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# Magnetospheric Filter Effect for Pc 3 Alfven Mode Waves

X. Zhang[1], R. H. Comfort[1], D. L. Gallagher[2], J. L. Green[3], Z. E. Musielak[1], T. E. Moore[2]

## Abstract

We present a ray-tracing study of the propagation of Pc 3 Alfven mode waves originating at the dayside magnetopause. This study reveals interesting features of a magnetospheric filter effect for these waves. Pc 3 Alfven mode waves cannot penetrate to low Earth altitudes unless the wave frequency is below approximately 30 mHz. Configurations of the dispersion curves and the refractive index show that the gyroresonance and pseudo-cutoff introduced by the heavy ion $O^+$ block the waves. When the $O^+$ concentration is removed from the plasma composition, the barriers caused by the $O^+$ no longer exist, and waves with much higher frequencies than 30 mHz can penetrate to low altitudes. The result that the 30 mHz or lower frequency Alfven waves can be guided to low altitudes agrees with ground-based power spectrum observations at high latitudes.

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[1] Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899

[2] Space Science Laboratory, NASA/Marshall Space Flight Center, Huntsville, AL 35812

[3] National Space Science Data Center, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

## Introduction

Studies have shown the magnetopause to be an important wave source region for Alfven mode Pc 3 waves. Guided propagation of Alfven waves in the magnetosphere has generally been discussed in terms of so-called toroidal and transverse poloidal modes of oscillation [*Dungey*, 1955, 1967]. It is established that many of the disturbances in the Earth's magnetosphere are a response to variations in the solar wind. Much evidence has shown that plasmas can penetrate through the Earth's bow shock to ionospheric altitudes in the cusp *region* [*Heikkila and Winningham*, 1971; *Frank*, 1971]. There are several possible mechanisms for the generation of Alfven mode waves. One is the perturbation of fluid elements at the magnetopause by a sudden change in solar wind pressure. This change will move the boundary from its equilibrium position, and the disturbance would propagate in the form of Alfven waves [*Sibeck*, 1990]. Another wave generation mechanism is the surface wave model, involving the Kelvin-Helmholtz instability at the magnetopause [*Miura*, 1984, *Yumoto*, 1984]. A third wave generation mechanism is the penetration by upstream ULF waves of the collisionless bow shock region, across the magnetosheath and the magnetopause. Studies have shown that Pc 3 pulsations are related to activity in the ion foreshock region of the solar wind upstream of the Earth's bow shock and magnetosphere [*Odera*, 1986; *Arnoldy et al.*, 1988; *Engebretson et al.*, 1990].

In a previous paper [*Zhang et al.*, 1993] we examined propagation properties of compressional Pc 3 waves generated in the upstream dayside magnetopause using a ray tracing analysis. The results show that the magnetosphere filters the high frequency components of Pc 3 compressional waves, allowing the low frequency component waves to penetrate to low altitudes.

The penetration of Pc 3 compressional waves is, to a great extent, controlled by the $He^+$-$O^+$ relative concentration. In this paper, we present preliminary results of a ray tracing study of Pc 3 Alfven mode waves started from the dayside magnetopause. We demonstrate that a similar magnetospheric filter effect also applies to Pc 3 Alfven mode waves. We then compare the ray tracing results with ground observations from South Pole Station and McMurdo, Antarctica (at invariant latitudes of $-74^0$ and $-79^0$, respectively), reported by *Engebretson et al.* [1989, 1990].

## Models for this Study

In a previous paper [*Zhang et al.*, 1993], we introduced our ray-tracing program, and the plasma and magnetic field models. Briefly, the basic ray-tracing equations are from *Haselgrove* [1954], and this ray-tracing program is based on the *Stix* [1962] cold plasma index of refraction. In this study, we use a modified ray tracing code from *Green et al.* [1977]. The original ray tracing code was written by *Shawhan* [1967]. The magnetic field model used in this study is from the empirical model of *Mead and Fairfield* [1975]. The distribution of plasmaspheric plasma density is from the empirical density model of *Gallagher et al.* [1994], and plasma composition is based on the observations of thermal ion distributions by *Horwitz et al.* [1986], and *Comfort et al.* [1988]. For this study we use 75% $H^+$, 20% $He^+$, 5% $O^+$ throughout the magnetosphere.

## Characteristics of dispersion curves and the refractive index for Pc 3 Alfven mode waves

Figure 1 shows cold plasma dispersion relation curves for the model magnetopause region in the Pc 3 wave frequency range. In the dispersion curves, we mark two types of wave modes, Alfven mode and fast mode. Figure 2 shows contours of the refractive index for the transverse Alfven mode wave in the meridian plane for a frequency of 100 mHz. Comparing this topology of the refractive index of Pc 3 Alfven mode waves with the dispersion relation (Figure 1), we can identify three resonance regions in Figure 2 which correspond to the three ion cyclotron resonances for $H^+$, $He^+$, and $O^+$, for Pc 3 Alfven mode waves. For a fixed frequency, heavier ions will have a cyclotron resonance closer to the Earth, at higher magnetic field strengths, than lighter ions. The $H^+$ resonance, therefore, is found at the largest radial distance from the Earth (in the polar region), the $O^+$ resonance is closest to the Earth, and the $He^+$ resonance is in between. The other two intense gradient regions correspond to the plasmapause and to the boundary between the closed field and polar regions. For decreasing wave frequency, the resonances will occur at larger radial distances. This is seen in Figure 3 which shows the contours of the refractive index for a wave frequency of 40 mHz. Note that the $O^+$ resonance no longer encircles the Earth, but is open at low latitudes. The significance of this becomes apparent below.

In order to understand the behavior of Alfven mode waves, we need to discuss some new features besides cutoffs and gyroresonances and their corresponding characteristic frequencies. In the 3-ion-species dispersion relation, there are two locations in which the fast mode waves and the Alfven mode waves have the same phase velocity at zero wave normal angle. The corresponding frequency is called a cross-over frequency, defined by *Smith and Brice* [1964]. For three-ion-species plasmas, we have two cross-over frequencies, which we denote by $F_{cr1}$ and

$F_{cr2}$. These crossover frequencies occur between the $H^+$-$He^+$ and $He^+$-$O^+$ resonances respectively. There are two other special locations in the dispersion curves (Figure 1). The first of them is located in the frequency range between the $He^+$-$O^+$ cutoff frequency and $F_{O+}$, the $O^+$ cyclotron frequency, and the second between the $H^+$-$He^+$ cutoff frequency and $F_{He+}$, the $He^+$ cyclotron frequency. At these two special locations, the dispersion curves show steep slopes, similar to resonances and cutoffs. We will refer to them as pseudo-cutoffs (or pseudo-resonances), since their properties are similar to cutoffs or resonances for waves. Their corresponding frequencies are called bi-ion-hybrid frequencies [Rauch and Roux, 1982], which we refer to as $F_{bi1}$ and $F_{bi2}$, respectively.

We note in Figure 3 that when the wave frequency is lower than 40 mHz, the $O^+$ resonance band becomes open at low latitudes. This frequency (40 mHz) is near the 'critical frequency' for Pc 3 Alfven mode waves. Similar to that defined by *Zhang at al.* (1993), this 'critical frequency' is defined as the frequency for which the $O^+$ resonance location just becomes tangent to the magnetopause at the equator. Waves with frequencies below the 'critical frequency' are located leftward of $F_{O+}$ in the dispersion relation curves (Figure 1). Since the general tendency for these waves is to travel toward the intense magnetic field strength region along field lines, the waves move to the left in the dispersion curves. Therefore, Pc 3 Alfven mode waves below the 'critical frequency' (or below the local $O^+$ gyrofrequency) are free from all cutoff or resonance (including pseudo-cutoff or pseudo-resonance) barriers. These waves are able to penetrate to the Earth's ionosphere. Unlike the situation of cutoffs for fast mode waves, the locations of the resonances do not vary with the plasma relative concentrations. However, if we eliminate an ion species, say $O^+$, the corresponding resonance disappears.

## Ray tracing examples of Alfven mode waves

In the figures below, we present families of ray paths for Pc 3 transverse Alfven mode waves. All rays are launched from the magnetic equator on the dayside magnetopause. Rays are launched in the noon-midnight magnetic meridian plane at varying initial wave normal angles. We use a solid line for rays with WKB condition [*Zhang et al.*, 1993] equal to or less than 0.1, a dashed line when the WKB condition is greater than 0.1 but less than or equal to 1.0, and small 'x' when the WKB condition is greater than 1.0. A solid line means that the ray tracing well satisfies the WKB approximation. A dashed line gives a warning for the WKB approximation. Small 'x' in the ray tracing means that the WKB approximation has clearly broken down. We disregard waves after they have encountered this condition.

Figures 4, 5, and 6 show rays of transverse Alfven waves with frequencies of 100 mHz, 40 mHz and 30 mHz. We display rays launched with a range of initial wave normal angles from 0° to 180°, at 10° intervals. We can see that Pc 3 Alfven mode waves are guided by the magnetic field line, as is characteristic of Alfven waves and required by the index of refraction. From Figure 4, the 100 mHz rays are guided along magnetic field lines to the increased magnetic field strength region, so that each of the gyrofrequencies increases. In the dispersion relation (Figure 1), we can see that the 100 mHz wave frequency is between $F_{O^+}$ and $F_{He^+}$. As the magnetic field increases along the wave trajectory, the dispersion curves in Figure 1 move to the right. At the location where $F=F_{cr2}$, the waves undergo a polarization reversal and are converted from left-hand polarized to right-hand polarized waves. As the waves move farther along the dispersion curve, they encounter the pseudo-cutoff at the point $F=F_{bi2}$, the second bi-ion-hybrid frequency, and waves are reflected. If we compare this ray plot with the contours of the refractive index for both fast mode [*Zhang et al.*, 1993] and Alfven mode (Figure 2) waves for this same frequency, we find that the location of reflection for 100 mHz in Figure 4 is between the $He^{+}$-$O^{+}$ cutoff and the $O^{+}$ gyroresonance. This position just corresponds to the location of the pseudo-cutoff in the dispersion relation (Figure 1).

The situation for 40 mHz rays in Figure 5 is quite different. This frequency (40 mHz) is just slightly below $F_{O+}$ in the dispersion relation (Figure 1). These Alfven mode waves propagate along an L-shell into a region of decreasing magnetic field strength (a feature of the realistic dayside magnetic field). In the dispersion relation (Figure 1), the gyrofrequencies move leftward, showing that the wave will propagate into the $O^{+}$ gyroresonance and be absorbed. If we overlay the contours of the refractive index for 40 mHz for Alfven mode waves (Figure 2) with the ray trajectory traces (Figure 5), we can see that these rays stop at the location where they encounter the $O^{+}$ gyroresonance.

The 30 mHz rays in Figure 6 are below the 'critical frequency'. The wave source is in a location below $F_{O+}$ in the dispersion relation (Figure 1). When these waves propagate along magnetic field lines, they narrowly miss (individual rays encounter) the $O^{+}$ gyroresonance. After these rays pass the region of decreasing magnetic field strength, they enter a region of increasing magnetic field strength, so that the wave locations move leftward along dispersion curves in Figure 1 (in the dispersion relation (Figure 1), the gyrofrequencies move rightward). Therefore, when the rays escape from the $O^{+}$ gyroresonance, they are also free from all the cutoff or resonance *(including pseudo-cutoff or pseudo-resonance)* barriers at frequencies above $F_{O+}$. Therefore, most 30 mHz rays are able to be guided along magnetic field lines to the Earth's ionosphere.

Since an $O^+$ concentration in the magnetosphere introduces cutoff and resonance (including pseudo-cutoff or pseudo-resonance) barriers in the magnetosphere in the Pc 3 frequency range, it is of interest to check the case where there is no $O^+$ concentration. Figure 7 shows Alfven mode rays at 100 mHz with no $O^+$, where the concentration of $H^+$ is 80% and $He^+$ is 20%. Because the $O^+$ concentration is removed, all the cutoffs and resonances (including pseudo-cutoffs or pseudo-resonances) at frequencies below $F_{He^+}$ in the dispersion relation (Figure 1) are gone. There are no more barriers for 100 mHz Alfven mode waves, so that they are able to penetrate to the Earth's ionosphere. This plot further supports our suggestion that $O^+$ is the main factor which keeps Pc 3 transverse Alfven waves from reaching the ionosphere.

## Discussion and summary

There have been extensive experiments and theoretical reports [e.g. *Anderson et al.*, 1990] on the role which Pc 3 waves (20-100 mHz) play in energy transport from the solar wind to the inner magnetosphere. However, the fundamental question as to how wave energy is transported from the solar wind in the foreshock magnetosheath to the low altitude magnetosphere remains unclear. Our previous ray tracing study [*Zhang, et al.*, 1993] revealed important features regarding transport of wave energy from the magnetopause into the inner magnetosphere through Pc 3 compressional waves. This study reveals magnetospheric wave energy transport through the other wave mode branch, Pc 3 Alfven mode waves.

The penetration of upstream ULF magnetic pulsations across the magnetopause was studied by *Troitskaya et al.* [1971], *Hoppe and Russell* [1983], and *Yumoto et al.* [1985]. *Yumoto et al.* [1985] suggested that the magnetopause wave source of high latitude Pc 3 pulsations can be either surface waves excited by solar wind-driven instabilities or upstream waves in the Earth's foreshock. Observations support the idea that wave energy could be transported via cusp field lines from the magnetopause to the ionosphere through Pc 3 Alfven mode wave propagation [*Bol'shakova and Troitskaya,* 1984, *Plyasova-Bakounina et al.*, 1986, *Morris and Cole,* 1987, *Engebretson,* 1989]. Our ray tracing study of Pc 3 Alfven mode waves provides a more concrete picture of how wave energy at the magnetopause might be transported to the high latitude ionosphere and also what constraints on this transport might be imposed by the magnetospheric plasma medium.

This study shows that the dominant behavior of the Earth's magnetosphere is like that of a low pass filter for transverse Alfven waves generated at the equatorial magnetopause. Figure 8 shows schematically the characteristics of the filter action of the magnetosphere for Pc 3 transverse Alfven mode waves. The vertical coordinate is wave frequency, and the horizontal coordinate is the penetration altitude. This figure shows that when the wave frequency is below about 30 mHz, Pc 3 Alfven mode waves are able to penetrate to the 1 $R_E$ (ionosphere) region, so the pass band to the ionosphere for Pc 3 transverse Alfven mode waves is below 30 mHz. There is also a stop band in the characteristics of the filter. The stop band is from about 40 mHz to about 60 mHz, for which there are no Alfven mode waves. The reason for the existence of the stop band is that between the gyrofrequency and bi-ion cutoff, Alfven mode waves do not exist. At somewhat higher frequencies, Alfven mode waves can propagate into the magnetosphere before being turned back by the $He^+$-$O^+$ ion-ion resonance. Just above this band and above the lower frequency transmission band, the Alfven mode wave encounters either the $He^+$ or the $O^+$ gyroresonance and is absorbed.

The results from our ray tracing study match very well with high latitude ground station observations. *Engebretson et al.* [1989, 1990] reported that Pc 3 wave activity was observed at South Pole Station, which is located at a latitude near the nominal foot point of the dayside cusp/cleft region, and McMurdo, Antarctica (at invariant latitudes of $-74^0$ and $-79^0$, respectively). During selected days in March and April 1986, Pc 3 activity correlated with the low interplanetary magnetic field (IMF) cone angle, suggesting that this Pc 3 activity was related to upstream wave activity. The power spectra observed at these two high latitude observatories have a steep drop-off in spectral density toward high frequencies. The cutoff frequency in the pass band of the power spectrum is near 30 mHz, which is consistent with the results from our ray tracing studies.

From the above analysis, we can conclude that the cold plasma approximation is sufficient to explain a low pass effect for Alfven mode waves propagating from the equatorial magnetopause to the ionosphere. The pass band is located below about 30 mHz; this frequency is a function of the magnetopause magnetic field strength. That means that increased solar wind pressure should raise the magnetic field strength there and increase the maximum frequency of Pc 3 waves observed on the ground. The characteristics of the magnetospheric filter are largely determined by the magnetic field strength at the magnetopause and along the magnetopause L-shell. However, removal of the $O^+$ concentration in our plasma model dramatically enlarges the passband of the filter. In that case, the magnetosphere lets almost the full frequency range of Pc 3 transverse Alfven waves pass to the ionosphere.

The characteristics of the Pc 3 Alfven mode waves are quite analogous to those of Pc 3 compressional fast mode waves. Our previous study [*Zhang et al.*, 1993] also reveals the low pass feature of the magnetosphere to the Pc 3 compressional fast mode waves. The mechanism of this low pass feature for Pc 3 compressional fast mode waves is also attributed to the existence of the $O^+$ concentration in the magnetosphere, which along with the $He^+$ concentration, produces the $He^+$-$O^+$ cutoff barrier to the propagation of the Pc 3 compressional fast mode waves. The difference between the propagation characteristics of Pc 3 Alfven mode waves and Pc 3 compressional fast mode waves is that the Alfven mode waves could propagate to the high latitude ionosphere along the magnetic field line, while the compressional fast mode waves could penetrate to the low latitude plasmasphere, if their frequencies were all lower than corresponding 'critical frequencies'. Another difference is that the propagation characteristics of Pc 3 Alfven mode waves are less sensitive to the relative concentrations of helium and oxygen ions than the Pc 3 compressional fast mode waves.

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## FIGURE CAPTIONS

Figure 1. Cold plasma wave dispersion curves for conditions at the equatorial dayside magnetopause (11 $R_E$ geocentric).

Figure 2. Log scale contours of the refractive index for Alfven mode waves in the noon-midnight meridian plane (100 mHz).

Figure 3. Log scale contours of the refractive index for Alfven mode waves in the noon-midnight meridian plane(40 mHz)

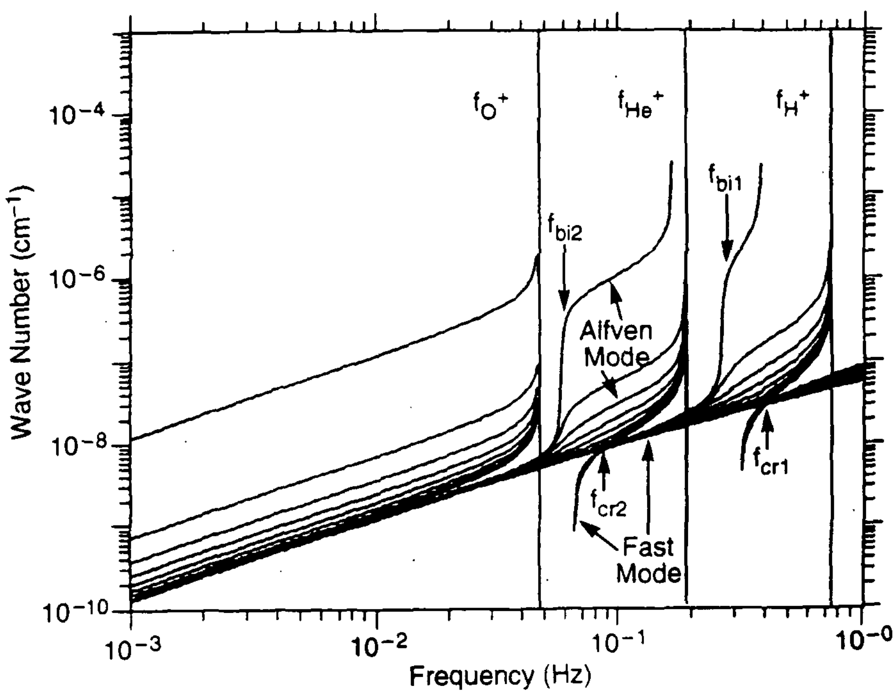
Figure 4. Meridian ray paths for 100 mHz Alfven mode waves starting at the equatorial dayside magnetopause (11 $R_E$ geocentric).

Figure 5. Meridian ray paths for 40 mHz Alfven mode waves starting at the equatorial dayside magnetopause (11 $R_E$ geocentric).

Figure 6. Meridian ray paths for 30 mHz Alfven mode waves starting at the equatorial dayside magnetopause (11 $R_E$ geocentric).

Figure 7. Meridian ray paths for 100 mHz Alfven mode waves (in a magnetosphere without $O^+$) starting at the equatorial dayside magnetopause (11 $R_E$ geocentric).

Figure 8. Schematic characteristics of the filter action of the magnetosphere for Pc 3 Alfven mode waves.



$f_{O^+}$
$f_{He^+}$
$f_{H^+}$
$f_{bi2}$
$f_{bi1}$
Alfven Mode
$f_{cr2}$
$f_{cr1}$
Fast Mode
Wave Number (cm$^{-1}$)
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{-0}$
Frequency (Hz)


FIG 1

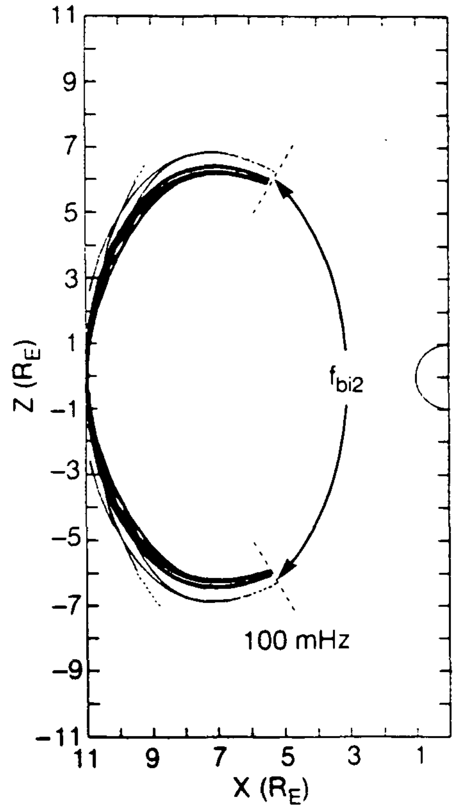
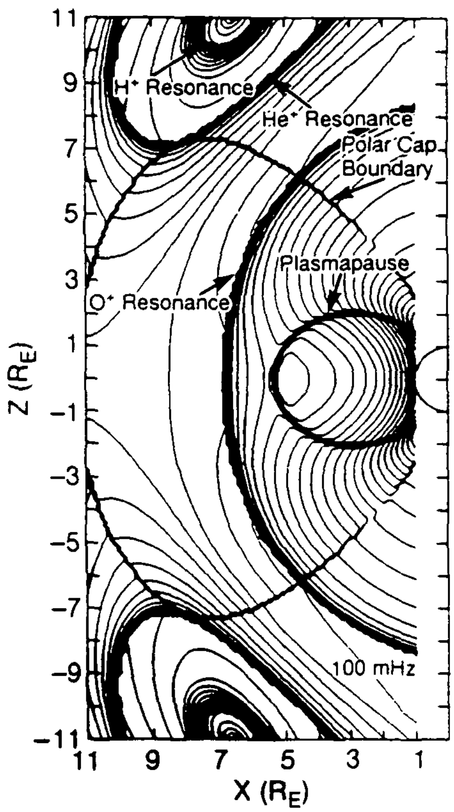
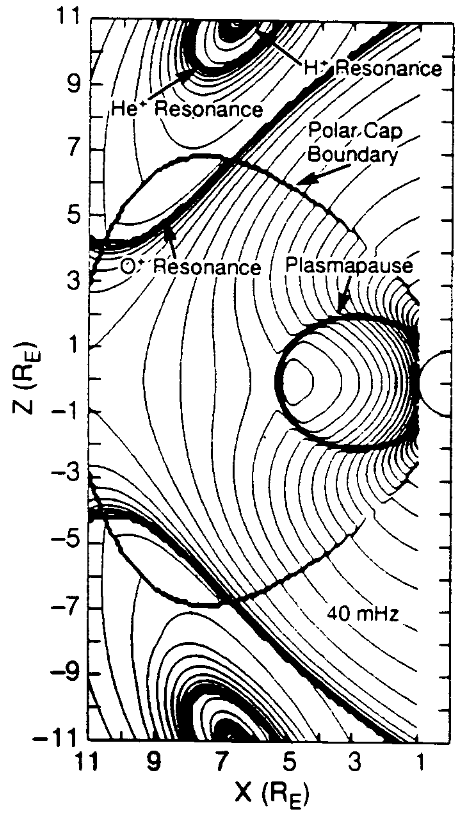



FIG 2



H⁺ Resonance
He⁺ Resonance
Polar Cap Boundary
Plasmapause
O⁺ Resonance
100 mHz
Z (R_E)
X (R_E)
11
9
7
5
3
1
−1
−3
−5
−7
−9
−11
11
9
7
5
3
1


FIG 3



H+ Resonance
He+ Resonance
Polar Cap
Boundary
O+ Resonance
Plasmapause
40 mHz
Z (R_E)
X (R_E)


FIG 4.

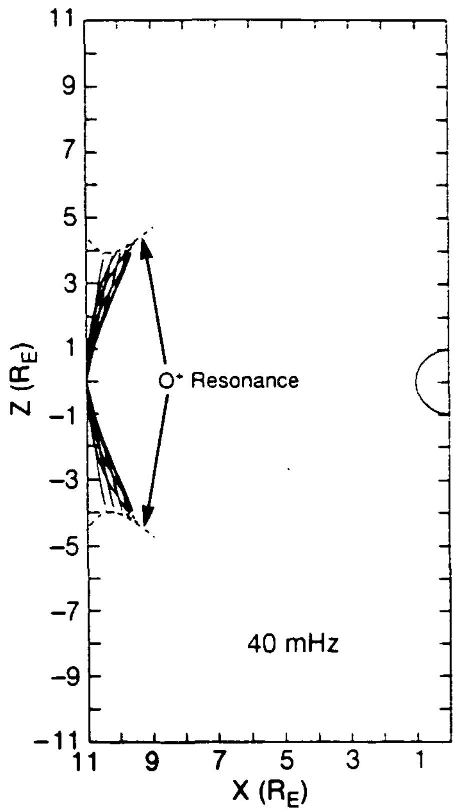
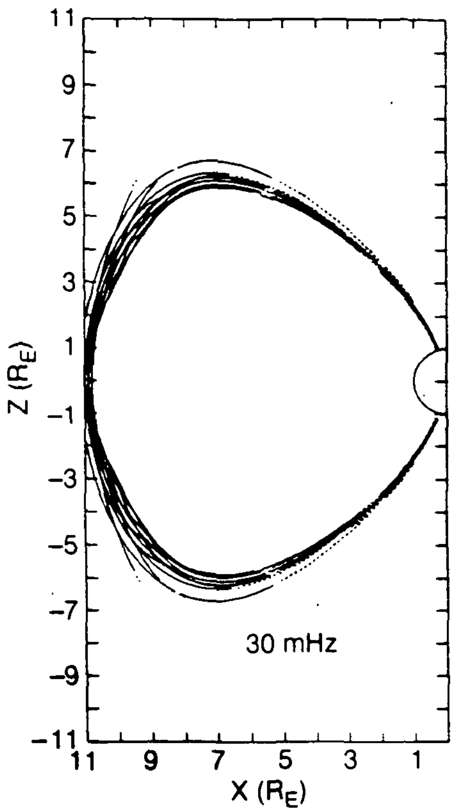



FIG 5




F1G 6

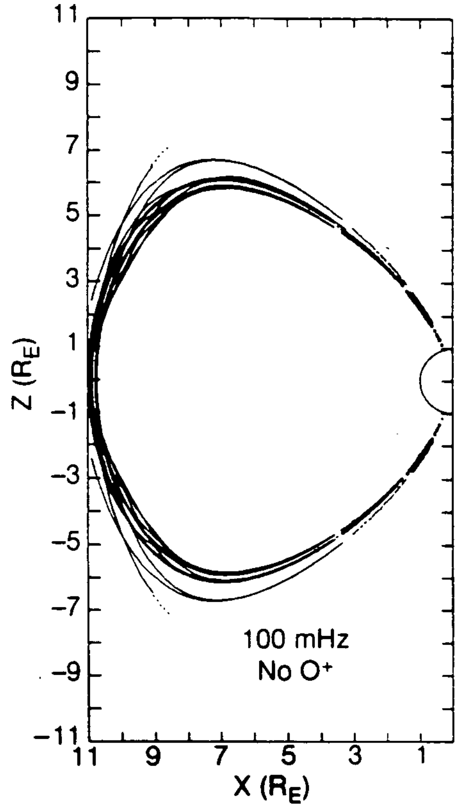



FIG 7

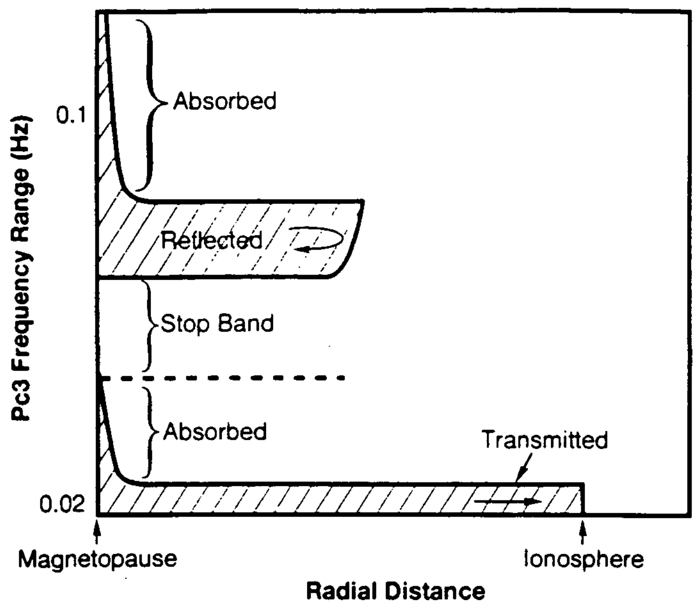

Absorbed
0.1
Pc3 Frequency Range (Hz)
Reflected
Stop Band
Absorbed
Transmitted
0.02
Magnetopause
Ionosphere
Radial Distance

FIG 8.