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Investigation of Whistler Waves in the Venusian Atmosphere

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Abstract

This study explores whistler waves in the Venusian atmosphere, using data from the Venus Express mission to examine their dispersion relation, and electric, and magnetic field components. Findings confirm the right-hand circular polarisation of these waves and suggest a minimal impact of electron number density on the dispersion relation. The research also investigates the magnitude of the electric and magnetic fields associated with these waves.

1. Introduction

Whistler waves are VLF electromagnetic waves (3-30 Hz) that originate from lightning strikes [1] (amongst other sources such as ionospheric disturbances caused by solar flares or geomagnetic storms) which cross the ionospheric boundary to attach themselves to the magnetosphere of a planet. This process of attachment, known as ducting, facilitates their propagation over large distances with minimal attenuation to the environment. This is the reason why these waves can be heard even in the conjugate hemisphere on Earth as bursts of descending tones similar to that of a whistle when converted into audio signals. The frequency range of Whistler waves is given by:

$$\omega_{LH} < \omega < \min(\omega_{ce}, \omega_{pe}) \qquad (1)$$

where, ω is the frequency of whistler waves, ω_{LH} is the lower hybrid frequency, ω_{ce} is the electron cyclotron frequency and ω_{pe} is the electron plasma frequency.[2]

2. Lightning on Venus

As mentioned earlier, the generation of the whistler waves is attributed to lightning strikes. The possibility of lightning on Venus is still a debate. The first signatures were detected by the Soviet Union's Venera missions in the 70s and 80s in the form of whistler waves followed by NASA's PVO, which recorded VLF electrical impulses[3], and Galileo which recorded noise bursts at much higher frequencies. However, Cassini's failure to capture lightning's radio static during its two flybys dimmed the expectations[4]. In the first decade of this century, ESA's Venus Express confirmed the measurements of the electrical discharges, results further consolidated by Japan's Venus Climate Orbiter, also called Planet-C[5]. Japan's currently operational Akatsuki mission saw some mysterious flashes in March 2020 which is suspected to be either a powerful lightning strike, (roughly 10 times more energetic than lightning on Earth) or a large meteor explosion[6]. Parker's solar probe, in Feb 2021, picked up signals of Venus' mysterious "lightning" storms in the form of whistler waves. It turns out that what was regarded as lightning bolts turned out to be a result of disturbances in the magnetic field surrounding the planet[7], as the direction of propagation of these waves was downwards and not upwards as one could've expected if they had originated from lightning[8].

3. Whistler waves: Dispersion relation, Ducting and Polarisation

The dispersion relation for whistler waves in plasma using "Quasi-longitudinal" approximation [1] is expressed as:

$$\lambda_e^2 \left(k_{/\!/} k \frac{\omega ce}{\omega} - k^2\right) - 1 = 0 \qquad (2)$$

Where k is the wave vector, $k_{/\!/}$ is the parallel component of wave vector and λ_e is called the electron inertial length or skin depth [9]. The study of dispersion highlights the importance of understanding the behaviour of whistler waves accurately.

Whistler waves can be ducted along magnetic field lines due to density irregularities in the ionosphere, creating waveguides that allow these waves to propagate with minimal loss. There are two kinds of ducts: High Density Ducts (HDD) with density enhancement (crests) and Low Density Ducts (LDD) with density depletion (troughs). Irregularities with small density enhancements of 10-20% and transverse size larger than $d_0 \sim 1$ km serve as separate channels for VLF waves. Irregularities narrower than d_0 are not considered individual ducting structures[2].

Whistler waves in the Venusian atmosphere are observed to be strongly right-hand circularly polarised (RHCP) with frequency near 100 Hz, similar to that observed in the

Earth's ionosphere and magnetosphere[3][10]. The magnetometer onboard VEX detected nearly circularly polarised waves propagating almost parallel, i.e., within 20^0[11] to the background magnetic field in a frequency window of 42–60 Hz[12]. The probability of detecting a whistler wave emission in the Venusian atmosphere depends on the occurrence of lightning discharges and is influenced by the background magnetic field and the local ionospheric conditions.

4. Methodology and Data Analysis

For this section, the work of Saburo Adachi [13] has been taken into account.

Consider an infinitely long duct with uniformly distributed plasma slab that is aligned with a magnetic field, oriented perpendicular to the x-axis with a thickness of 2a, as illustrated in Figure 1.

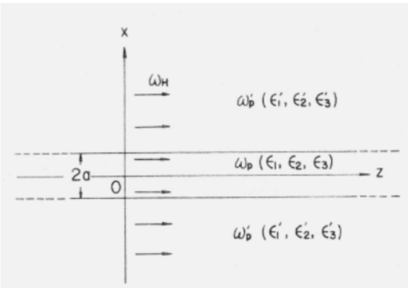

Figure 1: A magnetoplasma slab embedded in an infinite magnetoplasma of a different plasma density than that of a slab.

The environment is subdivided into 3 parts- the upper part, the duct, and the lower part with the different plasma parameters. These plasma parameters inside the plasma slab are ϵ_1, ϵ_2, ϵ_3, and the plasma parameters in the surrounding region, ϵ_1', ϵ_2', ϵ_3', which can be found by replacing ω_{pe} with ω_{pe}'. The electric and magnetic equations for these regions are given by:

For the upper region, i.e., $x \geq a$,

$$E_x = A(s_1'^2 + \Lambda'^2 + \epsilon_2'^2/\epsilon_1'^2)e^{-s_1'k_0x} + B(s_2'^2 + \Lambda'^2 + \epsilon_2'^2/\epsilon_1'^2)e^{-s_2'k_0x} \quad (3a)$$

$$E_y = -j\epsilon_2'\left(Ae^{-s_1'k_0x} + Be^{-s_2'k_0x}\right) \quad (3b)$$

$$E_z = j\frac{\epsilon_1'}{\epsilon_3'h}\left\{As_1'(s_1'^2 + \Lambda'^2)e^{-s_1'k_0x} + Bs_2'(s_2'^2 + \Lambda'^2)e^{-s_2'k_0x}\right\} \quad (3c)$$

$$H_x = j\frac{\epsilon_2'h}{Z_0}\left(Ae^{-s_1'k_0x} + Be^{-s_2'k_0x}\right) \quad (3d)$$

$$H_y = \frac{\epsilon_1'}{Z_0h}\left\{A(s_1'^2 + \Lambda'^2)e^{-s_1'k_0x} + B(s_2'^2 + \Lambda'^2)e^{-s_2'k_0x}\right\} \quad (3e)$$

$$H_z = -\frac{\epsilon_2'}{Z_0}\left\{As_1'e^{-s_1'k_0x} + Bs_2'e^{-s_2'k_0x}\right\} \quad (3f)$$

For the lower half, i.e., $x \leq -a$ the signs of s_1' and s_2' are changed.

For the duct region, i.e., $|x| \leq a$, the equations are:

$$E_x = C(s_1^2 + \lambda^2 + \frac{\epsilon_2^2}{\epsilon_1})coshs_1k_0x + D(s_2^2 + \lambda^2 + \frac{\epsilon_2^2}{\epsilon_1})coshs_2k_0x \quad (4a)$$

$$E_y = -j\epsilon_2(Ccoshs_1k_0x + Dcoshs_2k_0x) \quad (4b)$$

$$E_z = -j\frac{\epsilon_1}{\epsilon_3h}\{Cs_1(s_1^2 + \Lambda^2)sinhs_1k_0x + Ds_2(s_2^2 + \Lambda^2)sinhs_2k_0x\} \quad (4c)$$

$$H_x = j\frac{\epsilon_2h}{Z_0}(Ccoshs_1k_0x + Dcoshs_2k_0x) \quad (4d)$$

$$H_y = \frac{\epsilon_1}{Z_0h}\{C(s^2 + \Lambda^2)coshs_1k_0x + D(s_2^2 + \Lambda^2)coshs_2k_0x\} \quad (4e)$$

$$H_z = \frac{\epsilon_2}{Z_0}(Cs_1sinhs_1k_0x + Ds_2sinhs_2k_0x) \quad (4f)$$

where, h is the relative axial propagation constant, s_1 and s_2 are relative transverse propagation constants, $Z_0 = \sqrt{\mu0/\epsilon0}$, $\Lambda'^2 = (\epsilon_1'^2 - \epsilon_2'^2)/\epsilon_1' - h^2$, and $\Lambda^2 = (\epsilon_1^2 - \epsilon_2^2)/\epsilon_1 - h^2$.

This work utilises electron density data for the near night side (SZA = 83.93^0) of the Venusian atmosphere dated 2007/01/16 from the Venus Express (VEX) mission to find detailed analysis of dispersion relation, and equations of electric and magnetic fields for the whistler waves using the formulas written above. The frequency for the whistler wave is set to 100 radian/sec while the upper and lower limits of the duct are taken at 180 km and 120 km resp. The mean of electron density is considered for the electron density inside the duct while the maximum value of electron density is considered for the case of enhanced plasma density outside the duct. After calculating the electric and magnetic field components for each region, the magnitude of both electric field and the magnetic field is calculated.

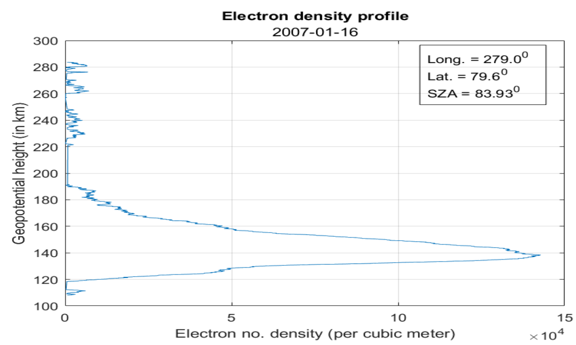

Figure 2. Electron density profile for the Venusian atmosphere.

5. Results and Discussion

5.1 Dispersion relation curve

The plot is generated for 3 different values of electron number density - the minimum value of the electron no. density, the mean electron no. density and the max. electron no. density.

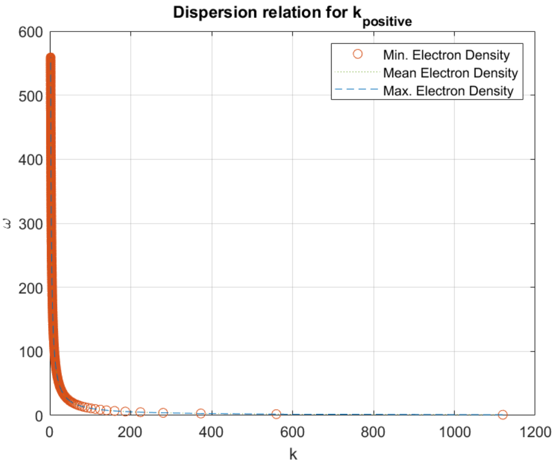

Figure 3. Dispersion relation curve for positive solutions of k.

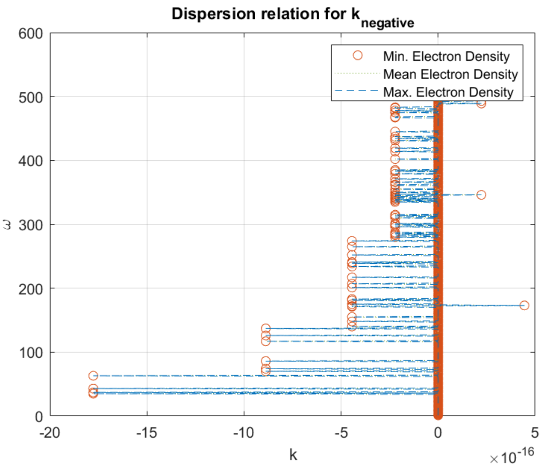

Figure 4. Dispersion relation curve for negative solutions of k.

Since the 3 curves exactly overlap with each other, it can be said that the effect of the value of electron no. density is minimal.

Moreover, the expected inverse curve is obtained only for the positive solution of k while the negative solution of k leads to a bogus trajectory. This gives strong evidence that the whistler waves are ALWAYS right circularly polarised.

It should be noted that the condition of ducting of whistlers from the equation (1) has been taken into consideration.

5.2 Magnitude of electric and magnetic fields

The plots of the electric and magnetic wave equations wrt. B and x, i.e., height is given by the Figures 5 and 6 respectively.

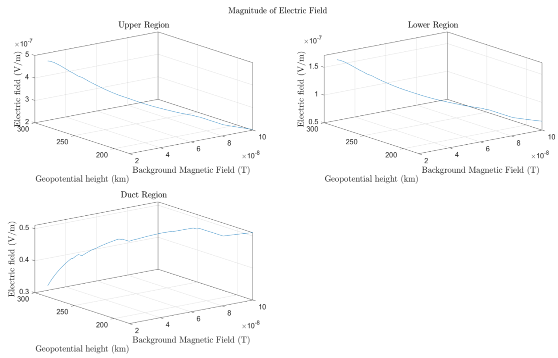

Figure 5. Variation of Electric field (z-axis) with background magnetic field, B (x-axis), and geopotential height (y-axis).

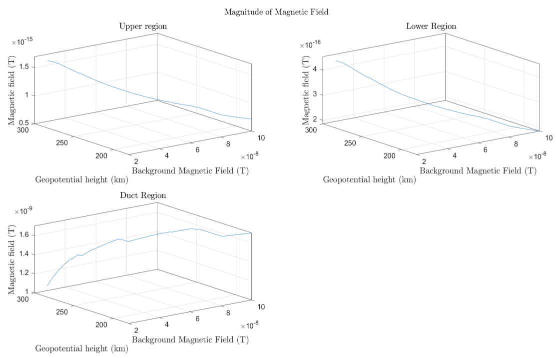

Figure 6. Variation of Magnetic field (z-axis) with background magnetic field, B (x-axis), and geopotential height (y-axis).

From Figure 5 it is observed that the electric field strength for the upper and lower regions decreases with altitude while being relatively uniform with the variation in the background magnetic field. This means that the intensity of the electric field is maximum at the origin of the whistler wave, gradually decreasing over the increasing geopotential height. A similar trend is observed for the lower region. However, the electric field magnitude in the lower region is much less than in the upper region.

Figure 6 depicts the behaviour of magnetic field components in the three regions. The behaviour is the same as that of the electric field component. The duct region's magnetic field is significantly stronger than the upper and lower regions, again indicating the presence of an electromagnetic field within the duct.

6. Summary and Conclusion

This study provides an in-depth investigation into the properties and behavior of whistler waves in the Venusian atmosphere, using data from the Venus Express mission. The research highlights the following key findings:

1. Dispersion Relation: The dispersion relation analysis indicates that the electron number density has a minimal impact on the propagation characteristics of whistler waves. The positive k solution produces the expected inverse curve, supporting the right-hand circular polarization of these waves.

2. Electric and Magnetic Fields: The analysis of electric and magnetic fields reveals that the field strengths are most significant within the duct region, confirming the critical role of this region in wave propagation. The intensity of these fields decreases with altitude in the upper and lower regions, but remains high within the duct, facilitating efficient wave propagation.

These findings enhance our understanding of the interaction between the Venusian atmosphere and its magnetosphere, particularly in relation to whistler waves.

7. Acknowledgements

We would like to express our sincere gratitude to Dr. A.K. Rastogi from IEHE Bhopal for his guidance in this work.

8. Data Availability

Data for electron density profile for the Venusian atmosphere was provided by Dr. Martin Patzold, University of Cologne on personal communications.

9. References

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