

RAY TRACING PLANETARY RADIO EMISSIONS

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Abstract

Ray tracing calculations can help determine or confirm many important details about a wave's origin, plasma mode, and polarization. In addition, ray tracing can help obtain a better understanding of composition and propagation effects causing multi-ion resonances, shadow zones, and wave energy build up forming caustic surfaces. The ray tracing technique provides a framework for a valid comparison to be made between multiple space or ground-based observations and source region characteristics. As a diagnostic tool along a computed ray path, wave growth rates and estimates of plasma densities have also been calculated. These calculations do provide rigorous tests for theoretical wave generation and amplification.

This paper will briefly review results from planetary ray tracing calculations of free escaping electromagnetic waves. The most extensive work in this area has been done with respect to the Earth and Jupiter magnetospheric systems. Auroral kilometric radiation (AKR) and the non-thermal continuum radiation from the Earth has been studied extensively using ray tracing techniques. At Jupiter, the kilometric emissions and the decametric emission has been extensively ray traced. In all cases, ray tracing calculations were used many times to continue to provide insight into the generation of these magnetosphere waves as new observations were made or theories proposed. In addition, we will begin with a brief review of the physics of ray tracing and some of the most important procedures necessary in order to adequately apply the ray tracing technique to real physical problems.

Introduction

The ray tracing technique provides the ability to match diverse radio wave observations and separate propagation effects from source region and/or wave generation characteristics. Ray tracing calculations provides a framework to test theories and can provide insight into additional constraints on existing theories. Information can be obtained about source region characteristics such as location and extent from ray tracing calculations. In addition, plasma wave modes or polarization of the wave can be inferred by matching ray tracing calculations with observations such as the angular extent of an emission. Ray tracing is a particularly useful technique that provides insight into propagation effects. This includes refraction and reflection, wave energy build-up forming caustic surfaces, and shadow zones for regions where radiation is not allowed, not because of the characteristics of the generation mechanism, but because of the intervening plasma between the source region and the spacecraft.

The calculation of growth rates for proposed generation mechanisms has been done along individual ray paths to compare against observed wave intensities. Ray tracing has been used to determine densities along a ray path, and can be used to understand or separate compositional effects on the propagation of electromagnetic waves. In this review, only ray tracing calculations of what is called “free escaping” electromagnetic radiation will be discussed. Free escaping means an observer can be outside a planetary magnetosphere and still observe the radiation.

Ray tracing and index of refraction equations

The first formulation of ray tracing equations that are suitable for integration by standard numerical methods using computers was done in the mid-1950's by Haselgrove. Haselgrove (1955) developed six first order differential equations that describe the motion of the energy in electromagnetic waves propagating in an anisotropic medium in three dimensions. Equations 1, 2, and 3 describe the time rate of change in the position of a ray. Equations 4, 5 and 6 describe the time rate of change of the components of the index of refraction with respect to position (r , θ and ϕ). These equations express the motion of the energy of the wave in spherical coordinates.

$$\frac{dr}{dt} = \frac{1}{N^2} \left(n_r - N \frac{\partial N}{\partial n_r} \right) \quad (1)$$

$$\frac{d\theta}{dt} = \frac{1}{rN^2} \left(n_\theta - N \frac{\partial N}{\partial n_\theta} \right) \quad (2)$$

$$\frac{d\phi}{dt} = \frac{1}{rN^2 \sin \theta} \left(n_\phi - N \frac{\partial N}{\partial n_\phi} \right) \quad (3)$$

$$\frac{dn_r}{dt} = \frac{1}{N} \left(\frac{\partial N}{\partial r} + n_\theta \frac{d\theta}{dt} + n_\phi \frac{d\phi}{dt} \sin \theta \right) \quad (4)$$

$$\frac{dn_\theta}{dt} = \frac{1}{r} \left(\frac{1}{N} \frac{\partial N}{\partial \theta} - n_\theta \frac{dr}{dt} + rn_\phi \frac{d\phi}{dt} \cos \theta \right) \quad (5)$$

$$\frac{dn_\phi}{dt} = \frac{1}{r \sin \theta} \left(\frac{1}{N} \frac{\partial N}{\partial \phi} - n_\phi \frac{dr}{dt} \sin \theta - rn_\theta \frac{d\theta}{dt} \cos \theta \right) \quad (6)$$

$$\text{where : } N^2 = n_r^2 + n_\theta^2 + n_\phi^2$$

The ray tracing equations of Haselgrove allowed for the inclusion of one of many formulations for the index of refraction N . One expression for the index of refraction for radiation in cold plasmas has been developed by Stix, (1962) and has been used extensively for ray tracing calculation in model Earth and Jovian magnetospheres.

As can be seen in Equation 7, the index of refraction is a function of the electron and ion gyrofrequencies (f_g), the multi-species plasma frequencies (f_p , also note the summations are over all species, s), the initial wave normal angle (θ , which is the angle between the phase velocity of the wave and the local magnetic field at the ray position), and the wave frequency, f . The cold plasma formulation of the index of refraction by Stix (1962) implies a plasma for which there are immobile electrons and ions, and does not take into account any hot plasma effects, but provides significant ability to perform ray tracing calculations in order to model a large variety of phenomenon in the Earth and other magnetospheres.

For cold plasma (Stix):

$$N^2 = \frac{[RL \sin^2 \theta + PS(1 + \cos^2 \theta)] \pm [(RL - PS)^2 \sin^2 \theta + 4P^2 D^2 \cos^2 \theta]}{2(\sin^2 \theta + P \cos^2 \theta)} \quad (7)$$

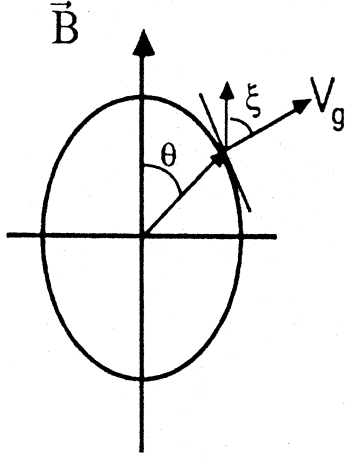
where

$$\begin{aligned} R &= 1 - \sum_s \frac{f_{ps}^2}{f(f + f_{gs})} \\ L &= 1 - \sum_s \frac{f_{ps}^2}{f(f - f_{gs})} \\ P &= 1 - \sum_s \frac{f_{ps}^2}{f^2} \\ S &= \frac{1}{2}(R + L) \\ D &= \frac{1}{2}(R - L) \end{aligned}$$

As shown in the left panel of Figure 1, a surface of the index of refraction can be generated by determining the magnitude of the index of refraction as a function of θ about the local magnetic field. If a wave is launched at the angle θ at a point in space whose index of refraction is shown in Figure 1, the direction that the wave energy will take is in the direction of the group velocity of the wave (V_g). The group velocity direction is perpendicular to the tangent to the index of refraction surface (thus forming the angle ξ). Note that the ξ and θ angles may not be the same, therefore, the energy flow of an electromagnetic wave in isotropic media is not generally in the same direction as the phase velocity of that wave.

It is important to note that the phase velocity of the medium is proportional to the inverse of the index of refraction. As described by Equation 7, the index of refraction has two values corresponding to the $+$ or the $-$ sign. The two solutions form two surfaces of the index of refraction at any location in an anisotropic media, (except when one of the expressions may be zero or less than zero). The right hand side of Figure 1 shows the phase velocity surfaces for the two solutions of the index of refraction at a point in space. Note that even the phase velocity surfaces are different, depending upon what branch of the index of refraction is chosen. These two branches of the index of refraction are normally associated with different wave polarizations.

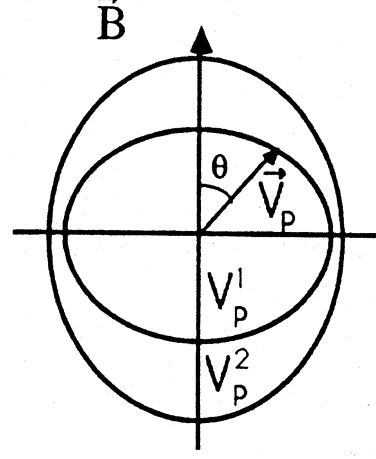
INDEX OF REFRACTION SURFACE



$$N(f_g, f_p, f_w, \theta)$$

V_g = group velocity

PHASE VELOCITY SURFACE



$$V_P^1 = \frac{c}{N_+} \quad V_P^2 = \frac{c}{N_-}$$

θ = Wave normal angle

Fig. 1: A cold plasma index of refraction surface, in a model plasma (described by the function N) is shown with respect to the local magnetic field in the left hand panel. The right hand panel shows the phase velocity surfaces where the inter surface corresponds to the index of refraction surface in the right hand panel. The group velocity direction of a wave is determined by the perpendicular to the tangent to the index of refraction surface pointed at by the wave phase velocity vector.

An extremely convenient graphical form that shows the index of refraction surfaces as a function of the local electron gyrofrequency and plasma frequency is shown in Figure 2. Figure 2 is commonly referred to as a CMA diagram or “plasma parameter space”. The origin of the CMA diagram is the location for which the index of refraction for both branches is equal to 1 and is commonly termed “free space”. Figure 2 is a CMA diagram for a cold electron and proton plasma. In each region of the CMA diagram are the phase velocity surfaces corresponding to the two branches of the index of refraction formula (see Equation 7). These phase velocity surfaces are shown as if the local magnetic field lies parallel to the ordinate of the plot. The R and L notation denoted above each of the phase velocity surfaces stands for the right hand and left hand circular polarization of the wave and point to the branch of the index of refraction formula necessary for that polarization. Propagation perpendicular to the magnetic field are for linear polarized waves and are termed the extraordinary (X) and ordinary (O) mode waves.

It is important to note that in each of these regions, the phase velocity surfaces can take on complicated shapes. In addition, the form or topology of the phase velocity surfaces remain the same throughout each individual region. Boundaries that are formed by, for instance, the x and y axis and the $R=0$ cutoff, as shown in Figure 2, represent the limits for which the free space R-X mode can propagate.

CMA DIAGRAM

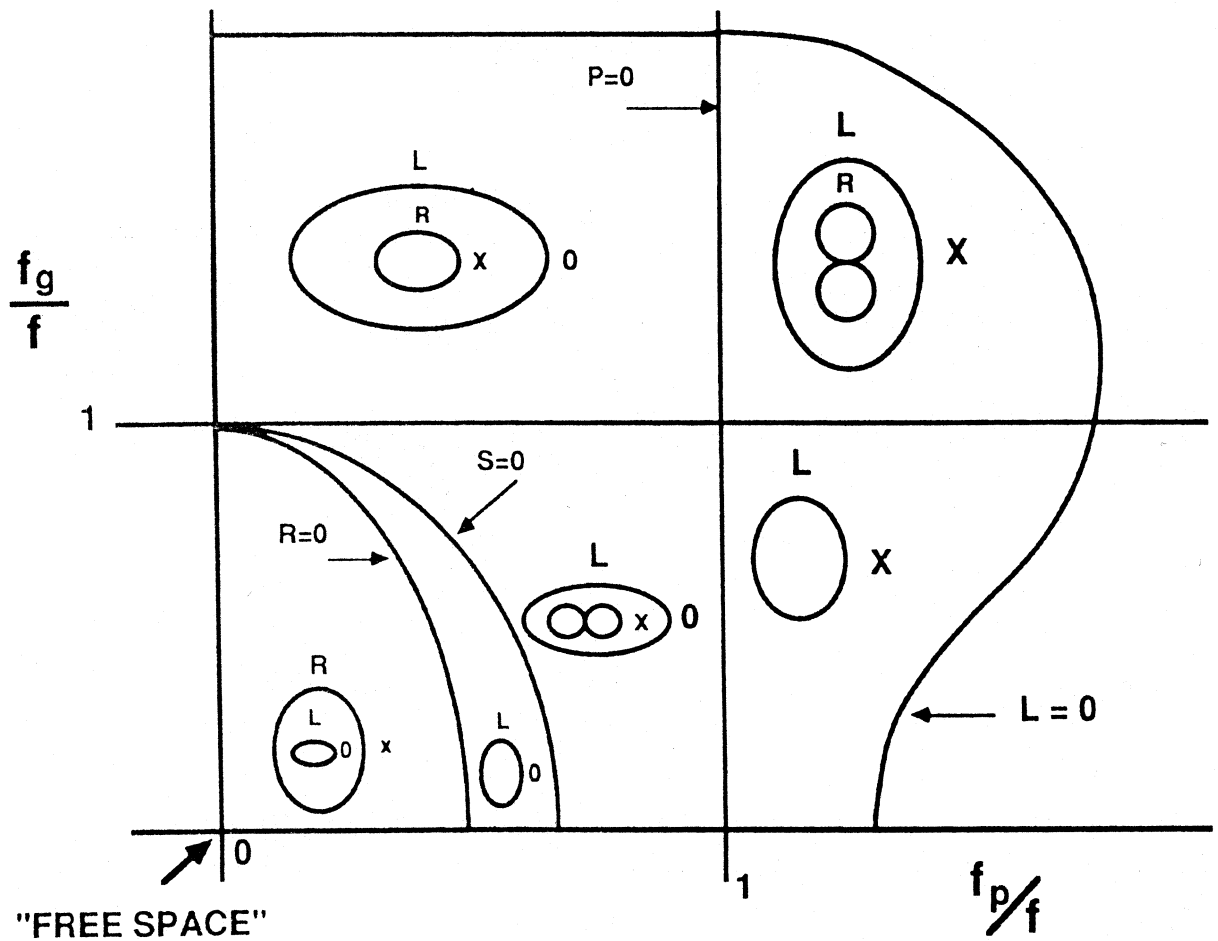


Fig. 2: A CMA diagram showing the topology of the phase velocity surfaces of a cold multi-species plasma. The labels on the phase velocity surfaces indicate a waves polarization as would seen from propagation along the ambient magnetic field (R = right hand, L = left hand circularly polarized) and perpendicular to the magnetic field (O = ordinary, X = extraordinary).

If one were to take a cut through the CMA diagram for which the gyrofrequency was greater than the plasma frequency and plot the available propagation modes, the result is shown in Figure 3. Here the R - X mode will only propagate down to the $R=0$ cutoff. The expression for the $R=0$ cutoff, as shown in Figure 3, indicates that it is greater than the local electron gyrofrequency and the local electron plasma frequency. If the local electron plasma frequency is extremely small, then from this expression the $R=0$ cutoff approaches the local electron gyrofrequency. Figure 3 also shows that the L - O mode free escaping waves can only propagate down to the local electron plasma frequency. Note that the L - O mode can exist at frequencies above and below the local electron gyrofrequency, the upper hybrid, and the $R=0$ cutoff. Other important modes to point out in Figure 3 are the Z mode which extends from the $L=0$ cutoff up to the upper hybrid resonance frequency.

PROPAGATION MODES

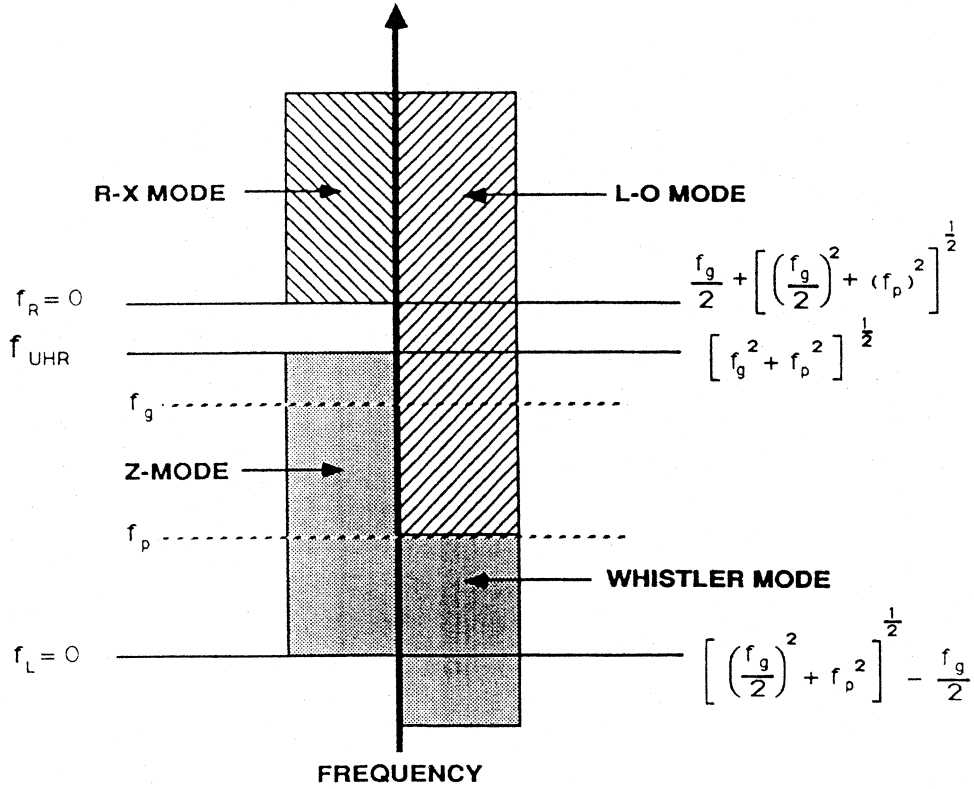


Fig. 3: Propagation modes supported by a cold plasma when the local electron gyrofrequency is greater than the local electron plasma frequency.

Finally, a note about the polarization of a wave as it relates to observations in space. Figure 4 shows a right hand and a left hand polarized wave in two polarization conventions. The plasma convention, which is what is shown in the CMA diagram, must have the wave electric field vector rotating about the local magnetic field (B). The upper left panel of Figure 4 shows an electric field vector rotating in the right hand direction about B . Also shown in this panel is the phase velocity or the K vector of the wave propagating anti-parallel to B and rotating about E in a left hand direction. This configuration is representative of an R-X mode wave generated in a source region. At large radial distances from the source, as shown in the upper right hand corner of Figure 4, the electric field vector is still rotating about K in a left handed convention and would be measured by a spacecraft at large radial distances from the source region as a left hand polarized wave, although it was generated in the R-X mode. In a similar fashion, the lower left hand corner shows an L-0 mode wave as would be described in the CMA diagram. As it propagates to large radial distances, the rotation of the electric field about the propagation vector K remains the same and it would be measured as a right hand polarized wave.

POLARIZATION

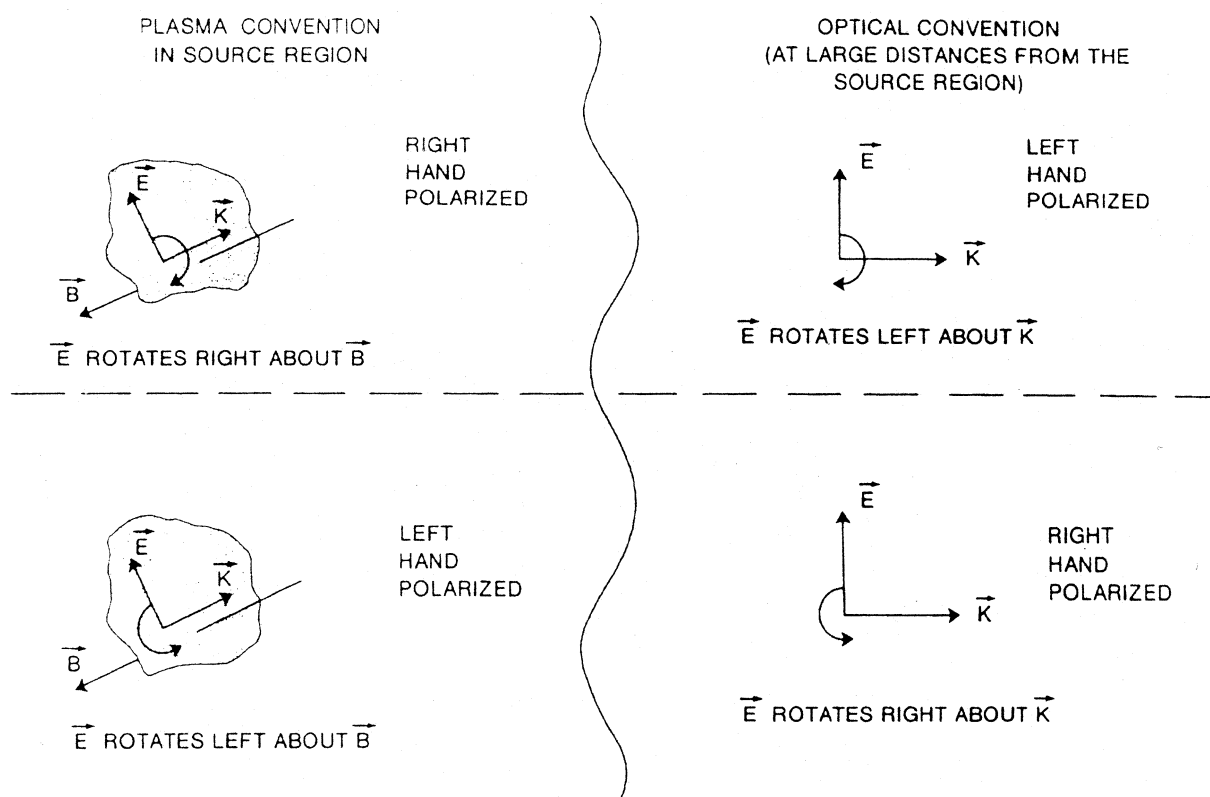


Fig. 4: The polarization of electromagnetic waves in the plasma convention (left hand side) and the optical convention (right hand side). As this figure illustrates the polarization measured by a distant spacecraft (optical convention) is not necessarily representative of the polarization in the generation region (plasma convention).

It is very important, therefore, to understand the locations of source regions in order to obtain information about the generating plasma wave mode or modes. Care must be taken to determine the source region and the orientation of the local magnetic field to properly interpret the plasma mode of a wave based on polarization observations from remote spacecraft. As we will see, different plasma modes of radio emissions will produce dramatically different propagation extents.

Plasma and magnetic field models

In order for a valid comparison to be made between observations and ray tracing results, the plasma and magnetic field models that are used in the computations must be acceptable representations of the physical environment that influences the radiation. Whether the models are analytical or numerical, their completeness is an essential ingredient in the degree of success in understanding the basic characteristics of the emission under study. A large part of the ray tracing effort (probably as much as 95%) goes into correct model implementation into the ray tracing program.

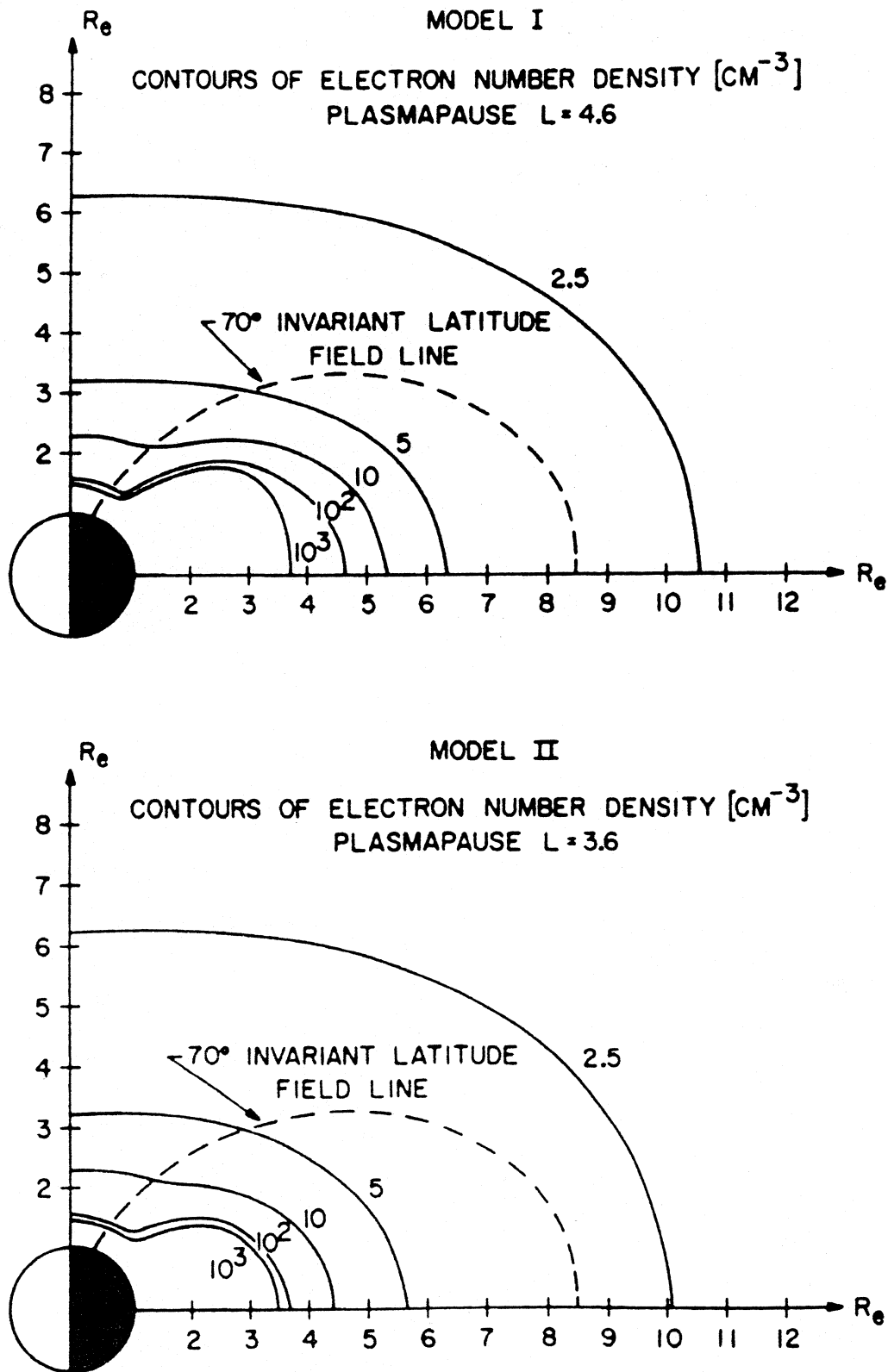


Fig. 5: Electron density contours from plasma and magnetic field models that are used in ray tracing calculations for a normal (top panel) and disturbed (bottom panel) terrestrial magnetosphere.

Over the last 25 years, there has been a large number of models describing various aspects of the ionosphere and magnetosphere of the Earth and, within the last ten years, of Jupiter's plasma and magnetic field environment as well. These models usually focus their attention on the detailed plasma or magnetic field characteristics over a rather limited distance. The following is a table of some of the commonly used plasma and magnetic field models:

Earth

Angerami & Thomas	(1964)	Diffusive Equil. Model
Eviatar et al.	(1964)	Collisionless Model
Kimura	(1966)	Ionosph. & Plasmasph.
Aikyo & Ondoh	(1971)	Plasmapause Model
Calvert	(1981b)	Auroral Density Cavity
Horwitz and Lockwood	(1985)	Polar Cap Densities

Jupiter

Acuña & Ness	(1976b)	O4 Magnetic Field
Sentman & Goertz	(1978)	Inner Magnetosphere
Warwick et al.	(1979a)	Io Torus
Divine & Garrett	(1983)	Updated Io Torus
Hashimoto & Goldstein	(1983)	Ionosphere

One of the problems of ray tracing planetary radio emissions is that these radio emissions are usually generated in the neighborhood of the planet and propagate through the intervening plasma to very large distances outside the magnetosphere. Therefore, a correct model implementation into the program may involve the piecing together of several diverse analytical and numerical models.

Figure 5 shows contours of the electron density of two models of the Earth in the noon/midnight meridian. These models are combinations of a dipole magnetic field, an ionosphere diffusive equilibrium model, an upper ionospheric and plasmaspheric model, and can contain additional small scale features such as a plasma cavity or large density fluctuations that have just recently been measured at high latitudes. Another problem with implementing computer models is that they must have enough versatility to be able to describe large scale variations of density and other plasma parameters based on magnetospheric conditions or substorm phases. The two models in Figure 5 represent conditions within the magnetosphere for which the plasmapause is extended to $L = 4.6$ Earth radii (R_e) in Model 1 (top panel), but has been pushed in or retracted to $L = 3.6 R_e$ in Model 2 (bottom panel).

The top panel of Figure 6 shows the electron plasma frequency contours for a Jovian magnetosphere model. This particular model combines a multi-moment magnetic field (valid only within $8 R_J$), an ionospheric model, an inner magnetospheric plasma model, and an Io torus. As the models for the distant planets improves implementation into ray tracing programs should follow.

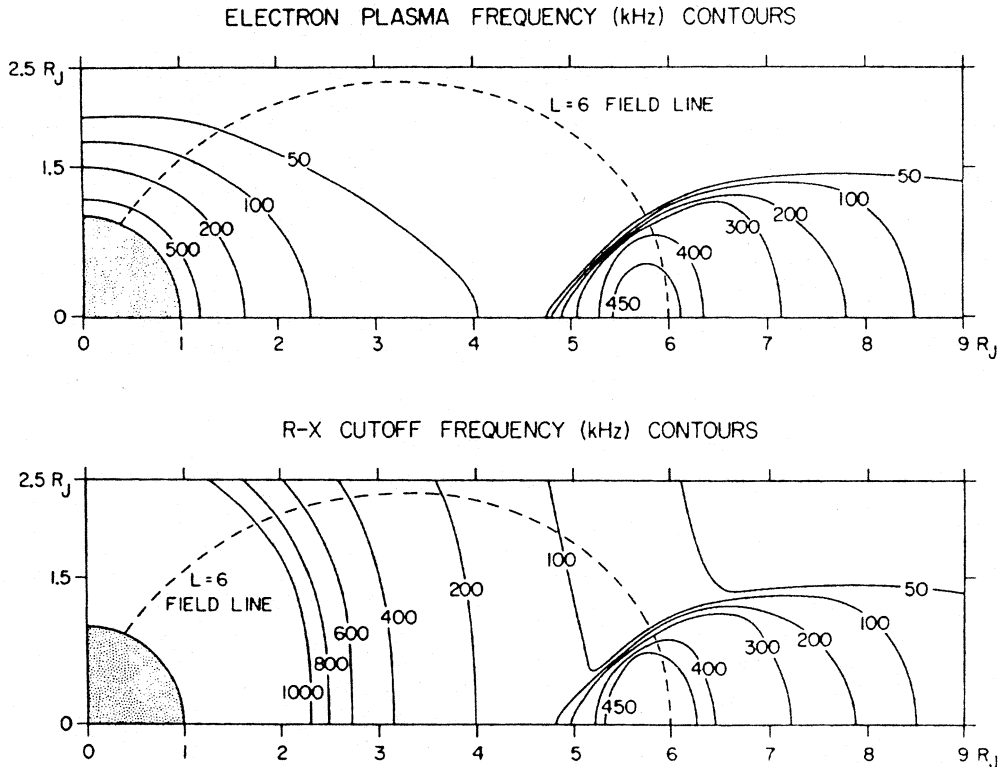


Fig. 6: The electron plasma frequency (top panel) and R-X cutoff frequency (bottom panel) contours of a Jovian magnetosphere is in ray tracing calculations.

Another key aspect of plasma and magnetic field models used in ray tracing applications is in determining the source regions for planetary radio emissions. When the source locations are unknown, a good starting point is to examine the characteristic frequencies or boundaries of the generated plasma mode. A valid source must be placed in a region which is consistent with the escaping emission. As discussed earlier, the lowest frequency of a possible L-O mode source must be the local electron plasma frequency as shown in the top panel of Figure 6. The bottom panel of Figure 6 shows the R-X cutoff frequency which shows us the lowest frequencies of a possible R-X mode source. Note that between the top panel and the bottom panel at any point, the large variation in the plasma frequency and the R-X cutoff frequency for Jupiter. This is due primarily to the very large planetary magnetic field and the Io torus. As we will see these large variations place major constraints on possible source regions for Jovian emissions. Contours of the plasma frequency and R-X cutoff mode frequency are invaluable in locating or understanding the positions of electromagnetic radiations that are possible within those magnetospheres.

Testing and validation

Once a source region and generation mode(s) have been determined, in an adequately described plasma and magnetic field model, the ray tracing calculations can begin. The next major task that must be undertaken is the verification that the program is operating correctly. There are several important procedures for testing and validating the results from a ray tracing program. One of the important tests is to take the output from a ray tracing computer run and replot that data in parameter space as shown in Figure 7. Figure 7 is an example of R-X mode waves propagating through a model Earth magnetosphere from a source region that is characteristic of auroral kilometric radiation. These waves are generated at a variety of wave normal angles as shown here. What is immediately obvious in the CMA diagram is that these waves do not propagate above the $R=0$ surface. This technique helps verify that the ray paths being calculated are using the correct branch of the index of refraction formula. In addition, it allows the easy detection of a variety of problems.

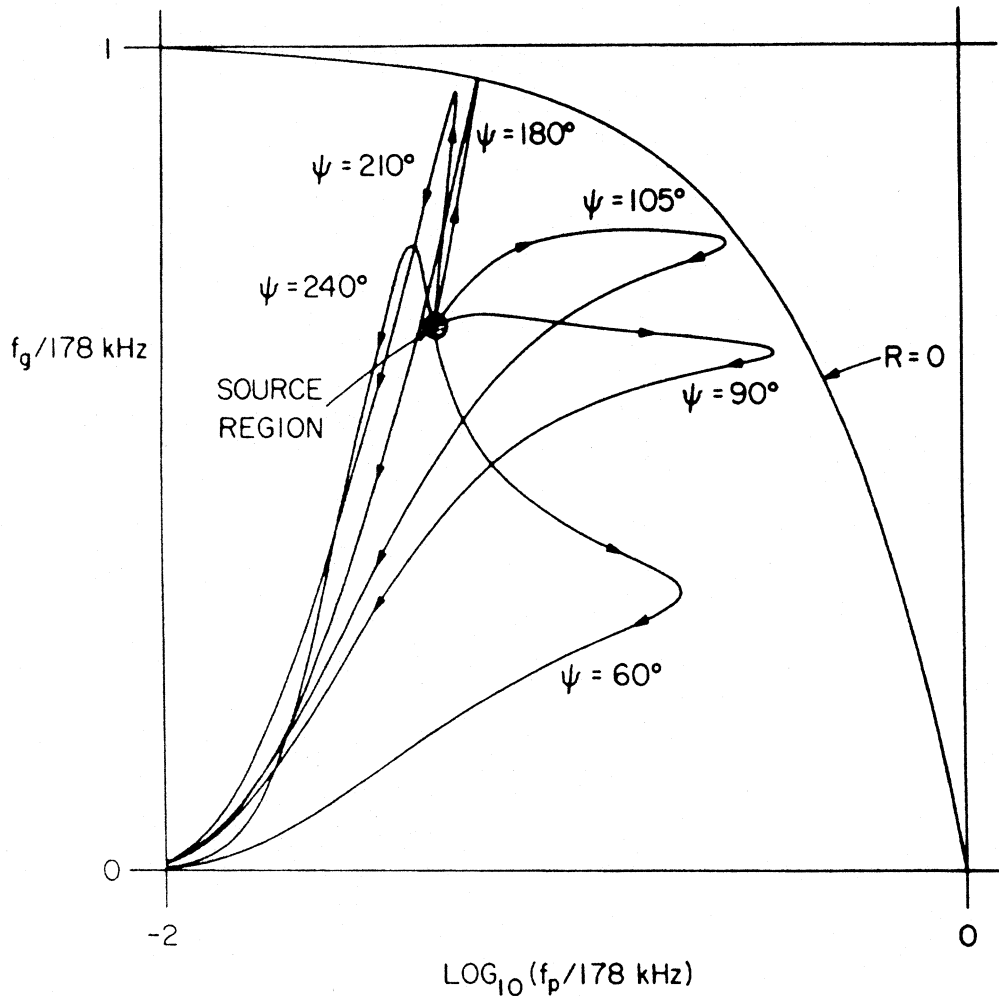


Fig. 7: AKR ray tracing calculations from an auroral zone source region as shown plotted in the CMA diagram. Note that these R-X mode rays are not allowed to propagate to regions at frequencies below the $R=0$ cutoff frequency.

It is important to note, for instance, that from a single source region, launching waves in a variety of directions produces rays that penetrate to a variety of depths in the plasma. In this example, Figure 7 shows all rays moving toward the $R=0$ cutoff. The rays that propagate to the $R=0$ cutoff and reflect were generated along the local magnetic field (180°). The calculations also show that the rays generated at different angles with respect to B refract further and further from the $R=0$ surface. These systematic results help verify that the program is operating correctly.

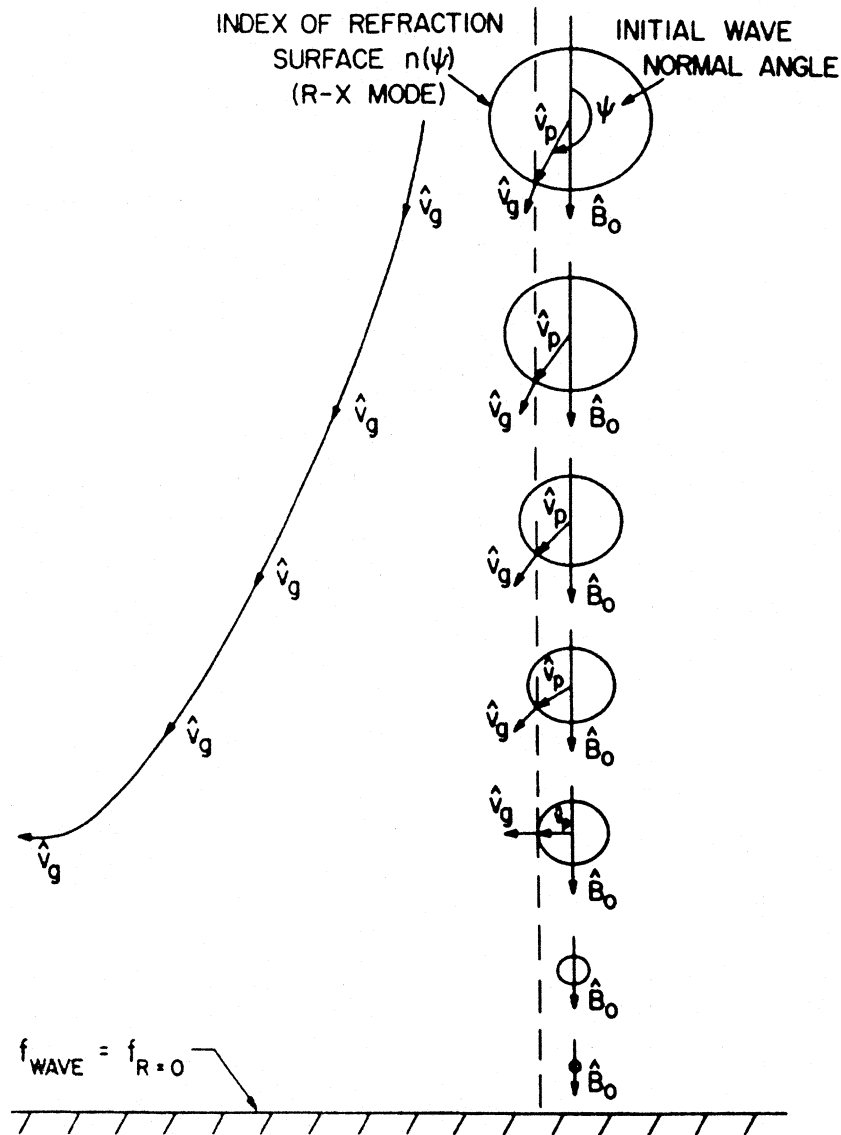


Fig. 8: At any point along the path of a ray the direction of propagation (the wave's group velocity, V_g) can be determined from a knowledge of the phase velocity direction (V_p) and the index of refraction of the media at that location.

Another important technique for testing and validating ray tracing results is the Poeverlein (1949a,b; and 1950) construction. As shown in Figure 8, the Poeverlein construction is a graphical method for doing ray tracing in two dimensions. At each point along the ray

the group velocity direction is determined and a finite step is taken into the plasma in that direction. After that step has been made, a new index of refraction surface is then calculated and a new group velocity determined. The parameter that must be conserved in this process is the K vector component parallel to the strata of the media (shown in Figure 8 with a dashed line). This is identical to applying Snell's law. Figure 8 illustrates that as the index of refraction surface becomes smaller, the phase velocity and the group velocity must adjust themselves in angle to conserve Snell's law until the wave is refracted away from the $R=0$ cutoff. The Poeverlein constructions allow the programmer to independently verify the ray tracing calculations.

Finally, an important technique for testing and validating the results of a ray tracing program is to retrace any ray. If a ray has been generated and, through many hundreds or thousands of calculations, has propagated to very large radial distances from the source region, it is important to determine if that ray position may have been largely due to round off errors in the numerical calculations. To determine the extent of the round off errors, the programmer uses the ray parameters at the final ray position and retraces that ray back toward the source. For computer round off errors not to be significant, the ray must go back through the source region at the original initial wave normal angle to within the desired accuracy.

In summary, successful ray tracing of electromagnetic waves in anisotropic media, such as planetary magnetospheres, involves an understanding of the ray tracing equations, the formalization of the index of refraction used, and the generation mechanism in order to determine the initial wave normal angles and the propagation modes or polarization of a particular emission. Believable results will be produced from accurate plasma and magnetic field models and from verifying the program calculations.

Ray tracing applications: Auroral Kilometric Radiation

In this section, we will discuss the application of ray tracing techniques to the Earth's auroral kilometric radiation. Over the last ten years, auroral kilometric radiation or AKR has been extensively studied through ray tracing techniques. The first AKR ray tracing was done by Jones and Grard (1976) assuming an auroral zone source of L–O mode waves from an unspecified generation mechanism. Jones (1977) later proposed that AKR could be generated through a conversion of Z mode rays into L–O mode free escaping rays. Both these papers relied on the very limited observations of AKR at that time.

Guided by comparisons with observations, Figure 9 from Green et al. (1977) shows four panels of rays at frequency covering 500 kHz down to nearly 60 kHz. As Green et al. (1977) pointed out, these nightside auroral zone rays adequately described the observations of an emission cone whose angular distribution increases with emission frequency. The best fit results were from the R–X mode ray paths (there were no measurements of the polarization of AKR at that time). In addition, their R–X mode tracing showed the dayside/nightside asymmetry of the radiation. The top of the nightside plasmasphere produced a sharp cutoff to AKR but there was no corresponding cutoff on the dayside of the Earth. These ray tracing calculations also agreed with earlier results of direction finding measurements that indicated that AKR was generated in the auroral zone along auroral field lines

R-X MODE RADIATION

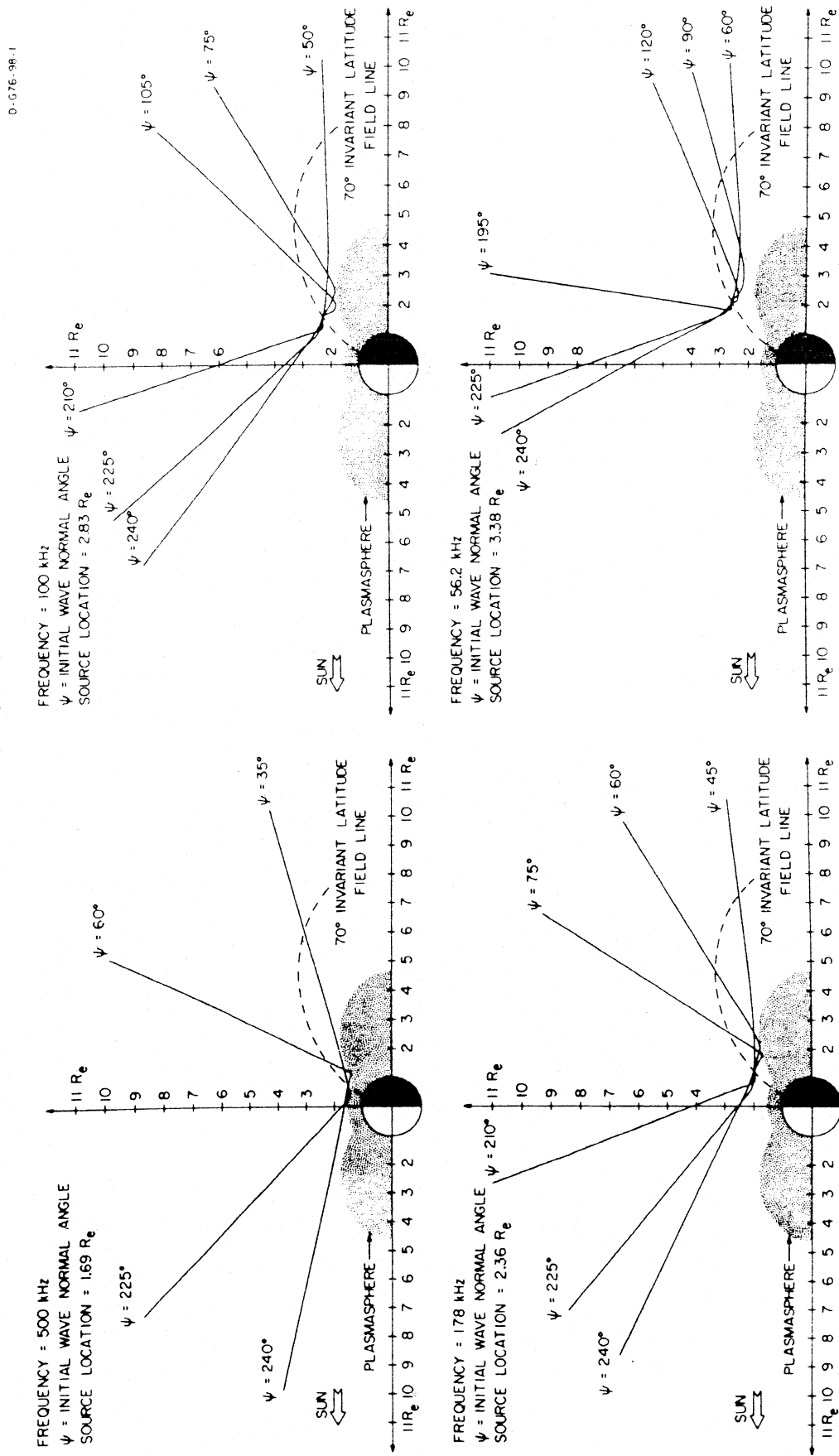


Fig. 9: Ray tracing calculations showing the angular extent of R-X mode waves at frequencies 500 to 56 kHz. These ray paths exhibit many of the observed characteristics of the Earth's auroral kilometric radiation.

perhaps above discrete auroral arcs. On the nightside, the plasmasphere also presented a propagation obstacle and formed a shadow zone for which, at low magnetic latitudes just outside the plasmasphere, the AKR source regions were unable to generate rays that could reach this area.

As observations of auroral kilometric radiation increased from 1977 to the early '80s, many refinements in the understanding of the source regions and the polarization characteristics of this emission were made. Hashimoto (1984) presented the first three-dimensional ray tracing of R-X and L-O mode AKR based on the Wu and Lee (1979) generation mechanism. As shown in Figure 10, Hashimoto ray traced L-O and R-X mode rays just above the $R=0$ cutoff. In addition, Hashimoto confined the ray tracing results to initial wave normal angles from 60° to 90° . The comparison of the two resulting emission cones show that the R-X mode rays, whose frequency is close to its local $R=0$ cutoff, are strongly refracted in the source region. In contrast, on the left side of Figure 10 are the L-O mode waves at 500 kHz (generated at the local $R=0$ cutoff) which form a very broad emission cone. The important point of Hashimoto (1984) is that it is the combination of both L-O mode and R-X mode waves with preferred wave normal angles that adequately describe the most recent observations of the angular extent and predominate, but not exclusive, R-X mode polarization of AKR.

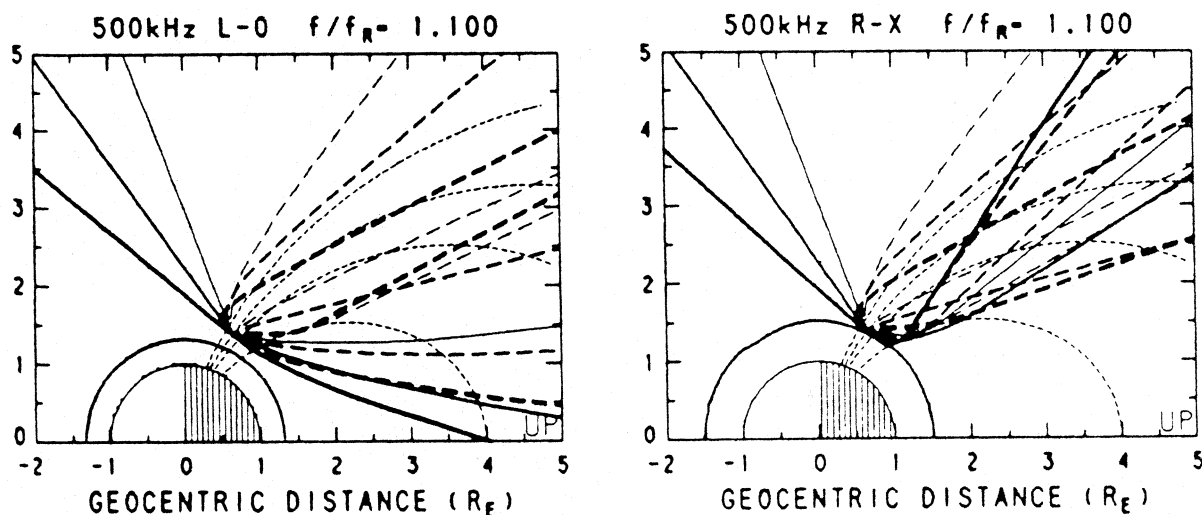


Fig. 10: Three dimensional ray path calculations at 500 kHz from an L-O mode (left hand panel) and R-X mode (right hand panel) auroral zone source.

The Earth's non-thermal continuum radiation

There have been several ray tracing studies in the last fourteen years on the Earth's non-thermal continuum radiation. Before any detailed understanding of the emission

mechanism and source of continuum radiation, Jones and Grard (1974) showed in Figure 11 that radiation at the frequency of 20 kHz generated somewhere in the magnetospheric cavity would not propagate through the magnetopause. It is now believed that multiple reflections like those shown in Figure 11 at the magnetopause broadened the spectrum of the initially narrow band continuum radiation generated near the morning plasmopause and produce the continuous spectral features of the emission. The 20 kHz continuum radiation seen within the Earth's magnetosphere is now referred to as the trapped continuum since it cannot propagate through the magnetopause, but at lower densities deep in the tail it may be able to propagate out into the solar wind.

It is now generally believed that the Earth's continuum radiation is generated at the equatorial morning plasmopause in association with strong electrostatic waves. Jones (1980) first used a model for which Z mode waves that are generated at the plasmopause are converted to the free escaping O mode waves. Figure 12 shows, at position S, a Z mode wave that propagates a very short distance within the plasmopause. The Z mode wave is refracted towards the magnetic field upon entering a region conducive of mode coupling, couples into an ordinary mode wave which can freely escape through this thin layer of the outer plasmasphere into space. The O mode waves leave the equatorial plasmasphere at the initial angle α (which is related to the local gyro and plasma frequencies) where the wave frequency equals the local electron plasma frequency. Within a certain thickness of the plasmasphere, multiple waves could be generated, producing a broad dual beam pattern. The broad dual beam pattern qualitatively matches recent observations by the Dynamics Explorer spacecraft.

Jovian decametric radiation

Jovian decametric radiation has been ray traced quite extensively for the last four or five years. The first three-dimensional ray tracing calculations of Jovian Io-dependent decametric radiation were done by Hashimoto and Goldstein (1983). To verify the proposed source regions of the decametric emission, Hashimoto and Goldstein (1983) traced rays from low altitude source regions (just above the $R=0$ cutoff) determined by the field lines of multiply reflected Alfvén waves in the Io torus. Figure 13 shows the results of their ray tracing calculations on an Io phase versus CML diagram as observed at 22 MHz from the Earth. Hashimoto and Goldstein's Jovian magnetosphere contained their model ionosphere and the inner magnetosphere model of Sentman and Goertz (1978). The X, Y, and Z symbols correspond to rays generated with wave normal angles of 70° , 80° , and 90° respectively to the magnetic field. In addition, at least 72 rays were generated azimuthally about the magnetic field of Jupiter forming a hollow emission cone. The observed radio frequency contours are also shown with the ray path calculations. As can be seen in Figure 13, the ray calculations closely match the observations and confirm that the decametric radiation sources may very well be described by hollow emission cones rather than uncoupled narrow beams of radiation generated at specific longitudes.

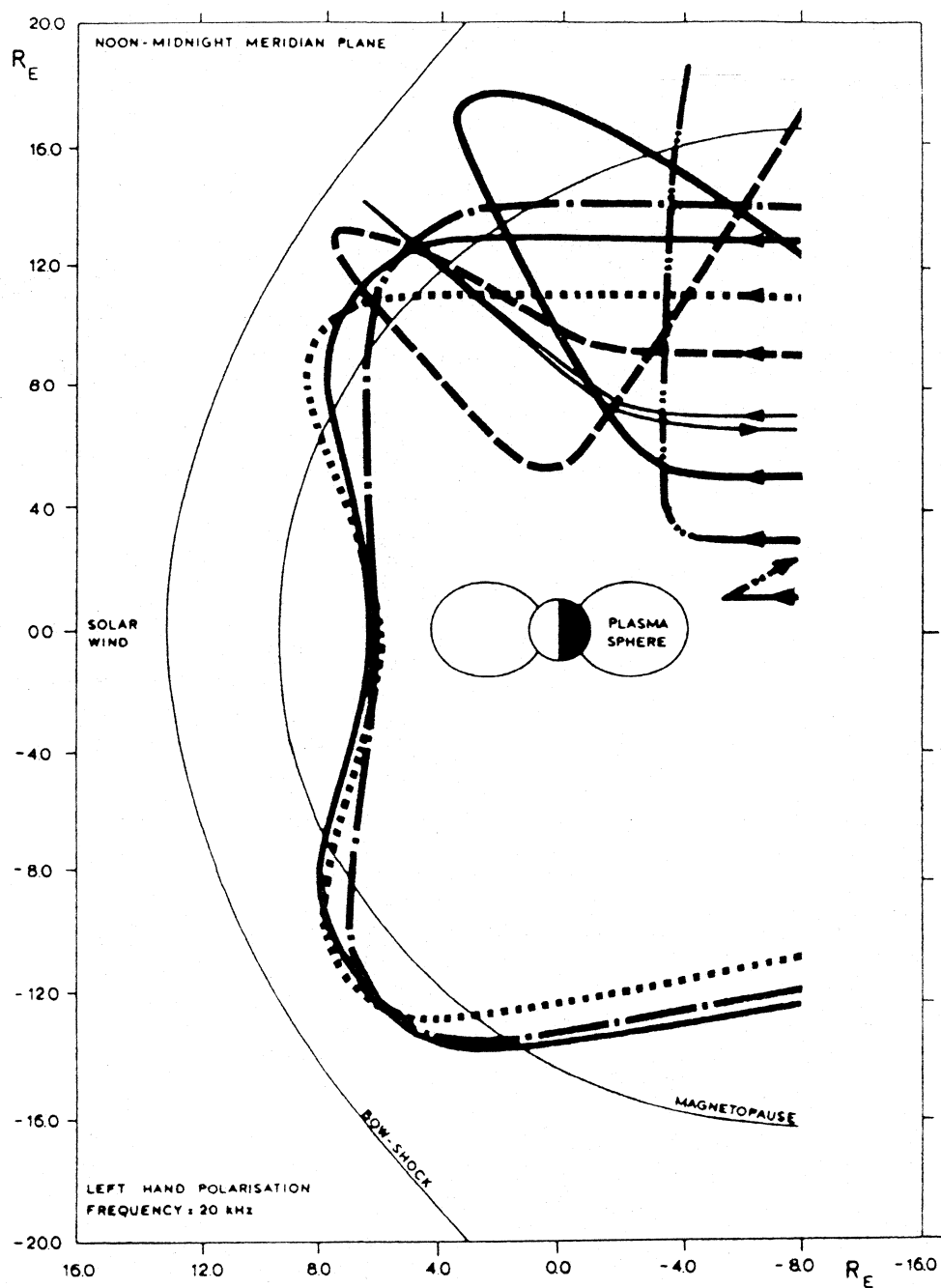


Fig. 11: Ray path calculations of magnetospherically trapped electromagnetic radiation. Multi-reflections near the magnetopause that are illustrated in this figure are believed to broaden the frequency band of the trapped continuum radiation generated just outside the Earth's plasmasphere.

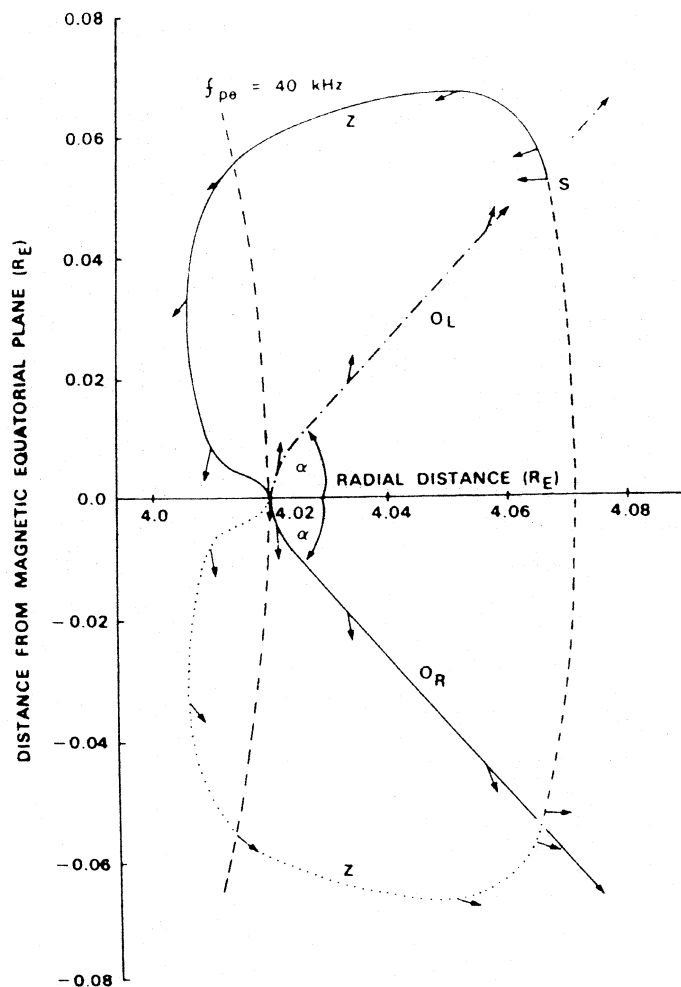


Fig. 12: Electrostatic Z mode radiation in the plasmopause propagates to the magnetic equator and couples out to the O - mode free space at the angle α . These complicated ray paths may be representative of the propagation of the Earth's non-thermal continuum radiation.

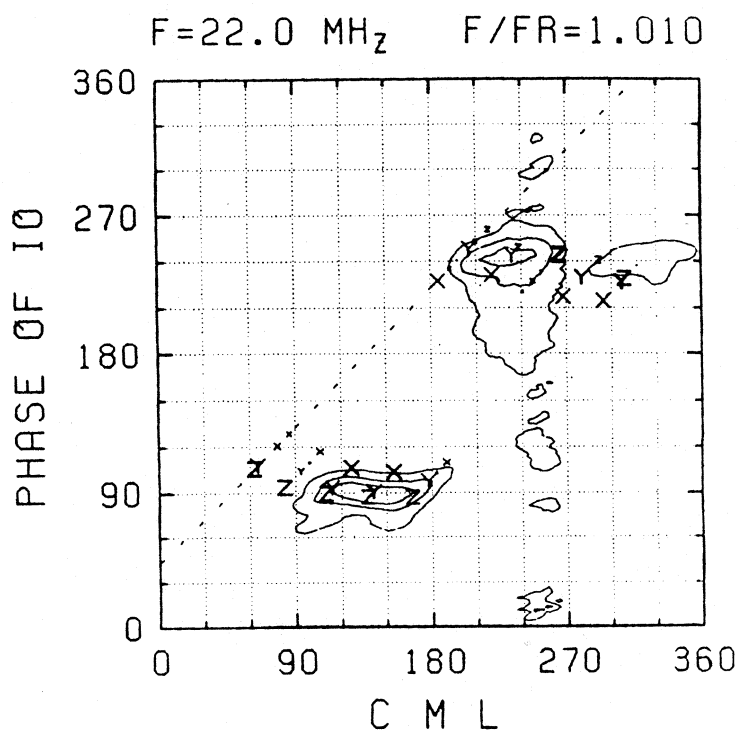


Fig. 13: Jovian decametric observations and ray path calculations at 22 MHz in the standard coordinate system of the Central Meridian Longitude (CML) of Jupiter as observed from the Earth versus the phase of the moon Io. The contours are of real measurements and the symbols X, Y, and Z show the resulting location of ray paths generated close to Jupiter.

Another study by Green (1984) used the ray tracing technique to explore the decametric arc structure extending the work of Hashimoto and Goldstein (1983) by also assuming the generation of hollow emission cones. As shown in the schematic of Figure 14, the dynamic spectra as observed by Voyager 1 and 2 are on the edges of the proposed hollow emission cone model of the Io-dependent decametric emission. These emissions are observed to have the characteristic vertex early and vertex late shape in frequency time spectrograms. A summary of the ray tracing calculations from Green (1984) is shown in Figure 15. The hollow emission cones that were computed from initial wave normal angles at approximately 90° in the source regions at 2, 20, 25 and 30 MHz are shown as a Mercator projection in the middle panel of Figure 15. The dotted line in the middle panel is the path of the Voyager 1 or 2 spacecraft going through these emission cones. The resultant frequency versus longitude diagram of the spacecraft as it cuts through these emission cones is shown in the bottom panel of Figure 15. The bottom panel shows that the left edge of the hollow emission cone consists of very small curvature arcs however, on the right edge of the emission cone the radiation pattern has a curvature which is much greater. The calculated ray paths qualitatively compare extremely well with the two observed edges of the emission cone from the dynamic spectra (compare with Figure 14) and can be fairly easily explained as propagation effects based mostly on the ionospheric and magnetic field models used in the ray tracing calculations.

The top panel of Figure 15 shows that at one edge of the hollow cone, as the rays leave the source, they propagate into a region of very large magnetic fields (O4 model) and are sharply refracted, therefore forming an arc of an extremely large curvature. On the right hand side of the cone, however, where the local magnetic field provides less of a propagation effect, we see a much greater range in the emission cone angles, therefore, generating an arc-like structure. This technique was extended by Menietti et al. (1984a) to multiple Io longitudes. Studies such as these indicate that only qualitative understanding of the complicated arc structure can be obtained; however, they support hollow emission cones that suffer major propagation effects due to the ionosphere and the large magnetic field of Jupiter for decametric emissions.

Jovian kilometric and hectometric radiations

A new two component emission discovered by Voyager 1 and 2 as it encountered the magnetosphere of Jupiter was discovered at kilometric wavelengths. This two component radiation has also been referred to as narrow band kilometric (nKOM) and broad band kilometric (bKOM) radiation. The bKOM emission exhibited a frequency dependent shadow zone (higher frequencies are observed at higher magnetic latitudes) with alternating polarizations in the northern and southern hemispheres.

Green and Gurnett (1980) ray traced the bKOM in an effort to determine a possible location of the source region of this new emission. Figure 16 shows the illumination pattern of a northern and southern hemisphere sources of bKOM assuming a low altitude origin emitting L–O mode waves at 400 kHz. These results indicate that the Io torus provides a major propagation effect to the waves. In these examples, the torus produces

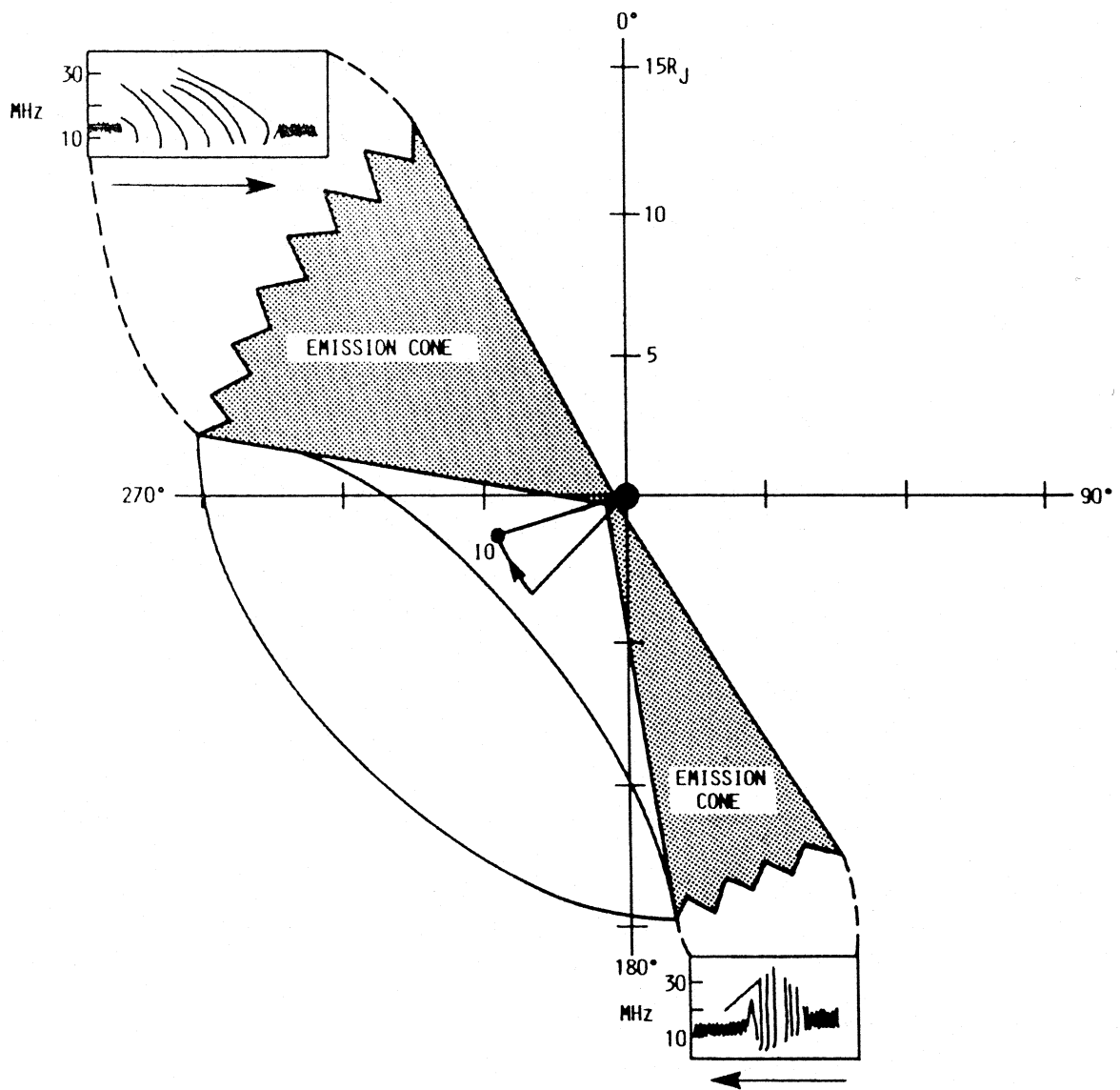


Fig. 14: A schematic of the observed decametric arcs from the PRA instrument on board Voyager 1 and 2 relative to a hollow emission cone model for the generation of Io-dependent decametric radiation.

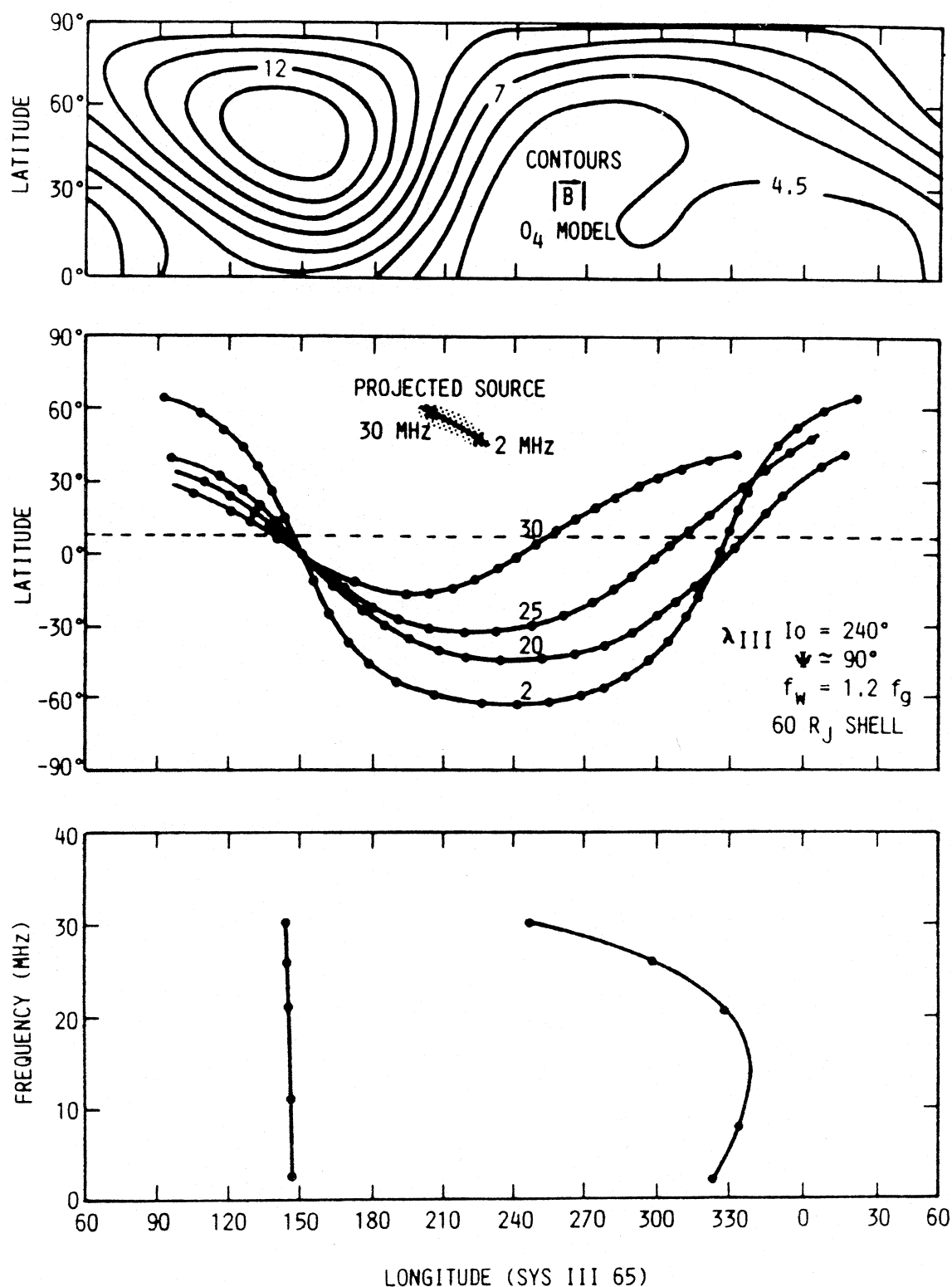


Fig. 15: Ray path calculation of Jovian decametric radiation in a Mercator projection. The observed decametric arc structure (bottom panel) appears to be the result of propagation effects occurring to different degrees on opposite edges of the hollow emission cones that are generated at low altitude along I_0 field lines.

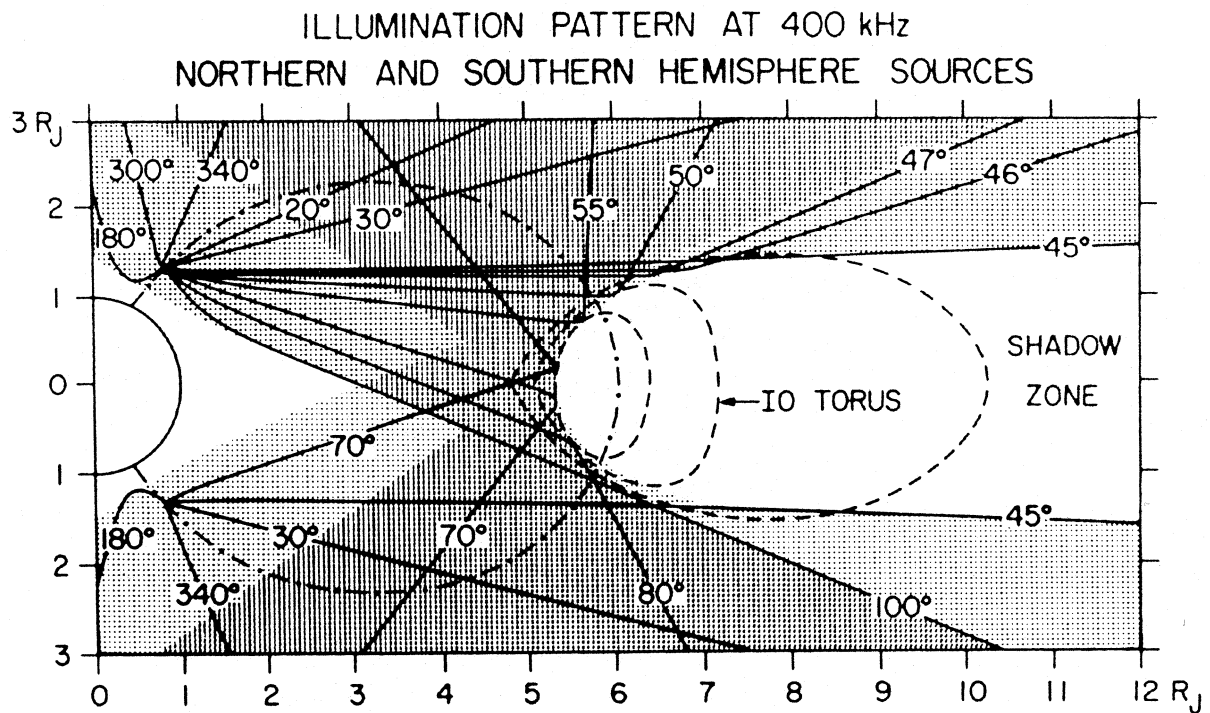


Fig. 16: Ray path calculations of L-O mode Jovian bKOM in a model Jovian magnetosphere with an Io torus. The Io torus produces a shadow zone since the rays are not able to completely propagate through the torus at frequencies below 400 kHz.

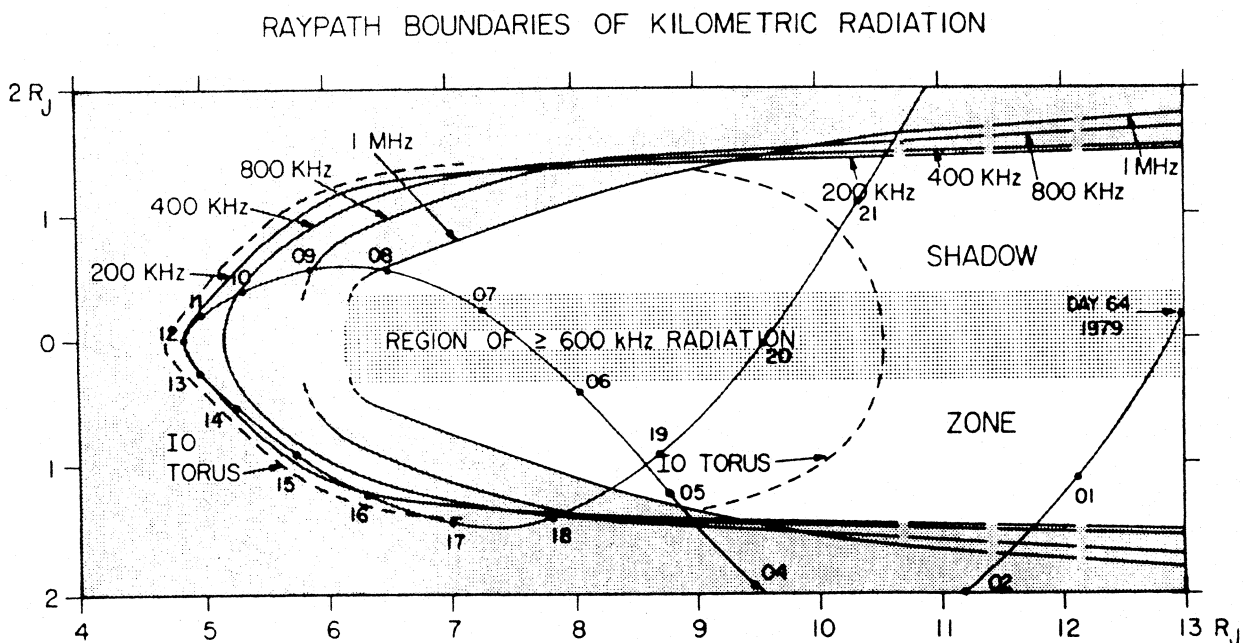


Fig. 17: Resulting boundaries of L-O mode ray path calculations from 200 kHz to 1 MHz. The path of Voyager 1 is shown as a solid line.

a shadow zone which was observed by Voyager 1 and 2. A summary of the results of the Green and Gurnett (1980) ray tracing calculations is shown in Figure 17. Draped about the Io torus are the caustic surfaces formed from many rays generated in the frequency range from 200 kHz to 1 MHz (typical frequency extent of the bKOM). There are several features shown that are characteristic of the observations. As the spacecraft follows the trajectory shown as a solid line, it will observe successively higher frequency emissions as it increases in latitude. The opposite effect is seen as the spacecraft moves to lower latitudes. Therefore as the spacecraft moves from the low latitude to high latitude and then to low latitude again, the PRA instrument will observe a Christmas tree structure in a frequency time spectrogram. This effect was observed by both Voyager 1 and 2.

It is important to note that the Green and Gurnett (1980) results are not unique in describing the observations from Voyager 1 and 2. Jones (1980 and 1981a) again proposed a Z to O mode conversion mechanism for the generation of bKOM in exactly an analogous manner as he proposed earlier for the generation of the Earth's non-thermal continuum radiation. The results of his initial study are shown in Figure 18. Here the Io torus is the host for the KOM source regions and produce major regions of emission that also can reproduce the Christmas tree and shadow zone effects for radial distances greater than $10 R_J$.

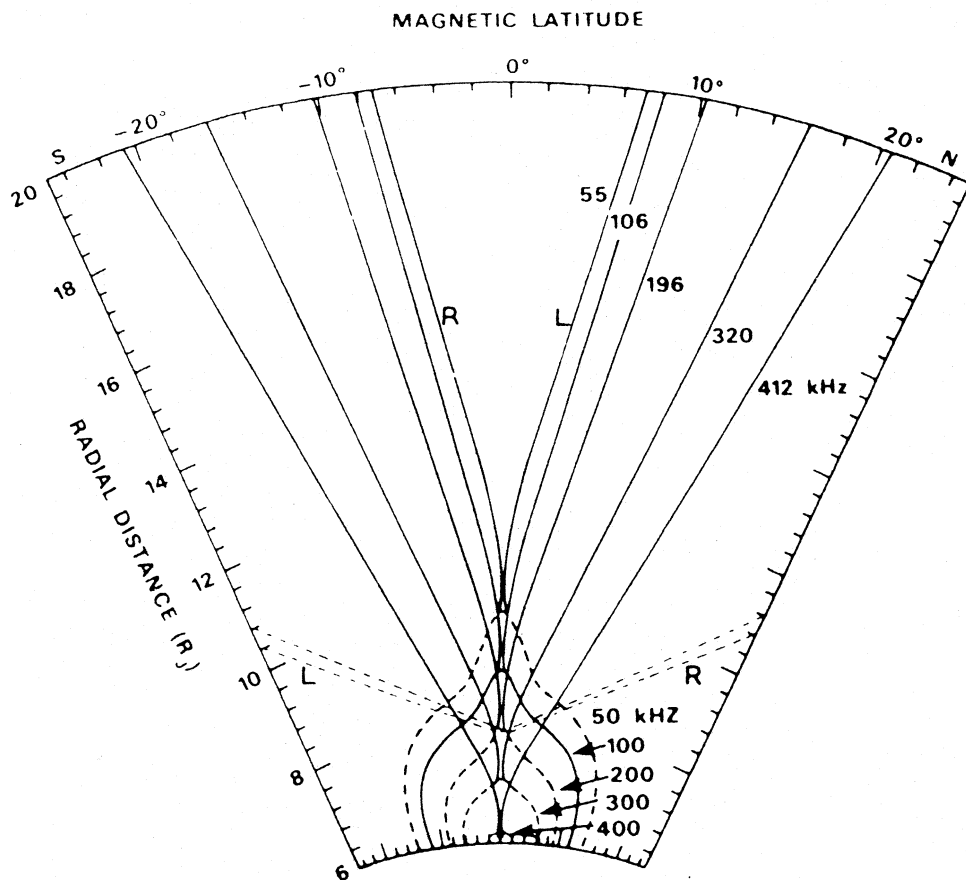


Fig. 18: Ray path calculations from a proposed generation mechanism of bKOM involving the conversion of Z mode waves into O mode waves within the Io torus.

Lecacheux (1981) ray traced kilometric and hectometric radiation and compared with the observations made by Voyager 1. In his unique analysis, Lecacheux ray traced multiple rays at specific frequencies, not from a specific source region, but as it would be observed from the Voyager spacecraft. The heavy lines in Figure 19 are the edges of the maximum extent of the 300 kHz radiation pattern generated in the R-X and L-O free escaping modes as would be seen from the Voyager 1 spacecraft at various times along its trajectory. Figure 19 shows that a region at approximately $x = 5.2$ and $y = -1.6$ Jovian radii is the most likely source region for the kilometric radiation observed at closest approach. The Lecacheux (1981) results are consistent with the Green and Gurnett (1980) ray tracing results of a high latitude but relatively low altitude source region for which both are inconsistent with the Jones (1981a) results.

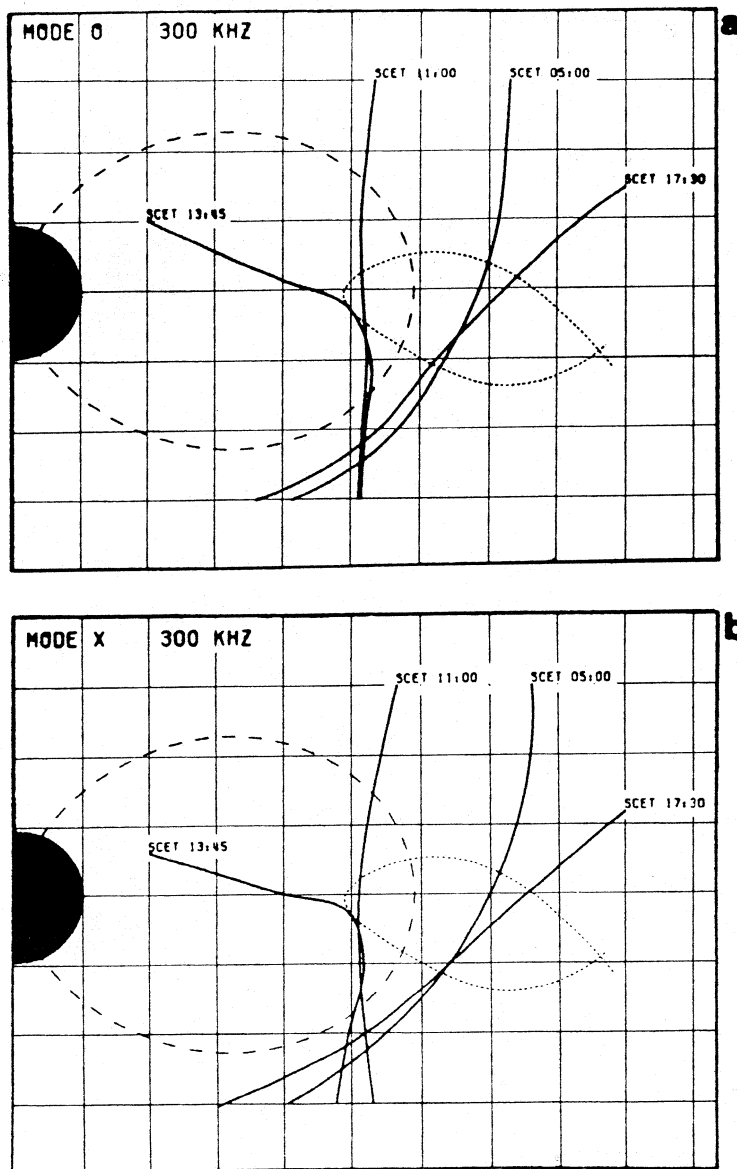


Fig. 19: Computed boundaries of O and X mode kilometric source regions that could be responsible for the emissions observed at closest approach by Voyager 1 (trajectory shown as a dotted line). The intersection of these boundaries indicates a probable source region for bKOM at high latitudes along (or near) the Io flux tube (shown as a dashed line).

The high frequency ray tracing calculations presented by Lecacheux (1981), in that same paper, did not provide adequate information to determine or localize a source region for the Jovian decametric radiation.

Summary and future applications

There have been extensive ray path calculations of the Earth's auroral kilometric and continuum radiations and for Jovian decametric and kilometric radiation over the last 10 years or more. These calculations have made significant contributions to the understanding of source region characteristics and have helped to place constraints on the possible generation mechanisms and initial wave normal angles. In this paper I have discussed only a few of the many papers that have used ray tracing in an effort to provide a brief review and demonstrate the usefulness of the ray tracing technique to planetary radio emissions.

With respect to AKR and DAM, the ray tracing calculations have been advanced to the point where they are nearly complete within the framework of the existing computer models. With respect to the ray tracing calculations of the Earth's non-thermal continuum radiation, we find that additional work can be done with the possible inclusion of hot plasma effects.

In the ray tracing of the Jovian bKOM radiation, we have obtained some estimates of where the source region may be located, however, it is clear that there are no unique solutions. Better plasma models (i.e., Io torus) need to be used to help determine or refine these source region locations. Ray tracing of nKOM, the Jovian non-thermal continuum, and hectometric radiations may substantially increase our understanding of these emissions and their relationship to the bKOM. In addition, much work needs to be done on understanding which plasma modes are involved in the generation of these emissions.

The outer planets, such as Saturn and Uranus, are fairly rich emitters of free escaping radiation for which our knowledge could greatly benefit from the application of ray tracing techniques. There are analytic models of the magnetic field for Saturn and Uranus, however, complete plasma models are not currently available but will be needed to adequately describe the environment.

In summary, ray tracing is a necessary tool for the understanding and studying of planetary radio emissions and provides a unique ability to bridge both theoretical and observational results. Through the use of ray tracing calculations a deeper understanding of the physical mechanism that generates the observed emission can result.

