Are ULF Wave Observations affected by the Plasmapause in the Presence of Heavy Ion Mass Loading of the Geomagnetic Field?

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ABSTRACT

The plasmapause discontinuity in the radial plasma density profile of the magnetopause at L ≈ 3 – 6 has often been considered a boundary region for the propagation of ULF hydromagnetic waves and a possible source of boundary layer waves. Typically, plasma density gradient measurements have been based on electron and H^+ density profiles, with the contribution of mass loading through heavy ions (He^+, O^+ etc) neglected. The simplest way to investigate the radial properties of mass loading at the plasmapause is to observe radial profile variations in the Alfven velocity $V_A = B/(\mu_0\rho)^{½}$ where $\rho = m_i n_i$ for i species of ions. The Dynamics Explorer (DE-1) magnetic field data from the fluxgate magnetometer and plasma composition data from the retarded ion mass spectrometer (RIMS) are used to calculate V_A profiles for specific days. Results show that the plasmapause gradient in ρ and V_A remain important when multiple species heavy ion mass loading is included, but the plasmapause discontinuity in ULF wave resonant frequency may be smoothed out.

INTRODUCTION

Properties of the cold plasma in the Earth's magnetosphere divide the cavity into two distinct regions, the plasmasphere and the plasmatrough. In the high density plasmasphere inner region (10^2 – 10^4 cm^{-3}) with its outer boundary at the plasmapause (L = 3 – 5 R_e), geomagnetic flux tube trajectories corotate with the Earth under the influence of the Earth's corotation electric field creating a closed region [1]. Flux tube trajectories further out are dominated by the magnetospheric convection electric field and intersect the dayside magnetopause. These flux tubes become open at the magnetopause and the plasmatrough flux tubes have low density (1 – 10 cm^{-3}) singular point at 18:00 LT and the plasmapause bulge region between 18:00 – 00:00 LT. The plasmapause density gradient is very steep at most local times, with the exception of the plasmasphere bulge region in the dusk sector which may show more gradual slope and multiple plasmaspheric structures [*2*] [*3*]. Convection in the plasmatrough is unsteady, mainly due to geomagnetic storm or substorm activity. When convection is reduced the corotating flux tubes are extended beyond the plasmapause and the new corotating tubes are refilled with plasma of ionospheric origin. Also, detached plasma regions, or plumes, may drift anti-sunward from the plasmapause towards noon and provide density enhancements in the plasmatrough [4] [*5*]. Consequently, the radial plasma density profile in the magnetosphere, including the plasmapause, may show considerable variability [*2*] [*6*] [*3*].

A wide variety of hydromagnetic waves propagate in the Earth's magnetospheric cavity. On the dayside the most common signals are field line resonances in the 1 –100 mHz Pc 3-5 frequency band. These are observed on the ground and also by spacecraft, and are standing wave harmonics of flux tube oscillations (see review [*7*]). Observations by radially moving spacecraft of monochromatic daytime azimuthally polarized standing transverse hydromagnetic waves, show a decrease in the eigenfrequency of resonant field lines with increasing radial distance, and the presence of harmonic structure over L = 3 – 9 [*8*] [*9*].

An important question yet to be answered is to what extent does the plasmapause and plasmasphere-plasmatrough density variability exerts control over the properties of standing wave field line resonance characteristics in the magnetosphere. The wave resonant frequency and harmonics can be simply calculated by integration along a field line using $T = 1/f = \int(V_A)^{-1}\,ds$ where the Alfven velocity $V_A = B(\mu_o\rho)^{-½}$ is the characteristic wave velocity and is dependent on the plasma density along the field line and the geomagnetic field flux density. Consideration of the radial variation in V_A can therefore provide insight into the resonant structure of the magnetosphere. The magnetosphere is known to contain significant populations of cool/cold heavy ions (H^+, O^+) in addition to protons and electrons and this introduces a mass loading factor to the plasma density since $\rho = \Sigma\ m_i\ n_i$, where m_i and n_i are the mass and number density respectively, of the i th ion species.

The radial plasma density profiles typically used to display the presence of the plasmapause is deduced from electron or H^+ ion measurements [*10*] [*11*]. However, ion composition measurements have shown He^+ is the second most abundant ion in the plasmasphere with an average relative concentration of 20%, but is sometimes comparable to that of H^+ [*12*]. Just inside the plasmapause heavy ion (O^+, O^{++} and N^+) densities have been found to increase by a factor of 10 or more when there is no corresponding variation in H^+ or He^+ ions. This is commonly called the oxygen torus [13].

Horwitz [*14*] showed that the ion composition in the plasmasphere and near the plasmapause is highly variable and typically includes H^+, He^+, He^{++}, O^+ and O^{++} ions. Therefore, mass loading will vary radially and the assumption of a constant mass loading, as assumed by Moore et al [*15*] and Fraser [*16*], is not appropriate.

The primary aim of this paper is to include heavy ion contributions in the radial mass loaded plasma density profile and compare the resulting Alfven velocity profiles with those for a simple H^+ plasma. The database employed in the study is based on a well documented magnetic storm recovery period using data from the retarding ion mass spectrometer (RIMS) experiment which provided cold plasma data [*17*]. The corresponding geomagnetic field data were provided by the DE 1 spacecraft magnetic field experiment. The resulting V_A profiles are then incorporated in calculations of ULF wave field line resonance harmonic structure following techniques used, for example, by Orr and Webb [*18*] and Fraser [*16*].

PLASMA DENSITY AND ALFVEN VELOCITY PROFILES

An important study on the replenishment of the outer plasmasphere following a geomagnetic storm using DE 1 cold multi-ion plasma density profiles was reported by Horwitz [*14*]. A sequence of five consecutive DE 1 dusk passes on November 12 and 13, 1981, were shown where magnetic activity decreased gradually from $K_p = 7$ at 03 - 06 UT on November 12 to $K_p = 0 – 1$ at 18 UT on November 13. During the period of quieting, the region outside L ~ 4 extending to L ~ 7 began to fill and a new outer plasmasphere formed. An enhanced 0^+ population comparable to H^+ was also observed.

In the present study we use the DE 1 multi-ion density data for one of the passes on November 12, 1981, between 1646 – 1715 UT, along with the corresponding measured geomagnetic field, to calculate the V_A profile and field line resonance harmonic structure over L = 1.5 – 5. The radial density profiles of the five species H^+, He^+, He^{++}, O^+ and O^{++} are plotted in panel C of Figure 2 in Horwitz [*14*]. This panel is reproduced here in Figure 1(a), where the intrusion of new cold plasma during plasmasphere refilling is seen in H^+ and He^+ concentrations over L = 2.5 – 4. In this region O^+ is enhanced to an extent that it sometimes exceeds the H^+ density. This is the so-called heavy ion “torus” or “shell” in the vicinity of the plasmapause [*13*] [*6*]. Figure 1(b) shows two mass loaded density profiles for the two component (H^+, He^+) and three component (H^+, He^+, O^+) plasmas, with the single ion H^+ profile plotted for comparison. The inclusion of He^+ doubles the density over L = 3 – 4 while the further addition of O^+ increases it by over one order of magnitude. It can be implied from these observations that the V_A and field line resonant frequency profiles will be very different when heavy ions are included, as compared with those derived from a simple H^+ plasma profile. Alfven velocity profiles, calculated from the three plasma density profiles in Figure 1(b) and the corresponding DE 1 magnetic field profile, are plotted in Figure 2. The shape of the V_A profiles for the H^+ and (H^+, He^+, O^+) density profiles show a significant decrease over L ~ 2 – 4.5, primarily due to the O^+ torus.

FIELD LINE RESONANCE

The increase in mass loading resulting from the presence of significant populations of He^+ and O^+ ions has a profound effect on the field line resonance harmonic structure shown in Figure 3. Here the eigenfrequencies of the first three harmonics were computed following the techniques of Cummings [*19*] and Orr and Mathew [*20*]. A dipole magnetic field and a magnetosphere plasma density power law variation $\rho = \rho_o\ (R_e)^{-m}$ with m = 3, are assumed [*16*]. For the (H^+, He^+) plasma, the expected decrease in resonant frequency with increasing radial distance is seen out to L ~ 2.5. The presence of the old plasmapause at this location, and the decrease in density of the H^+ and He^+ ions out to L ~ 4 creates a region of increased frequencies. For example, the fundamental with a frequency of 15 mHz at L = 2.5, shows an increase to 40 mHz at L = 3.3. The second and third harmonics respectively, show increases of 2 and 3 times this. The addition of the O^+ ion torus to the (H^+, He^+) plasma almost suppresses this plasmapause increase in resonance frequency. A significant frequency increase occurs beyond L = 4 where there is a rapid decrease in the O^+ density.

Throughout the study the contributions of He^{++} and O^{++} ions have been neglected. These species are typically two orders of magnitude lower in density than the H^+ and He^+ ions, and one order of magnitude lower than O^+ concentrations over L = 2.5 – 5 (Figure 1(a)).

DISCUSSION

The above example illustrates the importance of heavy ions in the evaluation of the Alfven velocity profile and field line resonance harmonic structure in the magnetosphere and is only one of a number of passes observed in the DE 1 data set over October-November, 1981. If a steep plasmapause is observed in the H^+ and He^+ ions, and O^+ contributions are minimal, then resonant structures similar to Figure 3(a), with a sudden frequency increase at the plasmapause will be observed. This has been seen in toroidal mode field line resonances on ISEE 1 and AMPTE [15] [9]. However, the presence of an O^+ torus may remove this frequency increase. Whether this can be seen in spacecraft data requires the observation of field line resonances in conjunction with multi-ion plasma species and will be the aim of a future study.

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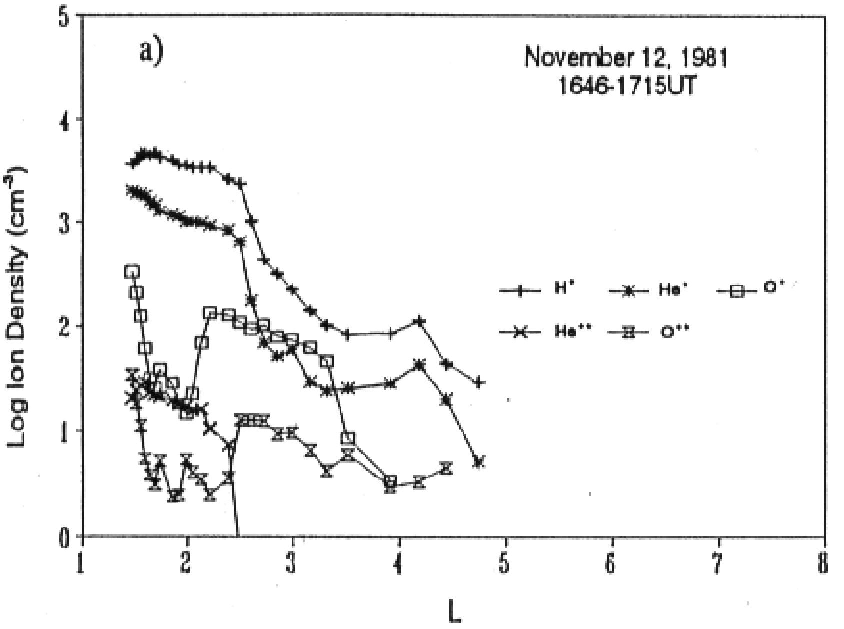

Figure 1(a). Radial variation in ion density of five species on one DE 1 inbound pass on November 12, 1981.

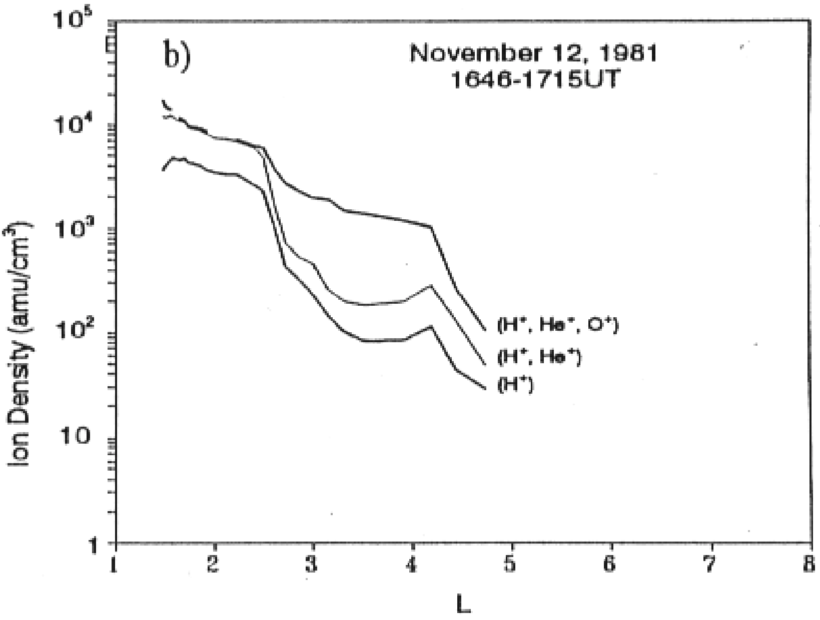

Figure 1(b). Mass loaded ion densities for two combination of ion species compared with the H^+ density.

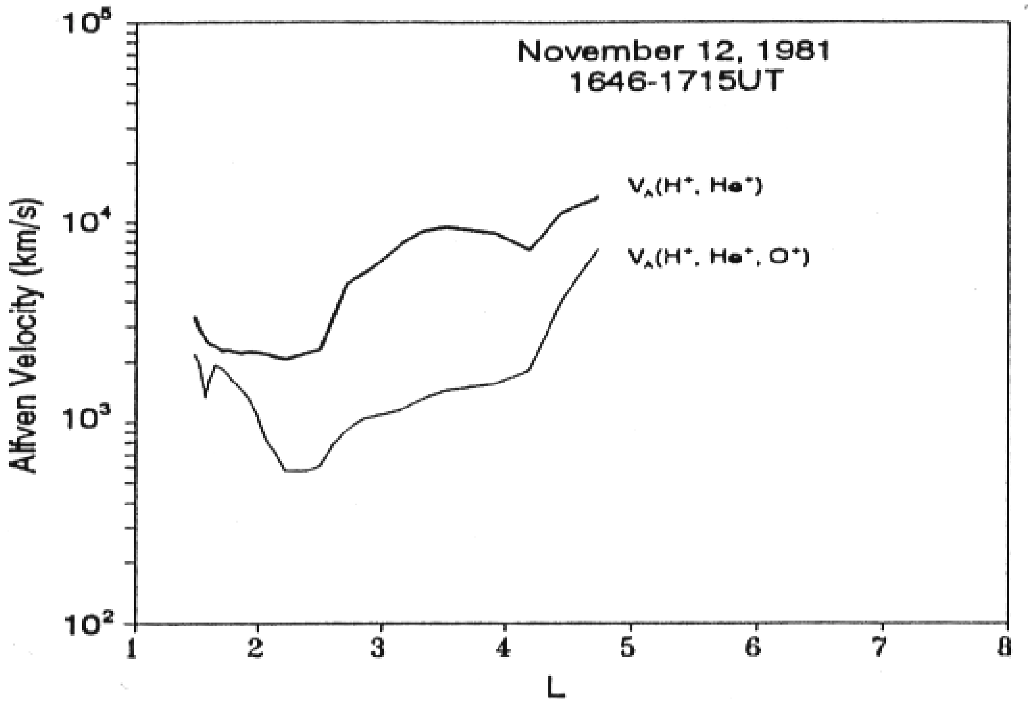

Figure 2. Radial Alfven velocity profile for the ion combinations of (H^+, He^+) and (H^+, He^+, O^+).

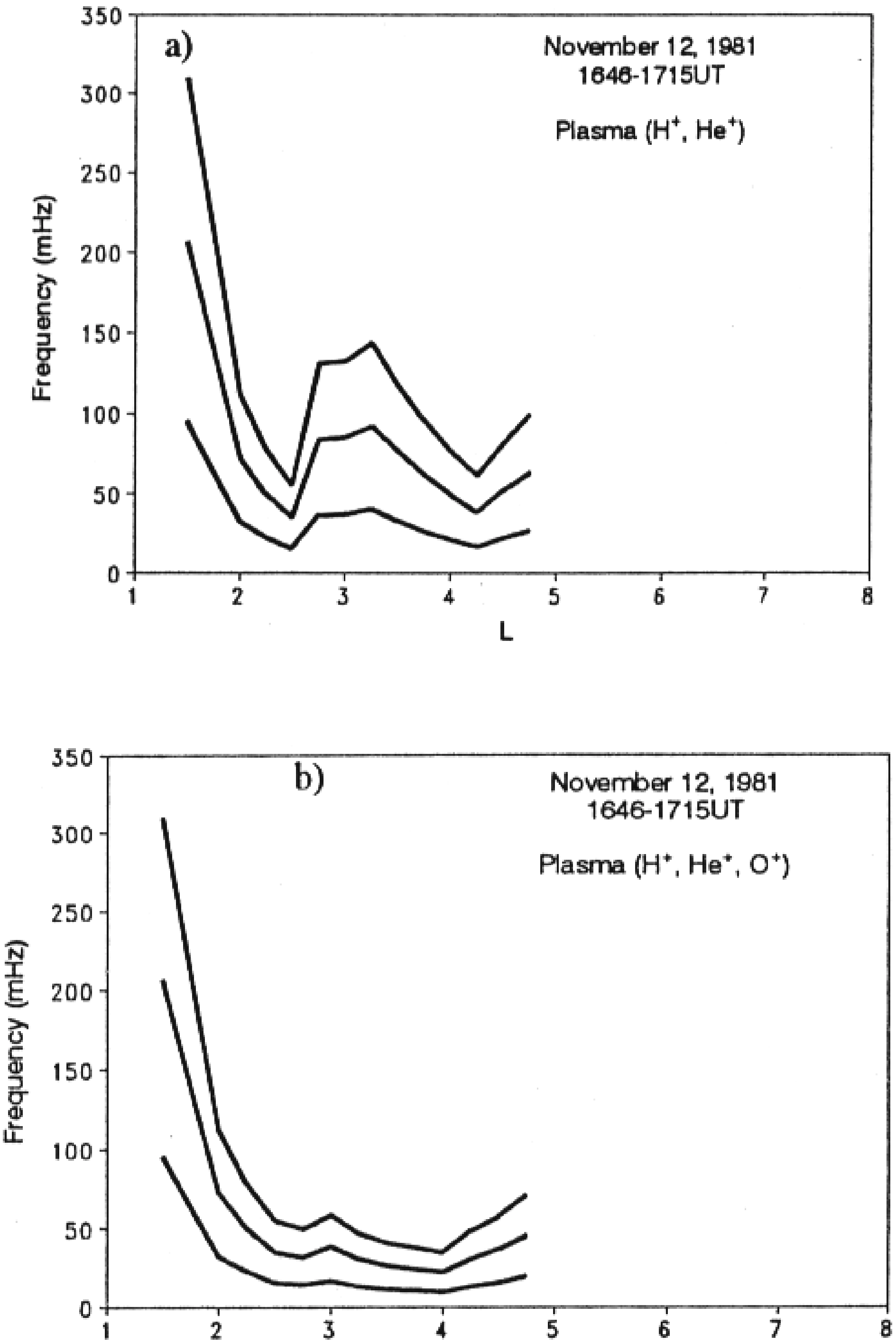

Figure 3. Field line resonance eigenfrequencies for the first three harmonics, computed using mass loading with, (a) H^+ and He^+ ions, and (b) with H^+, He^+, and O^+ ions.