Generation and detection of whistler wave induced space plasma turbulence at Gakona, Alaska

2013 Phys. Scr. 2013 014029

(http://iopscience.iop.org/1402-4896/2013/T155/014029)

Phys. Scr. **T155** (2013) 014029 (4pp) doi:10.1088/0031-8949/2013/T155/014029

Generation and detection of whistler wave induced space plasma turbulence at Gakona, Alaska

L A Rooker[1], M C Lee[1,2], R Pradipta[2] and B J Watkins[3]

[1] Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA
[2] Space Propulsion Laboratory, Massachusetts Institute of Technology (MIT), Cambridge, MA 02139, USA
[3] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA

E-mail: mclee@mit.edu

Received 23 July 2012
Published 16 July 2013
Online at stacks.iop.org/PhysScr/T155/014029

Abstract
We report on high-frequency wave injection experiments using the beat wave technique to study the generation of very-low-frequency (VLF) whistler waves in the ionosphere above Gakona, Alaska. This work is aimed at investigating whistler wave interactions with ionospheric plasmas and radiation belts. The beat wave technique involves injecting two X-mode waves at a difference frequency in the VLF range using the High-frequency Active Auroral Research Program (HAARP) heating facility. A sequence of beat wave-generated whistler waves at 2, 6.5, 7.5, 8.5, 9.5, 11.5, 15.5, 22.5, 28.5 and 40.5 kHz were detected in our 2011 experiments. We present Modular Ultra-high-frequency Ionospheric Radar (MUIR) (446 MHz) measurements of ion lines as the primary diagnosis of ionospheric plasma effects caused by beat wave-generated whistler waves. A magnetometer and digisonde were used to monitor the background ionospheric plasma conditions throughout the experiments. Our theoretical and data analyses show that VLF whistler waves can effectively interact with ionospheric plasmas via two different four-wave interaction processes leading to energization of electrons and ions. These preliminary results support our Arecibo experiments to study NAU-launched 40.75 kHz whistler wave interactions with space plasmas.

PACS number: 52.35.Hr

(Some figures may appear in colour only in the online journal)

1. Introduction

It has been observed in our Arecibo experiments that Navy transmitter code-named (NAU)-launched whistler waves can interact with energetic electrons trapped in the inner radiation belts at $L = 1.35$ (Pradipta *et al* 2007) as well as accelerate electrons in the ionosphere via a four-wave interaction process (Labno *et al* 2007). We recently conducted experiments at Gakona using two high-frequency (HF) X-mode waves to explore the beat wave technique for the controlled study of very-low-frequency (VLF) whistler wave interactions with ionospheric plasmas and the outer radiation belts at $L = 4.9$. A sequence of beat wave-generated whistler waves at 2, 6.5, 7.5, 8.5, 9.5, 11.5, 15.5, 22.5, 28.5 and 40.5 kHz had been successfully detected. Their intensities were greater than those produced by conventional HF wave modulation of electrojet currents. We present a data analysis and theoretical study to show the effectiveness of the newly developed beat wave generation technique for the controlled study of whistler wave interactions with space plasmas. The sequential presentations are (i) detection of beat wave-generated whistler waves and (ii) whistler wave interactions with ionospheric plasmas and outer radiation belts.

The rest of the paper is organized as follows. In section 2, we briefly discuss the beat wave generation technique and the theoretical basis. The detection of VLF waves and data recorded in our 2011 experiments using this technique is presented in section 3. The data include ground-based measurements of VLF signals, magnetometer and radar-detected ion lines. These sets of data provide evidence for us to suggest, in sections 4 and 5, that the generated whistler waves can interact with ionospheric plasmas over Gakona via two different kinds of four-wave interactions. Our discussions on whistler wave interactions with outer radiation belts and conclusions are presented in section 6.

2. Beat wave generation of whistler waves

We have been conducting experiments to generate VLF whistler waves in the ionosphere above Gakona, Alaska using the High-frequency Active Auroral Research Program (HAARP) Ionospheric Research Instrument (IRI) heater array over the last few years (Lee 2010). In order to create VLF waves via the beat wave technique, the HF heater array simultaneously transmits two X-mode waves with a difference frequency in the VLF range. For example, transmitting one wave at 3.2 MHz and the other at 3.202 MHz creates an artificial antenna in the ionosphere via the ponderomotive force that radiates at the difference frequency of 2 kHz. The force on an electron due to the two HF-injected waves is given by

$$\boldsymbol{F}_e = -e\widehat{E_1}E_1\cos[\omega_1 t - \boldsymbol{k}_1\cdot(\boldsymbol{r}+\Delta\boldsymbol{x}_2)] - e\widehat{E_2}E_2\cos[\omega_2 t - \boldsymbol{k}_2\cdot(\boldsymbol{r}+\Delta\boldsymbol{x}_1)],$$

where $(\omega_1, \mathbf{k_1})$ and $(\omega_2, \mathbf{k_2})$ denote the two HF-injected waves characterized by their wave frequencies and wave vectors; $\Delta\mathbf{x}$ represents the displacement of the electron oscillating in one wave electric field, as it experiences the force $\mathbf{F_e}$ from the other wave electric field. The quasi-dc component of the experienced electric force $\mathbf{F_e}$ is that at the difference frequency $(\omega_1-\omega_2)$ given by

$$F_{\rm NID} = -\widehat{E_1}(k_1\cdot\widehat{E_2})\frac{e^2E_1E_2}{2m_e\omega_2^2}\sin[(\omega_1-\omega_2)t-(\boldsymbol{k}_1-\boldsymbol{k}_2)\cdot r] + \widehat{E_2}(\vec{k}_2\cdot\widehat{E_1})\frac{e^2E_1E_2}{2m_e\omega_1^2}\sin[(\omega_1-\omega_2)t-(\boldsymbol{k}_1-\boldsymbol{k}_2)\cdot r].$$

It is the ponderomotive force (loosely called the radiation force) that is responsible for generating the VLF whistler waves from the two injected HF heater waves. This indicates that the efficiency decreases with the difference frequency $(\omega_1-\omega_2)$.

3. Detection of beat wave-generated VLF whistler waves

Beat wave-generated VLF whistler waves with frequencies at 2, 6.5, 7.5, 8.5, 9.5, 11.5, 15.5, 22.5, 28.5 and 40.5 kHz were detected using a VLF receiver setup a few miles away from the HAARP IRI heater array. Figure 1 shows the detection of two cycles of 11.5, 15.5, 22.5, 28.5 and 40.5 kHz waves created using the beat wave technique on 23 July 2011 in Gakona, Alaska. The whistler wave field intensity versus wave frequency is given in figure 2.

Generally, the generation efficiency is consistent with expected dependence of ponderomotive force on

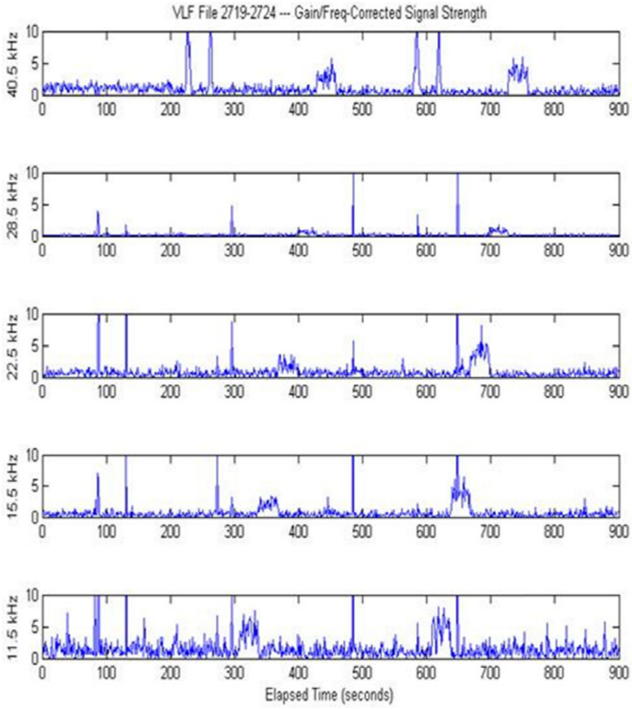

Figure 1. Detection of beat wave-generated VLF whistler waves at 11.5, 15.5, 22.5, 28.5 and 40.50 kHz.

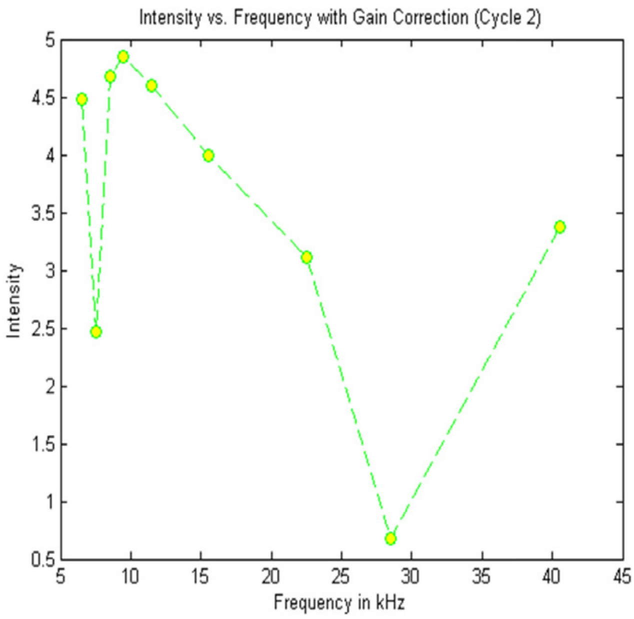

Figure 2. Whistler wave intensity versus wave frequency of those generated VLF whistler waves, showing monotonically decreasing intensity, in general, up to 28.5 kHz.

the difference frequency $(\omega_1-\omega_2)$ up to 28.5 kHz. The discrepancy from the expected monotonic decreasing of wave intensity may be attributed to possible beat wave interactions with electrojet currents. We note that the presence of electrojet currents in our experiments, marked by the green rectangular box in figure 3, may affect beat wave generation of whistler waves as well as the background plasma conditions. Shown in figure 4 is an enhanced zero-frequency mode, seen as a central line in the radar-detected ion line spectra, which was very likely induced by the electrojet current. We will look into

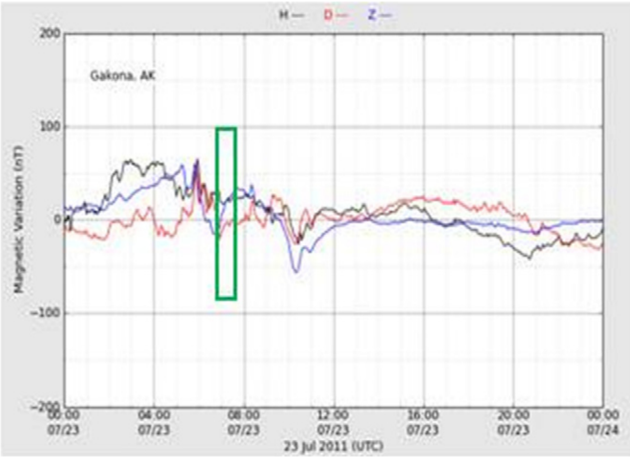

Figure 3. Magnetometer data recorded on 23 July 2011 from 7 to 7:30 UT.

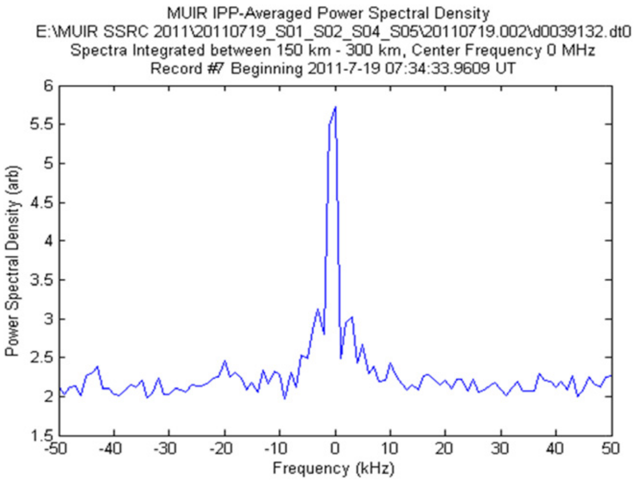

Figure 4. Ion lines recorded during beat wave experiments.

field-aligned, (Birkeland) current-induced, low-frequency plasma modes in our summer experiments (Rooker *et al* 2012). This problem will be further addressed in later sections for the radar detection of ion lines.

As mentioned earlier, beat wave-generated VLF waves are intense enough to cause significant impacts on ionospheric plasmas. Estimated wave field intensities are $1\,\mathrm{mV\,m^{-1}}$, which exceeds the thresholds required for the four-wave interaction process discussed by Labno *et al* (2007). We discuss this process and a new one which will lead to direct acceleration of ionospheric electrons.

4. Ionospheric electron acceleration via four-wave interaction processes

Illustrated in figure 5 is the four-wave interaction process considered by Labno *et al* (2007), which satisfies the following wave vector and wave frequency matching conditions:

$$\omega_o = \omega_{\ell h}^{+} - \omega_s, \quad \omega_o = \omega_{\ell h}^{-} + \omega_s^{*},$$
$$\mathbf{k}_o = \mathbf{k}_+ - \mathbf{k}_S, \;\; \mathbf{k}_o = \mathbf{k}_- + \mathbf{k}_S.$$

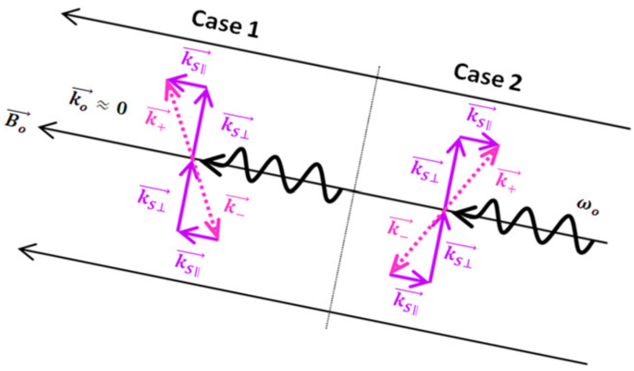

Figure 5. A four-wave interaction process showing that VLF whistler-mode waves (ω_o, $\mathbf{k_o}$) can parametrically excite Stokes ($\omega_{\ell h}^{-}$, $\mathbf{k}_-$) and anti-Stokes ($\omega_{\ell h}^{+}$, $\mathbf{k}_+$) lower hybrid waves together with zero-frequency (ω_s, $\mathbf{k_S}$) field-aligned density irregularities. The excited lower hybrid waves have a single frequency equal to the VLF whistler wave frequency and a range of wavelengths.

In Labno *et al*'s work, the excitation of meter-scale lower hybrid waves explained the ionospheric electron acceleration of up to 10 eV inferred from plasma line measurements. In this process $\mathbf{k}_o \ll \mathbf{k}_S$, thus $\mathbf{k}_+(\mathbf{k}_-) \approx \mathbf{k}_S$. Hence, the excited lower hybrid waves are equally likely to propagate upwards or downwards along the background magnetic field, as illustrated in figure 5. Indeed, these electrostatic waves can accelerate electrons in the ionosphere, resulting in simultaneous upshifted and downshifted ion line enhancement, as seen in our experiments (see figure 4). However, we examine a four-wave interaction process that Labno *et al* (2007) did not investigate and find a new electron acceleration process to be discussed in the next section.

5. A new mechanism leading to direct whistler acceleration of electrons

We consider the excitation of lower hybrid waves having a whistler wave vector as their parallel wave vector and a purely irregular wave vector as their perpendicular wave vector (notice the differences of the dotted lines in figure 5 and figure 6(a) denoting excited Stokes and anti-Stokes lower hybrid waves). Then, our theoretical analysis shows that electrons can be accelerated upward by beat wave-generated whistler waves, which preferentially propagate upward (Rooker 2012; Rooker and Lee 2012). Our ion line data support this expectation that upstreaming electrons yield frequency-downshifted ion lines, as displayed in figure 6(b).

6. Discussions and conclusions

We have successfully demonstrated the beat wave generation of VLF whistler waves using two HF heater waves at Gakona, Alaska. This research is aimed at the controlled study of whistler wave interactions with (i) ionospheric plasmas and (ii) energetic particles trapped in the radiation belts. Unlike the HF amplitude modulation process of generating whistler waves, the beat wave technique does not require the presence of a background electrojet. Therefore, whistler waves can be generated in regions at lower latitudes, such as Arecibo, Puerto Rico. Additionally, the beat wave technique

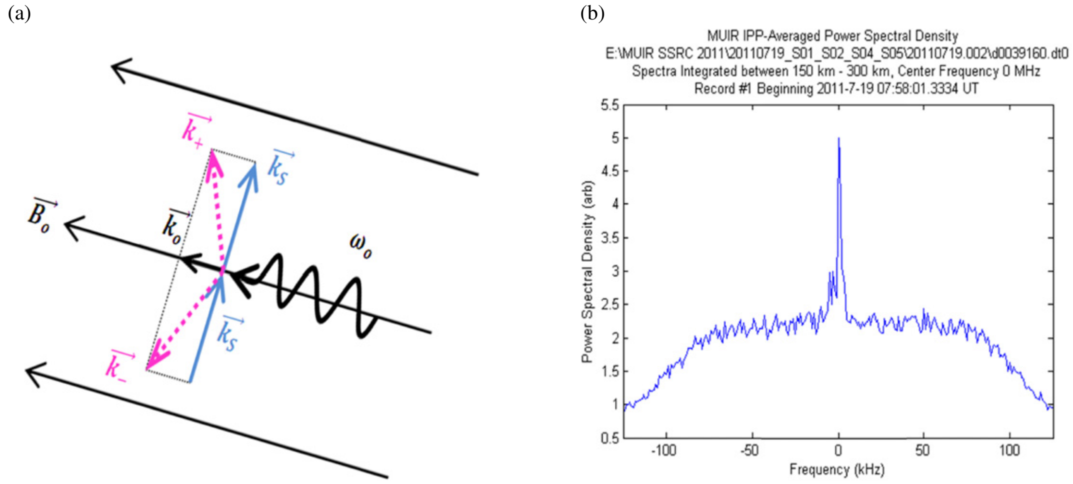

Figure 6. Illustration of upward electron acceleration by up-propagating whistler waves and the corresponding induced frequency-downshifted ion line enhancement due to the Doppler effect.

can generate electromagnetic waves in a broader range of frequencies (e.g., from a fraction of 1 Hz to kHz) than previous methods. However, in our reported experiments, we do not expect to see ionospheric plasma effects due to energetic charged particles precipitated from outer radiation belts over Gakona. The reason is given below.

Consider the whistler wave-particle resonant interaction condition,

$$\omega_o + k_\parallel v_\parallel = \omega_{ce}\left[1 - \left(v_\parallel^2 + v_\perp^2\right)/c^2\right]^{1/2},$$

where ω_o and $(k_\parallel)k_o$ denote, respectively, frequency and (parallel) wave number of the whistler-mode wave, and the dispersion relation: $(ck_o/\omega_o)^2 = 1 - \omega_{pe}^2/[\omega_o(\omega_o - \omega_{ce})]$. Here, ω_{ce} and ω_{pe} represent the angular cyclotron and plasma frequencies of cold plasmaspheric electrons; $v_\parallel$ and $v_\perp$ represent the velocity components of radiation belt electrons parallel and perpendicular to the magnetic field; c is the speed of light in a vacuum (Pradipta *et al* 2007). For simplicity, assuming that the whistler wave propagates along the geomagnetic field, we can determine $k_\parallel$ from the whistler wave dispersion relation. We found that whistler wave interactions with energetic electrons at high latitudes decrease drastically as frequency increases due to background plasma conditions in radiation belts. Therefore, whistler waves in the extremely-low-frequency (ELF) range are expected to interact more effectively with the electrons trapped in the outer radiation belt than VLF whistler waves can.

We have analyzed a new four-wave interaction process wherein whistler waves can accelerate ionospheric electrons directly along the geomagnetic field during their upward propagation. This process results in frequency-downshifted ion lines, as we have indeed observed in Gakona experiments. Furthermore, we can rely on this mechanism to understand the measured plasma lines at Arecibo, which have only frequency-downshifted spectra caused by NAU-launched 40.75 kHz whistler waves (Rooker 2012; Lee *et al* 2012). In our future Gakona experiments, we will examine the effects of electrojet currents on beat wave-generated whistler waves, possibly the excitation of low-frequency plasma modes, and changes in background plasma conditions. We should finally mention that we used the uncoded long pulse radar technique to record ion lines in our experiments. However, in our planned experiments for this upcoming summer at Gakona, we will adopt the coded long pulse technique to measure plasma lines for further investigation of whistler wave–plasma and whistler wave–particle interactions (Rooker *et al* 2012).

Acknowledgments

This work was supported by Air Force Office of Scientific Research (AFOSR) grant no. FA9550-09-1-0391. LAR's summer research was supported by a Lutchen Fellowship from the College of Engineering, Boston University. Part of this paper was presented by MCL as an invited paper at the 3rd International Conference on 'Turbulent Mixing and Beyond' (Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, 21–28 August 2010).

References

Labno A, Pradipta R, Lee M C, Sulzer M P, Burton L M, Cohen J A, Kuo S P and Rokusek D L 2007 Whistler-mode wave interactions with ionospheric plasmas over Arecibo *J. Geophys. Res.* **112** A03306

Lee M C 2010 Generation and detection of whistler wave-induced space plasma turbulence *3rd Int. Conf. on 'Turbulent Mixing and Beyond' (Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, 21–28 August 2010)*

Lee M C *et al* 2012 Investigation of naturally occurring and radio wave-induced ionospheric plasma turbulence *39th IEEE Int. Conf. on Plasma Science (Edinburgh, 8–12 July 2012)*

Pradipta R, Labno A, Lee M C, Burke W J, Sulzer M P, Cohen J A, Burton L M, Kuo S P and Rokusek D L 2007 Electron precipitation from the inner radiation belt above Arecibo *Geophys. Res. Lett.* **34** L08101

Rooker L A *et al* 2012 *Proposal for Summer Gakona 2012 Experiments (30 July–9 August 2012)*

Rooker L A and Lee M C (advisor) 2012 *Lutchen Fellowship Report* College of Engineering, Boston University

Rooker L A and Lee M C 2012 Beat wave generation experiments for study of VLF whistler wave interactions with ionospheric plasmas and radiation belts (Student Paper Contest) *39th IEEE Int. Conf. on Plasma Science (Edinburgh, 9–12 July 2012)*