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Observations and Simulations of Whistler Waves in the Van Allen Radiation Belts

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Observations and Simulations of Whistler Waves in the Van Allen Radiation Belts

Miles Bengtson, Morgan Matheny, Anatoly Streltsov, Rozanna Stein, & Sara Rosbrough

Abstract

When the first American satellite, Explorer I, was launched into space in 1958 it inadvertently discovered one of the most significant features of our local space environment: the Van Allen Radiation Belts. This region contains highly energetic protons and electrons from the sun which become trapped in the Earth's magnetic field. These particles are extremely hazardous for spacecraft, causing damage to electronics and endangering astronauts on the International Space Station. Certain natural or artificial events, such as solar coronal mass ejections or high-altitude nuclear explosions, can enhance the radiation belts and decrease satellite lifetimes by orders of magnitude. Therefore, there is a strong motivation to develop a means by which to deplete the radiation and protect our assets in space from this threat. We present one promising remediation mechanism based on the interactions between these particles and very-low-frequency electromagnetic waves known as whistlers. One important property of whistler waves is that they can be guided along narrow inhomogeneities of plasma density called ducts. We have analyzed several events of ducted whistlers observed by the Van Allen Probes satellites and reproduce them with numerical simulations based on whistler theory. We demonstrate quantitative agreement between our simulations and the observations, indicating that our model successfully explains the existing satellite observations and can be used to predict the results from future experiments of launching whistler waves into the radiation belts from ground stations and space-based transmitters.

1. Introduction

1.1. Background and Motivation

The Van Allen Radiation Belts are a region in the near-Earth space environment which contain highly energetic protons and electrons from the sun which become trapped in the geomagnetic field. The Radiation Belts were inadvertently discovered by the first American satellite, Explorer I, in 1958. Spacecraft flying through this region experience a number of adverse effects as the high energy particles can degrade circuitry, create computer logic errors, and cause spacecraft charging to occur. Additionally, the radiation presents a significant health hazard for any astronauts in this region. The size, location, and structure of the Radiation Belts are highly dynamic and depend on solar activity. Solar coronal mass ejections could launch excess energetic particles toward the Earth creating a prolonged enhancement of the Radiation Belts. High-altitude nuclear testing could also artificially enhance the Radiation Belts or create an additional region of radiation which would remain around the Earth for years. For example, in 1962 the United States detonated a nuclear warhead at high altitude over the Pacific Ocean in a famous experiment known as Starfish Prime. This explosion created an artificial radiation belt which destroyed several of our early communications satellites.

A prolonged enhancement of the Radiation Belts, of either natural or artificial origins, would be detrimental to our modern satellite fleet and space-based infrastructure. Therefore, there is a strong motivation to develop a means by which to deplete the energetic particles from the magnetosphere. We present work on one promising method of using very-low-frequency (1-30 kHz) electromagnetic whistler waves (also known as "whistlers") to remediate the radiation from space.

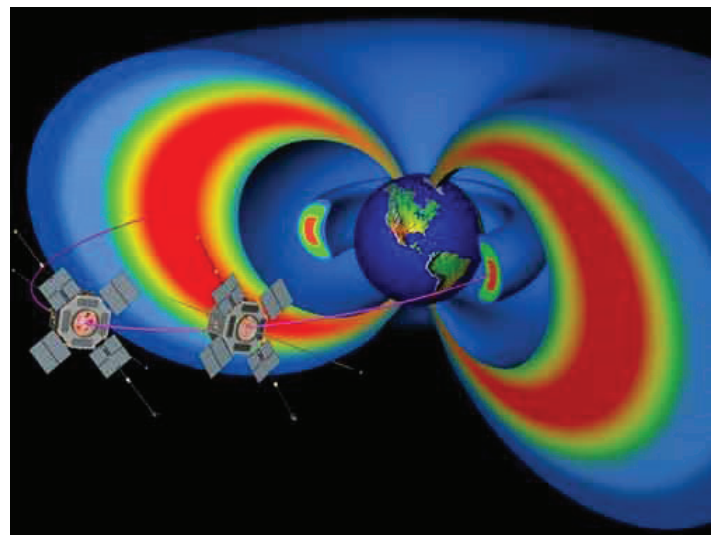


Figure 1: Artist's rendering of the Van Allen Radiation Belts and the Van Allen Probes around the Earth

1.2. Whistler Wave Physics

Whistlers are circularly-polarized electromagnetic waves which can be generated naturally by lightning strikes or beams of energetic electrons in the magnetosphere. They can also be generated artificially by power high-frequency radio transmitters. The frequency of whistler waves is close to the frequency at which charged particles gyrate around the magnetic fields in the magnetosphere. Therefore, they can exchange energy efficiently with the particles. This increases the overall energy of the particles and drives them closer to the Earth as they bounce between the Northern and Southern magnetic poles, as shown in Figure 2. At a certain point, the particles will penetrate into the atmosphere where they will be absorbed in collisions with neutral particles. Thus, the radiation will be depleted from the near-Earth space environment.

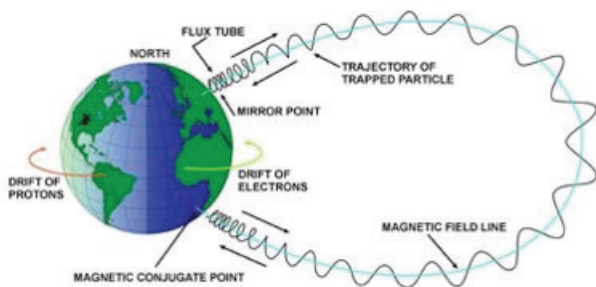


Figure 2: Schematic showing the bounce motion of energetic particles along a geomagnetic field line.

One interesting characteristic of whistler-mode waves is that they can be guided by inhomogeneities of the background plasma density, though the physics behind this process is not fully understood. Regions of higher or lower plasma density can confine the whistler wave in a “duct” along a magnetic field line. This was first documented in the classic paper by Storey [1]. Though a number of theoretical studies have been conducted to study whistler wave propagation using geometric optics methods [2-4], the researchers use a full wave simulation developed by our faculty advisor [5,6]. This approach allows consideration of the cases in which the width of the plasma duct is on the same scale as the transverse wavelength. In this paper, the researchers compare ducted whistler-mode waves observed by the Van Allen Probes satellites with the results from numerical simulations to achieve a better understanding of the fundamental physics of the whistler-mode wave.

1.3. Van Allen Probes

The Van Allen Probes (VAPs) (formerly known as the Radiation Belt Storm Probes (RBSP)) are two spacecraft collecting in-situ measurements in the Radiation Belts [7]. The two spacecraft were developed by Johns Hopkins Applied Physics Laboratory under contract from NASA and were launched on an Atlas V on August 30, 2012 from Cape Canaveral, Florida. It is possible to differentiate between changes which occur in time and those which occur only in space by having two spacecraft flying in line. Each spacecraft contains several instrument suites to collect high-quality data on the electric and magnetic fields, particle fluxes, and waves in the Radiation Belts, as shown in Figure 3.

In this paper, the researchers use and analyze data from the Electric Field and Wave (EFW) instrument [8] and the Electric and Magnetic Field Instrument Suite and Integrated Science instrument [9]. This research is particularly timely due to the ongoing operation of the Van Allen Probes satellites which provide unprecedented amounts of in-situ data with which to compare theoretical and numerical results. In addition, several missions have been planned to actively inject very-low-frequency waves into the magnetosphere to study wave-particle interactions, including the Air Force Research Laboratory’s upcoming Demonstration and Science Experiment (DSX) experiment [10].

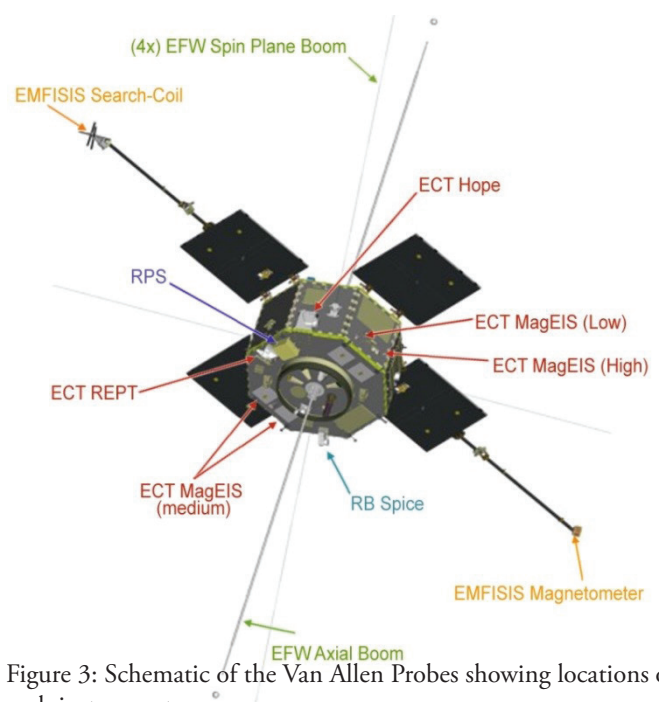


Figure 3: Schematic of the Van Allen Probes showing locations of each instrument.

2. Discussion of Results

2.1. Spacecraft Observations

On March 21, 2013 between 0200 and 0220 Universal Time (UT), VAP-A observed several packets of whistler waves. The first packet of waves was detected at approximately 0204 UT, and the second group was detected at approximately 0216 UT. They are illustrated in Figure 4 which shows a spectrogram of the electric field using EMFISIS data, meaning the electric field power is plotted as a function of frequency and time. The X-axis is time (in UT), the Y-axis is frequency (in Hz), and the power, or intensity of the wave (in $V^2/m^2/Hz$), is shown by color shading (darker shades of blue indicate little to no wave power, and vibrant shades of red/orange indicate high wave power). Plotted over the spectrogram is the EFW instrument plasma density (shown as a black line and in units of cm^{-3}). It can be seen in the figure that there are waves trapped, or ducted within regions where the plasma density is high.

The aim of this paper is perform a numerical modeling of the observations using a density profile similar to the one observed, and demonstrate that a wave launched into the duct with the same characteristics as those which were observed will remain confined within

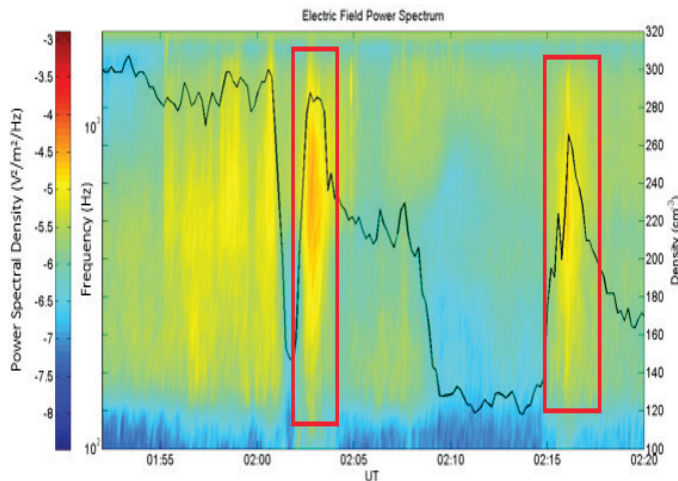


Figure 4: Electric Field power spectra with the plasma density profile overlaid.

it.

The density enhancements seen in Figure 4 are very large considering the region of the magnetosphere in which the observations are made. It is hypothesized that the density structures are remnants of a plasmaspheric plume. The plasmasphere is a region of cold, high density plasma which co-rotates with the Earth. A plume is a large tail of plasma that separates from

this main plasmasphere and becomes increasingly thin and extended as it rotates around the Earth. An example of this structure is shown in Figure 5 using the plasmaspheric model developed by Pierrard et al [11] and applied to the time interval in which the VAP events occur. It is thought that VAP-A entered and exited the

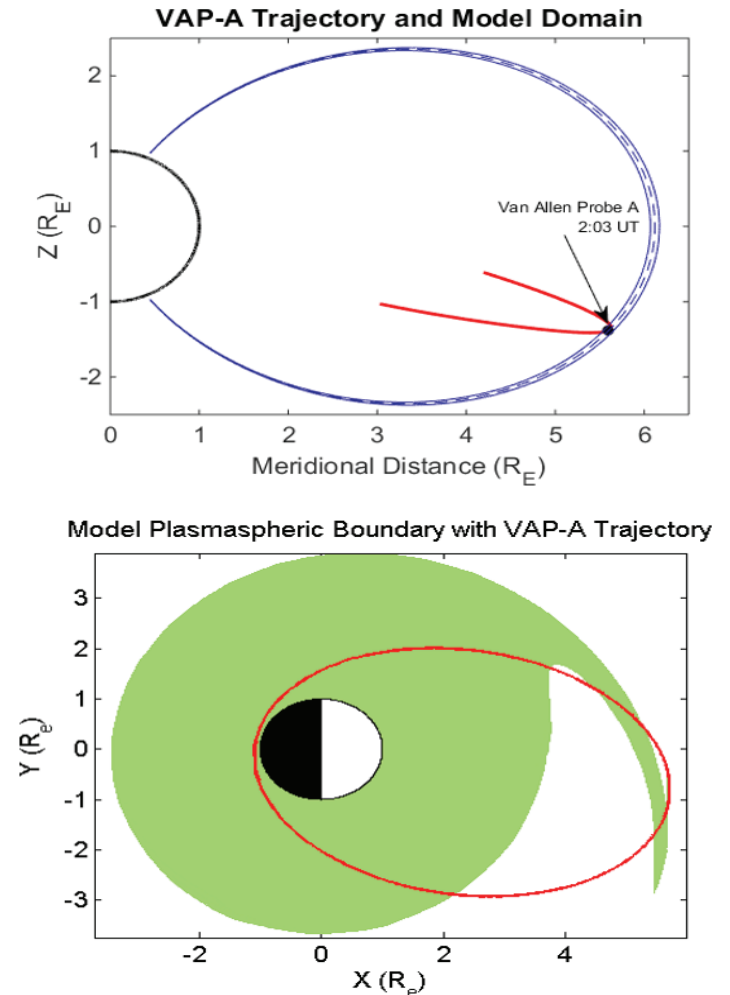


Figure 5: (Top) Trajectory of VAP-A around the time of the event projected onto the meridional plane. The blue lines indicate the magnetic field lines used to define the simulation domain. (Bottom) Example of a plasmaspheric plume which could have produced the observed density profile. The red line shows the actual orbit of VAP-A in the XY plane.

plume, reached apogee, then passed through the same plume again.

The trajectory of VAP-A is also shown in Figure 5 during the event interval in a solar magnetospheric (SM) coordinate system. In an SM coordinate system, the Z-axis is aligned with the Earth's magnetic field, and the Y-axis is aligned with the Earth-Sun plane. This system is also used to construct the domain in the simulation model used to model this event.

In addition to the orbital data of the spacecraft

during the event, other parameters are needed from the plasma environment in order to perform numerical simulations. The local electron cyclotron frequency, the plasma frequency, and the wave frequency are needed in order to recreate the plasma region and reproduce the electromagnetic waves.

2.2. Numerical Simulations

The numerical model used in this study runs in FORTRAN. It solves the electron continuity equation and Maxwell's equation at each gridpoint using the method of successive overrelaxation and uses a combination Adams-Moulton/Adams-Bashforth algorithm to advance the simulation in time. Figure 6 shows how the density profile observed by VAP-A was modeled in our numerical code using a Gaussian-like function. The modeled profile very closely resembles the observed profile in magnitude, width, and boundary slope.

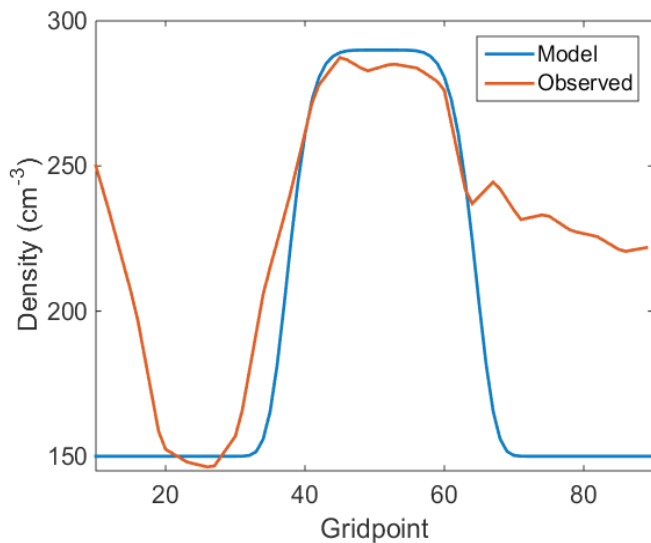


Figure 6: Comparison of model and observed density profiles.

In a physical environment, a wave which leaves the ducting region should propagate away from the domain and disappear. In order to achieve this effect in the simulation, a numerical absorber is used on the edges of the domain to force the wave to dissipate as it approaches the boundaries. Were this absorber not used, the waves would reflect off the boundaries and propagate back toward the duct, producing non-physical results. Figure 7 shows the absorber profile used in the simulation; it can be seen the inside the duct there is no absorption coefficient, but on the outside edges there is to ensure any waves which escape the duct do not interfere. Notice that the density profile is shown in the

left panel and the black dashed lines correspond to the edges of the duct.

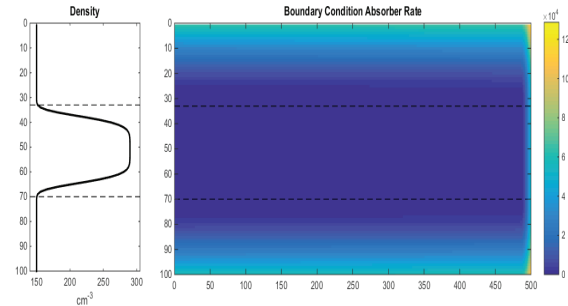


Figure 7: Absorber at the domain boundaries.

2.3. Simulation Results

The numerical simulation results in Figure 8 show that the wave launched along the ambient magnetic field into the density profile remains confined within the duct over the entire length of the domain. Figure 9 shows what happens when the same wave is launched into a domain without a density duct: the wave loses power and fades away before reaching the end of the domain. In both simulations, a wave with a frequency of 1000 Hz and a wavelength of 4 km was launched into the domain from an antenna placed on the left lateral boundary of the domain. These results show very good correlation with the observations by indicating that the wave could not propagate very far without the presence of the duct.

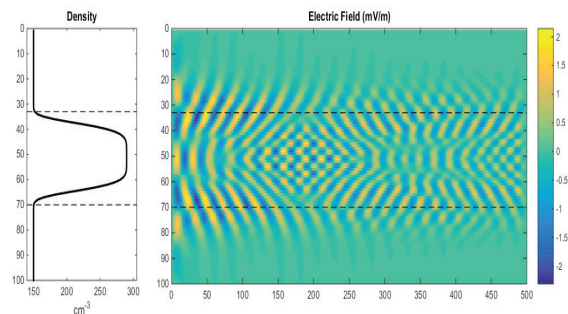


Figure 8: Results of simulation for the ducted case.

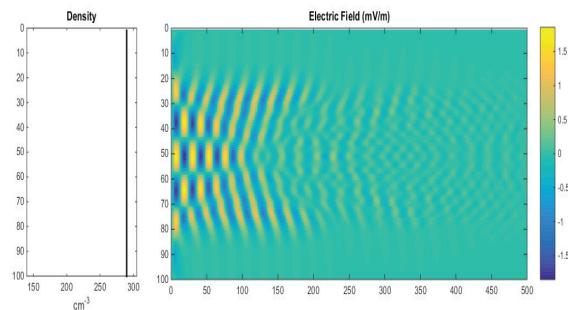


Figure 9: Results of simulation for the homogeneous density case.

Note the serpentine-like patterns present in the simulation results for the ducted case. This pattern is produced when the wave reflects off the edges of the

duct repeatedly as it propagates along the domain. When waves reflect off opposite edges they interfere in the center of the duct producing patterns like those seen between gridpoint 150 and 250 in Figure 8.

To help further demonstrate the efficacy of the duct in confining the wave in each simulation, a cut was taken through the above figures to show how the wave amplitudes change as a function of the distance they propagate. Figure 10 shows how the amplitudes of each wave decay as they move through the domain. It is seen that the non-ducted profile wave quickly dissipates as it propagates, having effectively an amplitude of zero by the end of the domain. In contrast, the wave launched into the duct maintains a relatively constant (and oscillating) amplitude as it propagates. Using the homogeneous density in simulation helps to confirm the whistler wave ducting theory that if there is no density duct, then there will not be any wave observed at some distance from the source antenna.

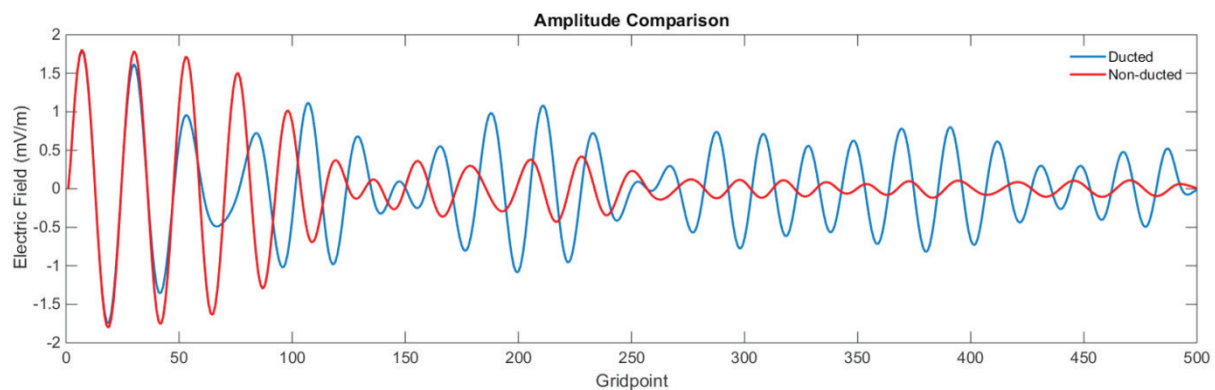


Figure 10: Comparison of wave amplitudes for ducted and non-ducted simulations.

3. Conclusion

This research has provided an example of a ducted whistler wave observed by the Van Allen Probes. Using spacecraft data from the Van Allen Probes EMFISIS and EFW instruments, the researchers analyzed an observation of a wave within a strong plasma density inhomogeneity on March 21, 2013. Using a two-dimensional full wave simulation, the observed wave in quantitative detail was modeled and showed that the wave can only propagate over long distances from the source only when they are ducted by an inhomogeneity of the background plasma density. The results of the simulations agree very closely with the spacecraft observations, indicating that the model accurately represents whistler wave ducting physics. Future work will be focused on modeling of additional VAP events, including those in which waves are observed

in low-density ducts or non-symmetrical ducts. The results from this study are very important for future proposed experiments of launching whistler waves into the Radiation Belts from ground stations or space-based transmitters.

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