Frequency Dependent Source Locations of Whistler Mode Waves in the Plasmasphere: A Raytracing Approach

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Abstract

Whistler mode waves play an important role in space weather dynamics. Plasmaspheric hiss and chorus are types of whistler mode waves prevalent in the magnetosphere. The source location of whistler mode wave energy has been a topic of research for nearly half a century. We present results of warm plasma whistler mode raytracing considering three source locations at *L*=2, 3.8 and 5 in the magnetosphere. Comparison of simulation results with frequency normalized observations from the Van Allen Probes spacecraft suggest that sources within the plasmasphere (*L*~2) provide a significant contribution to the observed whistler mode wave power distribution.

1. Introduction

Earth is surrounded by a sparse population of highly energetic (> 1 keV) electrons making up inner and outer radiation belts. These high energy electrons can damage spacecraft electronics and affect global communication and power systems. Interaction of radiation belt electrons with natural or man-made waves can precipitate the electrons on the upper atmosphere by un-trapping them from the magnetic bottle geometry of the Earth's magnetic field. The most common type of magnetospheric waves in the several kHz band are whistler mode waves. Due to their abundant presence and interactions with the high energy radiation belt electrons, whistler mode waves play a dominant role in magnetospheric energy dynamics and space weather [1].

Magnetospheric whistler mode waves are characterized into two types: chorus and hiss. Chorus waves are characterized by some level of coherence and are observed mostly outside of the plasmasphere. Typical frequency range of chorus waves is 1 kHz – 6 kHz. Generation of chorus waves is driven by increased geomagnetic activity from substorms[2 - 4]. Whistler mode hiss waves are less coherent and more broadband and typically observed inside the plasmasphere. Source locations of plasmaspheric hiss are a topic under debate for around 50 years. Draganov et al., [5] suggested lightning generated whistlers as a source of plasmaspheric hiss. By performing raytracing work they showed that energy of lightning entering the magnetosphere at different locations can be a possible source of these broadband waves. Thus under this model, plasmaspheric hiss is generated within the plasmasphere. On the other hand, a different scenario has been put forth by *Bortnik et al*. and others [6, 7], wherein chorus waves are a possible source of hiss. Li et al. [7] observed a correlation between the chorus waves generated further in the magnetosphere (*L*~ 9.8), and hiss waves inside the plasmasphere (*L*~5.5). The maximum correlation was observed in the frequency range 225 Hz – 350 Hz.

We have conducted numerical raytracing in order to investigate source regions of plasmaspheric hiss. Details about the numerical raytracing are described in the Methods section. The main goal is to determine whether statistical wave observations are consistent with plasmaspheric hiss being generated inside or outside the plasmasphere. We have chosen three different source locations distributed in *L* shells, 2, 3.8 and 5. We compare our simulation results with observations made by the EMFISIS instrument hosed at the Van Allen Probe spacecraft. Simulation results from the three sources are weighted in order to match the observed power distribution

2. Methods

2.1 Raytracing

Raytracing is a numerical method of determining the power flow path of a wave. This is done by solving the Haselgrove's equations [8]. Raytracing assumes a smoothly varying medium with no mode coupling. This method is well suited for the Earth's magnetosphere.

Majority of the previous raytracing work was conducted assuming the background magnetospheric plasma is cold: 0K. But in our work we consider the actual temperature of the magnetosphere which is around 1eV (11600 K). Formulation of this warm plasma raytracing is given in [9-11]. In this work we are comparing the whistler mode wave energy observations from the Van Allen Probe spacecraft at Magnetic Local Time (MLT) 06. According to *Decreau at el* [12] the electron and ion temperature at MLT 06 is 2.3eV and 1eV respectively. Hence we have considered those two electron and ion temperatures for this work. The Global Core Plasmasphere Model (GCPM) was used as the background plasmasphere [13] and the geomagnetic field was assumed to be a dipole.

2.2. Source Locations

The plasma pause location was set to be at L = 3.76, corresponding to Kp index of 4. Three source locations were selected inside the plasmasphere (*L* = 2), on the plasma pause (*L* = 3.8) and outside (*L* = 5) the plasmasphere. Waves were launched at the equator of each of these *L* shells with an initial wave normal angle distribution covering the range of -70^{o} to 20^{o} (as in [6]) in increments of 0.5^{o}, and frequency range 100 Hz to 3.5 kHz.

Interaction of the whistler mode waves with high energy electrons can cause Landau damping and growth. We have modeled Landau damping and growth using the bi-Maxwellian distribution given in [14]. Each source location was scaled in initial wave power so that the combined whistler mode wave energy from all sources would best match the observations. The scaling factors are given in the Results section.

3. Results

Figure 1 shows the wave energy observations from the EMPSISS instrument hosted at the Van Allen Probe Spacecraft at MLT 06 (dawn). Measurements were taken at a magnetospherically quiet condition and the plasma pause location was observed to be between *L*=3 and 4. All measurements were normalized to the highest amplitude at each frequency. On the x axis, zero is the location of the plasma pause. Earth-ward measurements from the plasma pause are given by negative numbers. We have used the same axis settings for all the figures in this paper. There are three main observations from Figure 1:

1. For frequencies less than 1 kHz, the peak whistler mode wave energy is observed around one Earth radii towards the Earth from the plasma pause.
2. As the frequency increases the energy peak moves further towards the Earth: about two Earth radii from the plasma pause.
3. For frequencies greater than 2.5 kHz, wave energy seems to be spreading across a broader *L* shell range, although the peak remains closer to the Earth.

Figure 2 shows the simulation results from the three source locations (*L* = 2, 3.8 and 5). We have plotted the total power including the effects of wave damping and linear cyclotron growth. Figure 2 was produced assuming equal contribution from all three sources.

Observation 1, from Figure 1 can also be seen in Figure 2. But at frequencies above 2 kHz, Figure 2 contains energy structures which are not visible in Figure 1. Therefore instead of assuming equal contributions from all sources we have scaled the contribution from the three sources at different frequency ranges to produce Figure 3. In scaling we have multiplied the original energy by a fraction, to produce a better match with Figure 1. Based on the observations we made with the individual sources, we used the following approach to create Figure 3:

Observation 1 made above, is mainly due to the sources located at the plasma pause. Therefore when producing Figure 3, sources at *L*=3.8 were given the highest scaling factor (0.7) for the frequencies below 1 kHz compared to the other two sources. Source at *L*=2 were given the next highest scaling factor (0.3) and source outside the plasma-sphere was given the lowest (0.01).

Observation 2 was due to the sources within the plasma-sphere. Therefore for frequencies above 1 kHz, highest scaling factor (0.7) was given to the source at *L*=2. Next highest was given to the source at the plasma pause (0.3).

In all cases the source at *L*=5 was given the lowest scaling factor (0.01). But observation 3 was due to the wave generated at *L*=5. Therefore for frequencies above 2.5 kHz, the scaling factor of the source at *L*=5 was increased to 0.3.

Finally the scaled energy was added and normalized to the highest at each frequency.

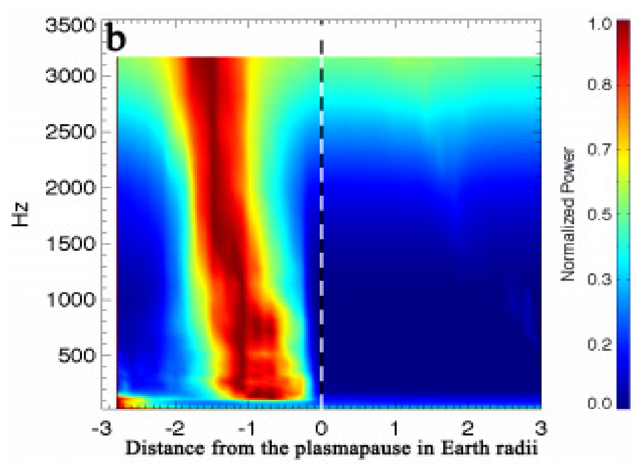

Figure 1. Whistler mode wave energy observed by the EMFISIS instrument at the Van Allen Probe spacecraft, normalized to the maximum at each frequency

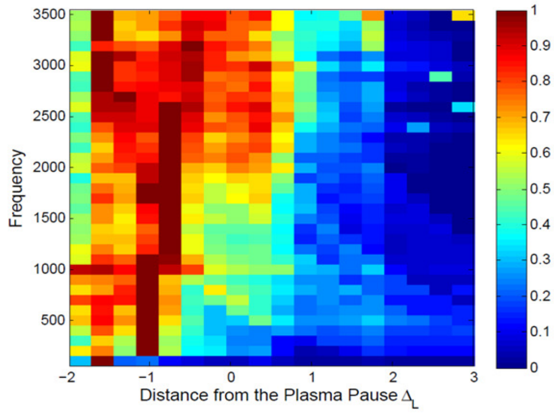

Figure 2. Normalized unscaled wave energy from three whistler mode source locations, located inside, on and outside the plasmasphere.

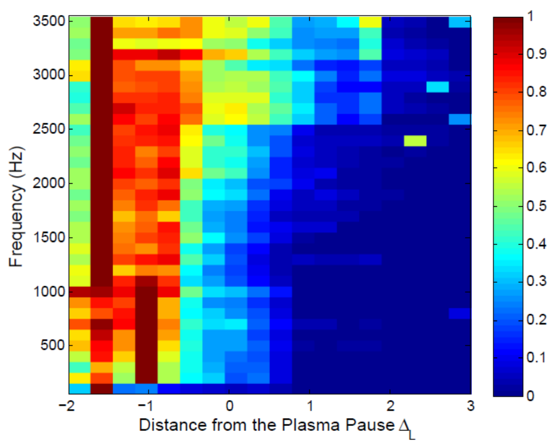

Figure 3. Normalized scaled wave energy from three whistler mode source locations, located inside, on and outside the plasmasphere.

4. Discussion

In this work we have investigated the statistical whistler mode wave power distribution inside the plasmasphere. Our goal was to identify the possible locations of whistler mode waves and their frequency ranges. We have compared our scaled simulation results with the observations made by the EMFISIS instrument hosted at the Van Allen Probe spacecraft.

From our scaled simulation results we make the following conclusion:

Whistler mode sources located at the plasma pause is a dominant contributor to the observed wave energy for the frequencies below 1 kHz.

For frequencies above 1 kHz, highest wave energy contribution is from the sources located inside the plasmasphere (*L*=2). The frequency spread of energy observed at frequencies above 2.5 kHz is due to the sources located outside the plasmasphere.

Our work suggests that the majority of the whistler mode hiss power is generated within the plasmasphere. Hence the method suggested by [5], where lightning generated whistlers leaking into the magnetosphere at different locations and then being reflected multiple times can be a possible source of plasmaspheric hiss.

We also see a portion of the whistler mode chorus generated around *L*=5 propagate into the plasmasphere and contribute to plasmaspheric hiss, in agreement with the observation made by Li et al. [7]. However, the frequency that we observe for this correlation is above 2.5 kHz, and according to [7] the authors observe the maximum correlation around 225 Hz – 350 Hz.

For future efforts we would like to extend this work to multiple sources, covering a broader range of L values. Also we would like to perform raytracing analysis for different MLT values and compare the results with actual spacecraft observations.

5. References

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