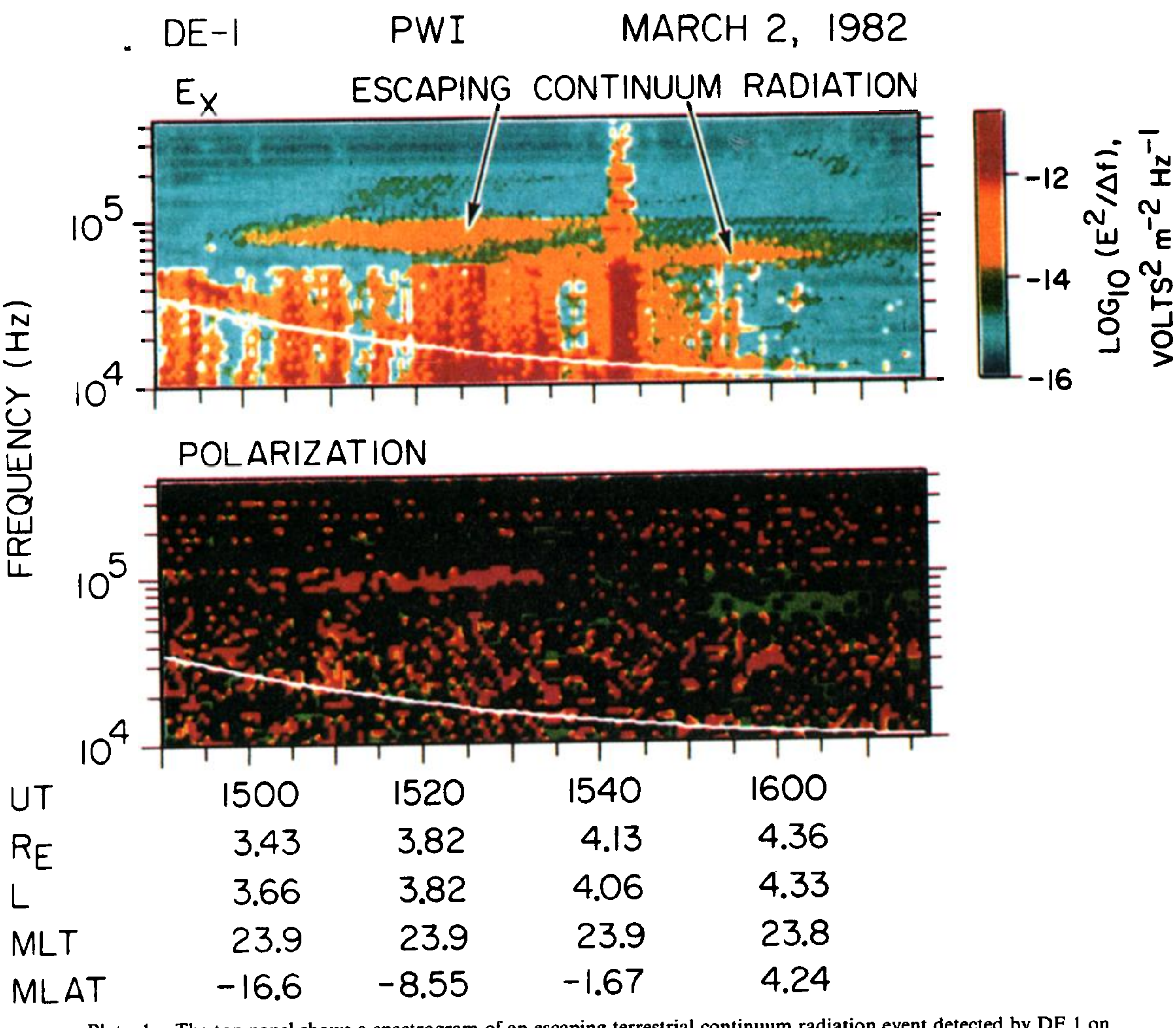

Plate 1. The top panel shows a spectrogram of an escaping terrestrial continuum radiation event detected by DE 1 on March 2, 1982. The bottom panel shows that the radiation is right-hand polarized (red) with respect to the radius vector from the Earth to the spacecraft in the southern hemisphere, before 1543 UT, and left-hand polarized (green) in the northern hemisphere, after 1543 UT. The white line indicates the local electron cyclotron frequency.

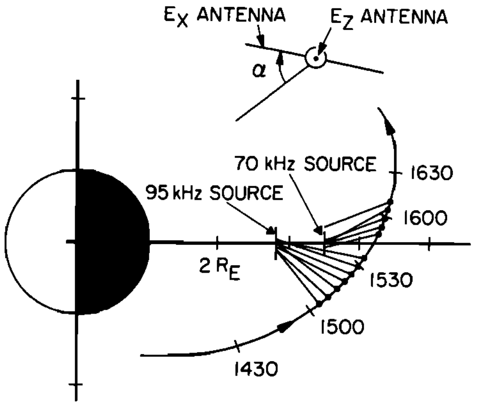

Fig. 1. The spacecraft trajectory in the magnetic meridian plane for the March 2, 1982, event. The lines show the direction of arrival determined using spin modulation measurements from the E_x antenna. The spacecraft spin axis is perpendicular to the orbital plane and parallel to the E_z antenna axis. The arcs through the equatorial plane at $L \simeq 2.85$ and $L \simeq 3.54$ indicate the source locations determined using *Jones*' [1981*b*, 1983] remote-sensing method.

be at a radial distance of about 3.5 R_E. According to currently accepted ideas, the continuum radiation is generated by equatorial upper hybrid waves, which tend to be most intense when $f_{UHR} \simeq (n + 1/2)f_c$. Using the remote-sensing technique described by *Jones* [1981*b*, 1983], it can be shown that the 70- to 120-kHz source is located at $L \simeq 2.85$ where $f_{UHR} \simeq (5/2)f_c$, and the 55- to 80-kHz source is located at $L \simeq 3.54$ where $f_{UHR} \simeq (7/2)f_c$. These source positions are indicated by the short arcs marked "70 kHz source" and "95 kHz source" in Figure 1. The downward frequency shift and the change in the source position suggest that the source may have moved outward away from the Earth during the time between the observations. Other possible explanations could also include north-south or longitudinal asymmetries in the beaming geometry.

The position of the source transverse to the meridian plane can be obtained using the two-dimensional direction-finding procedure described by *Calvert* [1985]. This procedure relies on measurements of the relative phase ϕ, between the E_x and E_z signals, as a function of the roll angle α of the E_x antenna (see Figure 1). The plot of ϕ versus α has a characteristic shape that depends on both the polarization and direction of arrival. Two such plots are shown in Figure 2. These plots were selected for times when the signal from the short E_z antenna is sufficiently large to provide a reliable fit. The dots show the measured values, and the solid line shows the best fit to the theoretical dependence, which is given by [*Calvert*, 1985]

$$\cot \phi = \left(\frac{\sin \delta_0}{b}\right) \cot (\alpha - \alpha_0) + \frac{a}{b} \qquad (1)$$

The quantities a and b give the principal axis orientation and ellipticity of the electric field, and the quantities α_0 and δ_0 give the in-plane and out-of-plane angles of the E plane normal. Since the E plane normal can be in either of two directions, we will assume that the E plane normal is directed away from the Earth, so that it is consistent with a wave propagating away from the Earth.

As can be seen in Figure 2, the phase pattern is very close to a square wave, with the phase switching back and forth between 90° and 270°. The square wave pattern indicates that the source is very close to the meridian plane. The out-of-plane angle δ_0 is determined by the parameter $\sin \delta_0/b$, which is given by the fitting procedure. To evaluate δ_0, one must determine the ellipse ratio b. For a circularly polarized wave, $b = 1$. As will be described in the next section, we estimate that $b \simeq 1.54$. For the southern hemisphere case, at the bottom of Figure 2, the fitting procedure gives $\sin \delta_0/b = 0.1$, so $\delta_0 \simeq 9°$. For the northern hemisphere case, at the top of Figure 2, the fitting procedure gives $\sin \delta_0/b = 0.0$, so $\delta_0 \simeq 0°$. It is clear that the source is located very close to the meridian plane. The in-plane angles in both cases are within 1°–2° of the arrival directions obtained from the E_x spin modulation analysis, thereby providing an independent check on the overall accuracy of the procedure.

The phase plots in Figure 2 also show the change in polarization from the northern to southern hemisphere. At a fixed roll angle, for example, $\alpha = 90°$, the phase is $\phi \simeq 90°$ in the northern hemisphere and $\phi \simeq 270°$ in the southern hemisphere. This phase corresponds to left-hand polarization with respect to an outward directed E plane normal in the southern hemisphere and right-hand polarization in the northern hemisphere. These results are summarized in Figure 3, which shows the approximate source geometry and the polarization with respect to the E plane normal.

Having established the polarization with respect to the E plane normal, we next consider the mode of propagation. Ac-

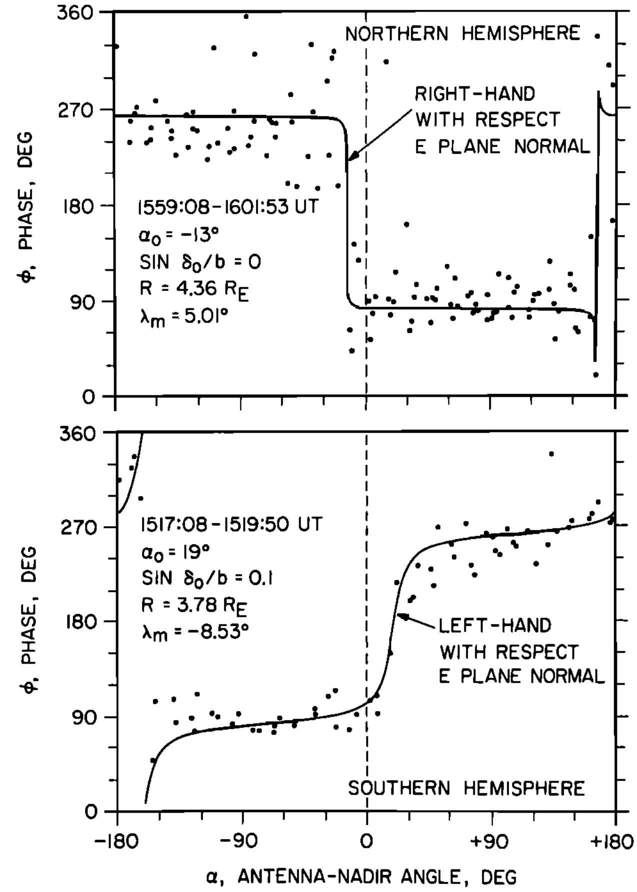

Fig. 2. Plots of the relative phase ϕ between the E_x and E_z signals as a function of the spacecraft rotation. The solid curve is a best fit to the theoretical phase function. The top panel, from the northern hemisphere, has a phase variation characteristic of a right-hand polarized wave, and the bottom panel, from the southern hemisphere, has a phase variation characteristic of a left-hand polarized wave. The polarization is referenced to an E plane normal that is directed outward, away from the Earth.

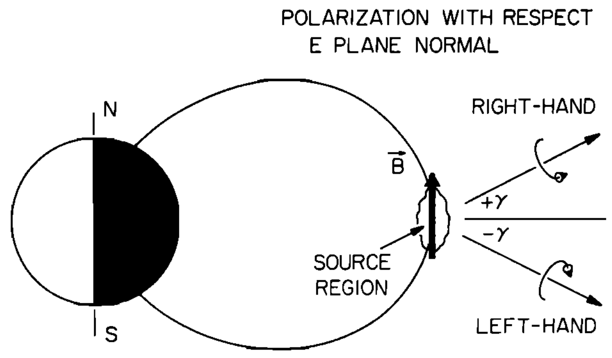

Fig. 3. A sketch showing the source region, direction of propagation, and polarization with respect to the E plane normal. *Jones'* [1981*a*] theory predicts that the radiation should be beamed outward at an angle relative to the magnetic equator of $\pm\gamma$, in good qualitative agreement with the direction-finding measurements in Figure 1.

cording to the usual plasma convention [*Stix*, 1962], the modes of propagation of the two free space modes are labeled *R-X* and *L-O*. The *R* and *L* labels stand for the sense of polarization (right and left) with respect to the static magnetic field, and the *X* and *O* labels stand for the type of propagation perpendicular to the magnetic field (extraordinary and ordinary). To determine the mode of propagation from the polarization, we must compare the E plane orientation to the magnetic field direction. Since the magnetic field is nearly perpendicular to the E plane normal, magnetic field measurements from the magnetometer have been used to provide a precise determination of the angle between the magnetic field and the E plane normal. See *Farthing et al.* [1981] for a description of the DE 1 magnetometer. The results of this comparison are shown in Table 1. The angles α_0 and α_B give the directions of the E plane normal and the magnetic field projected onto the spin plane. These angles are measured with respect to the nadir, with the positive direction defined as shown in Figure 1. To evaluate the sense of rotation of the wave electric field with respect to the magnetic field (*R* or *L*), the crucial parameter is the angle θ' between the E plane normal and the magetic field direction. Since both the E plane normal and the magnetic field are within a few degrees of the spin plane, to a very good approximation $\theta' = \alpha_0 - \alpha_B$. The angle θ' is given in the fourth column of Table 1. During the southern hemisphere portion of the pass, from 1505 to 1535 UT, the angle θ' is in all cases less than 90°. Therefore the sense of rotation with respect to the magnetic field is the same as the sense of rotation (left hand) with respect to the E plane normal, which indicates an *L-O* mode. During the northern hemisphere portion of the pass, from 1550 to 1610 UT, the angle θ' is in all except one case greater than 90°. Therefore, except for this one case, the sense of rotation with respect to the magnetic field is opposite the sense of rotation (right hand) with respect to the E plane normal, which again indicates an *L-O* mode.

Since the angle between the magnetic field and the E plane normal is in all cases very close to 90°, it is obvious that the mode identification is sensitive to small errors in angle. The E plane normal measurements are believed to have sufficient accuracy to determine clearly the sense of rotation with respect to the magnetic field, even though θ' is in most cases within 10° of perpendicular. The measured θ' values have a slight dependence on the ellipse ratio whenever the out-of-plane angle δ_0 is nonzero. The relation $\theta' = \alpha_0 - \alpha_B$ effectively assumes that the polarization is circular ($b = 1$) and that the out-of-plane angle is zero ($\delta_0 = 0$). For the observed parameters, $b \simeq 1.54$ and $\delta_0 \lesssim 9°$, it is easy to show that the correction due to the noncircular polarization is very small, typically less than 1°. This error estimate is supported by comparisons of auroral kilometric radiation source positions with auroral images [*Huff et al.*, 1988] which indicate that the E plane normal determination for circularly polarized radiation is of the order of 1°–2°. Since magnetic field measurements have an accuracy much better than 1°, the overall accuracy of the θ' determination should be more than adequate to resolve the mode of propagation. Nevertheless, we will explore two other methods of determining the mode of propagation.

TABLE 1. *E* Plane Parameters

Time, UT	α_0, deg	α_B, deg	θ', deg	Polarization*	Mode
1505	218.9	129.5	89.4	left	*L-O*
1510	210.7	127.4	83.3	left	*L-O*
1515	207.9	121.2	86.7	left	*L-O*
1520	199.5	117.4	82.1	left	*L-O*
1525	196.8	111.7	85.1	left	*L-O*
1530	194.1	107.1	87.0	left	*L-O*
1535	188.2	100.2	87.9	left	*L-O*
1550	168.5	82.0	86.5	right	*R-X*
1555	166.9	74.9	91.9	right	*L-O*
1600	165.2	66.4	98.8	right	*L-O*
1605	159.9	60.3	99.6	right	*L-O*
1610	166.7	55.2	111.5	right	*L-O*

*Polarization with respect to *E* plane normal.

E PLANE NORMAL AND ELLIPSE RATIO MEASUREMENTS

Further tests and checks on the mode of propagation can be made by comparing the direction of the E plane normal to theoretical predictions and by measuring the ellipse ratio of the electric field. As mentioned earlier, in a plasma the E plane normal is in general not coincident with the wave normal. The geometry involved is illustrated in Figure 4, which shows the relationship between the E plane normal angle θ' and the wave normal angle θ. The difference between these two angles, $\chi = \theta - \theta'$, is given by [*Allis et al.*, 1963]

$$\tan \chi = \left(1 - \frac{n^2}{P}\right) \tan \theta \tag{2}$$

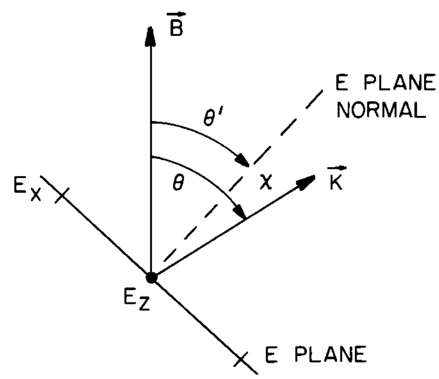

Fig. 4. In a plasma the E plane normal is tilted at an angle χ with respect to the propagation vector k. The E plane normal angle with respect to the magnetic field is given by $\theta' = \theta - \chi$, where θ is the wave normal angle.

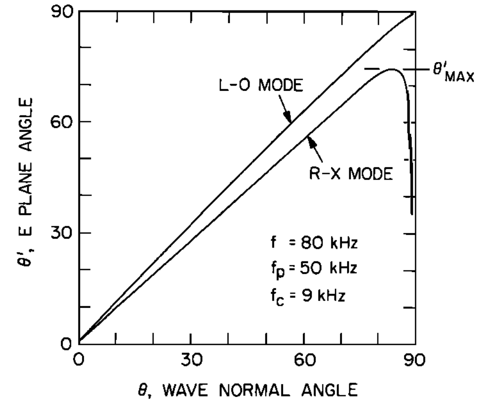

Fig. 5. A plot of the E plane normal angle θ' as a function of the wave normal angle θ for a representative set of parameters. Note that the R-X mode has a maximum θ_{max}' that cannot be exceeded for any wave normal angle. If the measured θ' angle exceeds θ_{max}', then the R-X mode can be excluded.

where n is the index of refraction and $P = 1 - f_p^2/f^2$. It is easy to show that in free space, χ goes to zero, so that $\theta' = \theta$. In a plasma the angle θ' depends on the magnetic field strength and plasma density and can differ considerably from the wave normal angle, particularly if the wave frequency is near the plasma frequency or cyclotron frequency. Figure 5 shows the dependence of θ' on θ for parameters typical of the continuum radiation. As can be seen, for the L-O mode, θ' is always larger than θ (i.e., χ is negative), whereas for the R-X mode, θ' is always smaller than θ (i.e., χ is positive). Furthermore, for the R-X mode, θ' has a maximum value θ_{max}' that cannot be exceeded. The maximum E plane normal angle depends on the plasma frequency and cyclotron frequency. This relationship is summarized in Figure 6, which shows θ_{max}' as a function of the parameters $X = f_p^2/f^2$ and $Y = f_c/f$.

The importance of the upper limit on θ' is that we can rule out the R-X mode if the measured E plane normal angle exceeds θ_{max}'. This test turns out to be useful. The cyclotron frequency f_c and plasma frequency f_p for the March 2, 1982, event are listed in Table 2, along with the measured θ' values and the θ_{max}' values determined from Figure 6 for a representative frequency of $f = 70$ kHz in the northern hemisphere and $f = 95$ kHz in the southern hemisphere. The cyclotron frequency was computed using magnetic field measurements from the magnetometer. The plasma frequency was determined from the upper hybrid resonance frequency, f_{UHR}, which is related to f_c and f_p by the equation $f_{UHR}^2 = f_p^2 + f_c^2$. As shown in Figure 7, strong UHR emissions were observed near the magnetic equator during this event. The frequency of these emissions was $f_{UHR} = 44$ kHz, which using the equatorial cyclotron frequency, $f_c = 9.0$ kHz, gives a plasma frequency of $f_p = 43.1$ kHz. Unfortunately, the UHR emissions disappear in the region away from the magnetic equator, so the equatorial plasma frequency provides the only indications of f_p in the region where the continuum radiation is observed. The next to last column in Table 2 shows the measured E plane normal angles. Where θ' exceeds 90°, the value has been replaced by 180° − θ', since θ_{max}' applies to the angle with respect to the magnetic field without regard to the sense of the field. As can be seen, the measured values for θ' are, in almost all cases, greater than θ_{max}', which excludes the R-X mode. Even if the plasma frequency were reduced by a factor of 2 from the equatorial value, which seems highly unlikely, a substantial

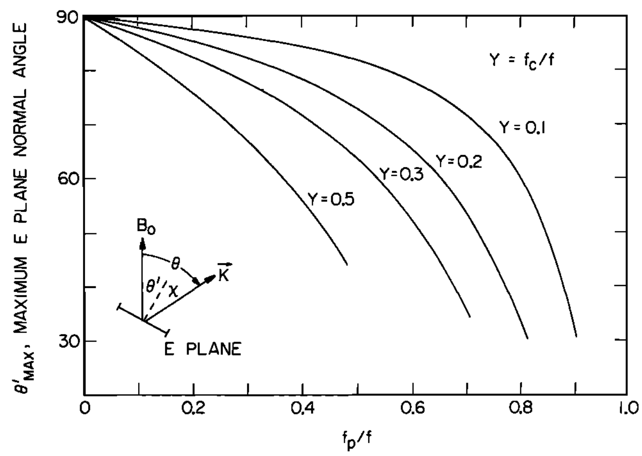

Fig. 6. A plot of θ_m' as a function of the parameters f_c/f and f_p/f.

TABLE 2. E Plane Tilt Angle

Time, UT	f_c, kHz	f_p, kHz	θ_{max}', deg	θ', deg	Possible Modes
1505	21.1	43.1	62.4	89.4	*L-O*
1510	18.2	43.1	65.7	83.3	*L-O*
1515	15.6	43.1	69.0	86.7	*L-O*
1520	13.8	43.1	72.3	82.1	*L-O*
1525	12.6	43.1	73.4	85.1	*L-O*
1530	11.1	43.1	75.6	87.0	*L-O*
1535	10.4	43.1	76.7	87.9	*L-O*
1550	8.24	43.1	80.0	86.5	*L-O*
1555	8.16	43.1	80.0	(88.1)	*L-O*
1600	8.01	43.1	80.0	(81.2)	*L-O*
1605	8.31	43.1	80.0	(80.4)	*L-O*
1610	8.67	43.1	78.9	(68.5)	*L-O* or *R-X*

For numbers in parentheses, 180° − θ'.

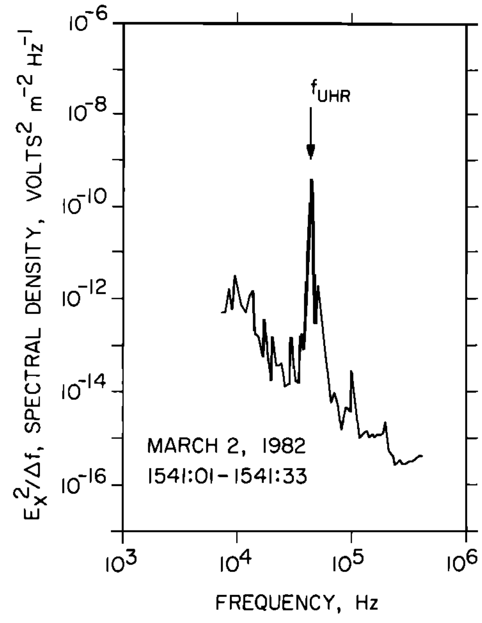

Fig. 7. An electric field spectrum near the magnetic equator showing an intense emission at the upper hybrid resonance (UHR) frequency. This emission is used to determine the electron plasma frequency.

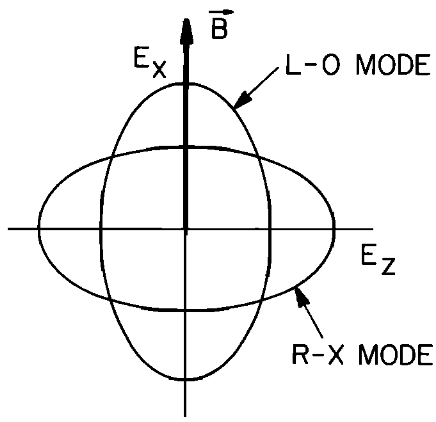

Fig. 8. A sketch of the electric field ellipses for the *R-X* and *L-O* modes. The *L-O* mode always has the major axis of the ellipse aligned parallel to the projected magnetic field. This alignment provides an independent method of identifying the mode of propagation.

number of cases would still exclude the *R-X* mode. Therefore the measured *E* plane normal directions strongly indicate that the continuum radiation is propagating in the *L-O* mode.

The electric field ellipse ratio provides the third method of distinguishing the *L-O* and *R-X* modes. Figure 8 shows a view of the *E* plane with the projected magnetic field oriented vertically. The ellipse ratio, E_z/E_x, can be computed using the matrix elements given by *Allis et al.* [1963] and is shown in Figure 9 as a function of the wave normal angle. As can be seen, the ellipse ratio E_z/E_x is greater than unity for the *R-X* mode and less than unity for the *L-O* mode. The electric field ellipse is elongated along the magnetic field for the *L-O* mode and across the magnetic field for the *R-X* mode. The elongation becomes progressively larger as the wave normal angle approaches 90°. Since the wave normal angle of the continuum radiation is large, ~80°, it should be easy to distinguish the two modes of propagation on the basis of the ellipse ratio.

Although the ellipse ratio provides a relatively strightforward way of distinguishing the two modes of propagation, in practice this test is difficult to apply because the E_z antenna signal is so small. Furthermore, the E_z antenna has a large base capacitance which must be taken into account when computing field strengths. To determine the base capacity, we have used auroral kilometric radiation to calibrate independently the effective length of the E_z and E_x antennas using the magnetic loop antenna, which has no base capacity correction. On the basis of these calibrations, we arrived at effective lengths for the two antennas of $l_z = 1.75$ m and $l_x = 101$ m. To give the best possible signal to noise ratio, the E_z and E_x fields (measured as the *X* axis antenna crossed the *E* plane) were averaged from 1515 to 1520 UT, where the continuum radiation has the highest intensity. After subtracting the *Z* axis receiver noise level, which amounted to 89% of the total signal, the ellipse ratio was found to be $E_z/E_x = 0.65$. This ellipse ratio corresponds to $1/b$ in equation (1). Since the ellipse ratio is less than unity, it follows that the mode of propagation must be the *L-O* mode. From the computed dependence of E_z/E_x on wave normal angles in Figure 9, which uses representative parameters for the March 2, 1982, event, the measured ellipse ratio is seen to correspond to a wave normal angle of about 70°. This angle is in good agreement with the actual wave normal angles, which, taking into account the tilt angle χ, are about 80°.

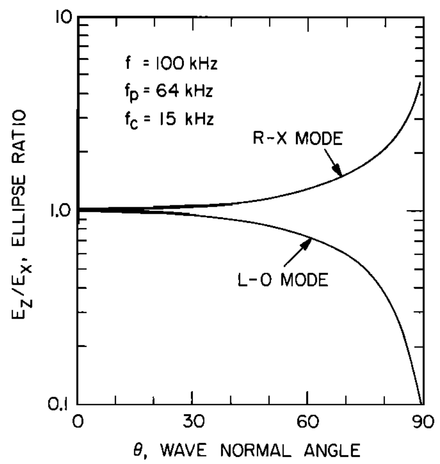

Fig. 9. A plot of the ellipse ratio E_z/E_x as a function of the wave normal angle for a representative set of parameters.

SOURCE REGION POLARIZATION

In the previous two sections we presented strong evidence that the continuum radiation observed during the March 2, 1982, event is propagating in the *L-O* mode. Although the radiation was clearly propagating in the *L-O* mode at the spacecraft, there is still a possibility that the radiation was propagating in the *R-X* mode at the source, since in all except one case the *E* plane normal and the magnetic field passed through perpendicular as the wave propagated from the source to the spacecraft. If the radiation remained in the same magnetoionic mode on both sides of the perpendicular point, then the measurements would imply that the radiation was generated in the *L-O* mode at the source. This situation is illustrated in Figure 10. Note that in this case the sense of rotation of the electric field with respect to the *E* plane normal reverses between the source and the spacecraft. On the other hand, if the sense of rotation of the electric field remained the same on both sides of the perpendicular point, as would be the case in free space, then the magnetoionic modes would be reversed between the source and the spacecraft. This situation is illustrated in Figure 11.

The question that must be resolved is whether the radiation had reached the so-called "limiting polarization" before it crossed the perpendicular point. The limiting polarization is discussed by *Budden* [1961, 1985], and also by *Titheridge* [1971], in terms of the Försterling coupled-wave equations (also, see *Clemmow and Heading* [1954] and *Budden and Jones*

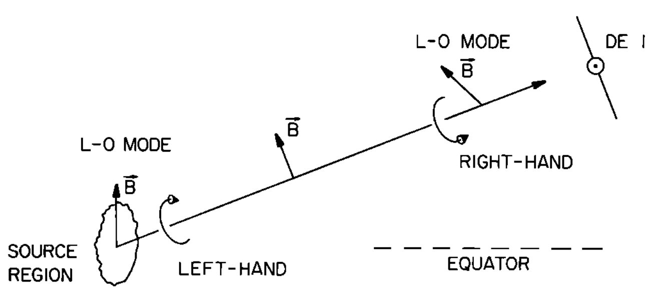

Fig. 10. If the spatial gradients are sufficiently small, the mode of propagation remains constant along the ray path. In this case the DE 1 observations imply that the continuum radiation is propagating in the *L-O* mode at the source. Note that the polarization with respect to the *E* plane normal switches from right-hand to left-hand between the source and the spacecraft.

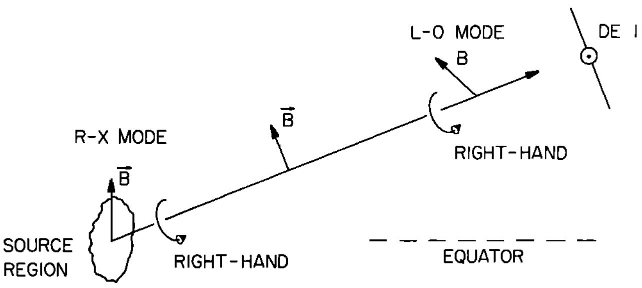

Fig. 11. In the absence of plasma effects (i.e., free space) the polarization with respect to the E plane normal remains constant along the ray path. In this case the DE 1 observations would imply that the continuum radiation is propagation in the R-X mode at the source. Our estimates show that the continuum radiation observed during the March 2, 1982, event has not yet reached the free space limit, so the model in Figure 10 applies, implying L-O mode polarization at the source.

[1987]). In the coupled-wave formulation the radiation is represented by independently propagating L-O and R-X mode waves which interact. Their interaction is dictated by the so-called coupling parameter:

$$\Psi = \frac{\lambda_0}{2\pi}\left(\frac{1}{\rho^2 - 1}\right)\frac{d\rho}{dz} \tag{3}$$

where λ_0 is the free space wavelength ρ is the polarization as defined by *Budden* [1961], and z is the distance in the direction of propagation. Whenever Ψ is small, as occurs in regions with small spatial gradients, the differential equations for the two modes are uncoupled and the two waves propagate independently. A wave initially propagating in one of the two modes then remains in that mode as it propagates. However, when Ψ becomes large, as occurs when large spatial gradients are present, the two waves interact, with the result that the wave polarization remains essentially unchanged except for Faraday rotation. In other words, as long as Ψ remains small, the waves retain their characteristic magnetoionic polarizations, but when it becomes large, they propagate with a polarization that is fixed at the point where Ψ becomes large. The result, for waves escaping from a magnetized plasma, is the final or "limiting" polarization.

Our problem thus becomes one of showing that Ψ remained sufficiently small for the waves to retain their magnetoionic mode between the source and the spacecraft. The pertinent criterion is that Ψ must be small as compared to one half of the difference between the wave refractive indices, or, in terms of Titheridge's parameter Q, that the quantity

$$Q = i2\Psi/(n_o - n_x) \tag{4}$$

must remain less than unity, where n_o and n_x are the ordinary and extraordinary refractive indices, respectively.

The coupling parameter can be evaluated by differentiating *Budden*'s [1961] equation 5.13, with the result that

$$\Psi = A\left\{\frac{dX}{dz} + (1 - X)\left(\frac{1}{Y}\frac{dY}{dz} - \tan\theta\frac{d\theta}{dz}\right)\right\} \tag{5}$$

where A is given by

$$A = -\frac{i\lambda_0}{2\pi}\left\{\frac{Y\sin^2\theta\cos\theta}{Y^2\sin^4\theta + 4(1 - X)^2\cos^2\theta}\right\} \tag{6}$$

The three derivatives in (5) correspond to spatial gradients in the electron density, the magnetic field magnitude, and the magnetic field direction, respectively. In order to evaluate the effects of these three gradients, we have approximated (5) for nearly perpendicular propagation and low magnetic latitudes. The result, to second order in the magnetic latitude λ_m, is given by

$$\Psi = \frac{i\lambda_0}{2\pi YR} \cdot \left\{R\delta\frac{dX}{dz} - 3(1 - X)\cos\varepsilon + (1 - X)(1 - 6\lambda_m{}^2)\sin\varepsilon\right\} \tag{7}$$

where $\delta = \theta - \pi/2$ is the wave normal angle relative to the perpendicular and ε is the wave normal angle with respect to the vertical. Notice in this equation that for small λ_m the coefficient of $\sin\varepsilon$ is at least 3 times less than the coefficient of $\cos\varepsilon$. This implies that the gradient in the magnetic field magnitude is more important than the gradient in the magnetic field direction. Furthermore, for electron density gradients occurring on spatial scales greater than

$$D = R\delta X/3(1 - X) \tag{8}$$

the gradient in the magnetic field magnitude is the dominant factor affecting the coupling coefficient.

Since $Y = f_c/f$ and $\lambda_0 = c/f$, the multiplicative factor in (7) is independent of frequency. For the March 2, 1982, event, where the cyclotron frequency f_c was greater than 10 kHz and R was approximately 4 R_E, this coefficient is at most 1.8×10^{-4}. The maximum value for Ψ, neglecting density gradients and assuming $X = 0.5$, is then about 2.7×10^{-4}. The minimum scale length for an electron density gradient to affect this estimate, according to (8), for $X \simeq 0.5$ and $\delta \simeq 20°$, is about 3000 km.

To evaluate Q, we must evaluate the difference in the refractive indices, $n_0 - n_x$. It is easy to show that this difference has a minimum for perpendicular propagation. Using the parameters observed at the spacecraft during the March 2, 1982, event ($Y = 0.2$ and $X = 0.5$) and assuming perpendicular propagation, $n_0 - n_x$ is about 10^{-2}. Furthermore, since $n_0 - n_x$ increases with both electron density and magnetic field strength, this value represents a minimum over the propagation path between the source and the spacecraft. Using these values for Ψ and $n_0 - n_x$, the parameter Q neglecting electron density gradients is at most 0.112, which is still 9 times smaller than what is needed to cause a limiting polarization. Consequently, unless the electron density changes significantly over a scale length that is about 9 times smaller than D, or less than about 330 km, a limiting polarization is not reached, and the mode of propagation is retained between the source and the spacecraft. Although electron density gradients on a scale length of less than 330 km cannot be ruled out, they are considered to be unlikely in the region where the wave normal crossed through the perpendicular, which was almost certainly well beyond the plasmapause. Therefore we conclude that the radiation was propagating in the L-O mode at the source.

CONCLUSION

In this report we have analyzed an escaping terrestrial continuum radiation event detected by the DE 1 spacecraft. The event analyzed, which occurred on March 2, 1982, is the only case available in our existing data set with an intensity sufficiently large to permit a direct measurement of the polarization. Direction-finding measurements for this event show that the radiation is emitted in two meridional beams from a source located in the magnetic equatorial plane. The source is located at a radial distance of about 2.8–3.5 R_E, roughly 1 R_E inside the spacecraft trajectory. Two beams are detected, one directed north at an angle of about 20°–30° with respect to the magnetic equator and the other directed south at a comparable angle, very similar to the event previously analyzed by *Jones et al.* [1987]. The source locations are found to be in good agreement with those determined by the remote-sensing technique based on *Jones*' [1981*b*, 1983] theory. Polarization measurements show that the radiation is right-hand polarized with respect to an outward directed E plane normal in the northern hemisphere and left-hand polarized in the southern hemisphere. When the direction of the Earth's magnetic field is taken into account, the radiation is found to be propagating in the L-O mode in both the northern and southern hemispheres. Both the E plane tilt and ellipticity are consistent with an L-O mode wave.

Because the measurements were made a substantial distance ($\sim 1\ R_E$) from the source, and not in the magnetic equatorial plane, the geometry is such that the angle between the magnetic field and the E plane normal rotates through perpendicular as the wave propagates from the source to the spacecraft. To determine the mode of propagation at the source, one must determine whether the mode of propagation remains the same along the ray path. The resolution of this question is determined by analyzing the mode coupling due to spatial gradients along the ray path. Using the criterion given by *Budden* [1961] and *Titheridge* [1971] and rough estimates of the spatial gradients from the source to the spacecraft, our calculations show that the mode of propagation should be retained along the ray path. In the terminology of Budden, the wave has not yet reached the "limiting polarization," beyond which the mode of propagation is no longer controlled by the plasma. On the basis of these considerations, we conclude that the wave is propagating in the L-O mode at the source. The mode of propagation is therefore in agreement with the predictions of the linear conversion mechanism of *Jones* [1980, 1981*a*, 1982].

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