Preliminary Study on Active Modulation of Polar Mesosphere Summer Echoes with the Radio Propagation in Layered Space Dusty Plasma*

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Abstract Radar echoes intensity of polar mesosphere summer echoes (PMSE) is greatly affected by the temperature of dusty plasma and the frequency of electromagnetic wave about the radar. In this paper, a new method is developed to explain the active experiment results of PMSE. The theory of wave propagation in a layered media is used to study the propagation characteristics of an electromagnetic wave at different electron temperatures. The simulation results show that the variation tendency of the reflected power fraction almost agrees with the results observed by radar in the European Incoherent Scatter Scientific Association (EISCAT). The radar echoes intensity of PMSE greatly decreases with the increase of the radio frequency and the enhancement of the electron temperature.

Keywords: Polar Mesosphere Summer Echoes (PMSE), electromagnetic wave, dust plasma, electron temperature

PACS: *52.25.Fi, 52.27.Lw, 52.50.Sw*

DOI: 10.1088/1009-0630/18/6/05

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

1 Introduction

Polar Mesosphere Summer Echoes (PMSE) are abnormally strong radar echoes primarily observed at polar latitudes for heights between 80 km to 90 km during the summer [1−4]. It is shown that there is a very good correspondence between the dust plasma and the PMSE [5−9], and the primary method contributing to the study of the wave transmission in dusty plasmas is the wave propagation theory in a layered medium from a recent observation [10]. In addition, It is shown from many active modulation experiments and modelling results that the PMSE backscatter power can be reduced by heating the ionosphere with high frequency radio waves [11−16] and radar echoes are greatly affected by the electron temperature. However, there is still no entirely convincing theory that can account for the reason why the radar echoes intensity can become very weak by means of heating the ionosphere with powerful high frequency radio waves so far.

In this paper, a statistical analysis has been made in the active modulation experiment results of PMSE and the permittivity calculated ranging from 50 MHz to 1300 MHz [16] at different electron temperatures. The partial reflection coefficients at the corresponding layer are obtained by calculating the permittivity. Then on the basis of the superposition principle, the entire reflected, transmitted, and absorbed powers are also calculated. Finally, conclusions of the study are given by comparing the calculated results with the experimental results observed by the EISCAT radar [17].

2 Experiment analysis

The results of successful active modulation experiments of PMSE are analyzed for the purpose of finding the relationship between PMSE backscatter reduction and electron temperature. An active modulation experiment of PMSE observed with the EISCAT VHF system on July 5th 2004 is shown in Fig. 1.

It is shown from the experiment results that the PMSE backscatter power can be reduced by means of heating the polar mesopause with powerful high frequency radio waves. The first 80 s of the plot illustrates the intensity of the PMSE backscatter power before heating with the radio wave. When it is at 80 s, the pump is switched on and the PMSE backscatter power immediately decreases to well below that of the unheated level. At 100 s when the heating is stopped, the PMSE backscatter power suddenly increases well

*supported by National Natural Science Foundation of China (Nos. 41104097 and 41304119) and by the National Key Laboratory of Electromagnetic Environment, China Research Institute of Radiowave Propagation (CRIRP)

beyond the unheated backscatter power, which is called 'PMSE overshoot'. The PMSE backscatter power then gradually returns to the background level for the remainder of the epoch. It can be established that the electron temperature becomes higher heated by the action of a powerful high frequency radiowave and electron temperature enhancement governed the PMSE power behaviour [18]. So it is demonstrated from the analysis above that the radar echoes intensity of polar mesospheric summer echoes is affected extremely by the temperature of dusty plasma.

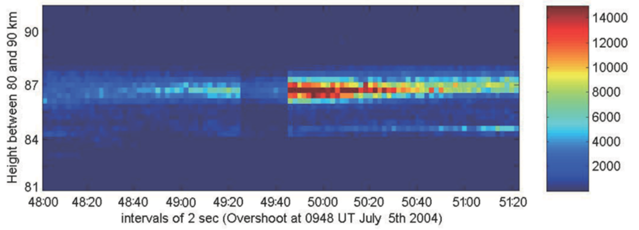

Fig.1 An example of an EISCAT VHF backscatter power profile showing active PMSE modulation on July 5th 2004. Left panel: the EISCAT VHF radar backscatter power profile with time. Right panel: the value of backscatter power energy

3 Simulation analysis

Based on the wave propagation theory in dusty plasma, the conductivity of weakly ionized dusty plasmas can be written as follows [19]

$$\varepsilon = \varepsilon_0 \left(1 - \frac{\omega_{\mathrm{pe}}^2}{\omega^2 + \nu_{\mathrm{eff}}^2}\right) + \eta_{\mathrm{e}} \frac{\nu_{\mathrm{ch}} + \nu_{\mathrm{eff}}}{(\omega^2 + \nu_{\mathrm{eff}}^2)(\omega^2 + \nu_{\mathrm{ch}}^2)}, \tag{1}$$

where, ε_0 is the dielectric permittivity constant in a vacuum. ω_{pe} is the plasma frequency of an electron. ν_{eff} represents the efficiency electron collision frequency. In addition, the ν_{ch} is called the charging frequency of a dust particle. ω is the frequency of the incident wave.

The charging response factor $\eta_{\mathrm{e}} = e^2 \pi r_{\mathrm{d}}^2 N_{\mathrm{e}} N_{\mathrm{d}} c / m_{\mathrm{e}}$. Here, N_{d} is the dust charge number density. N_{e} is the electron number density. The electron number densities and dust charge number densities are measured during the sounding rocket flight ECT02. These data are taken from the reference [20]. It is reasonably assumed that the average radius of the dust particles is $r_{\mathrm{d}} \approx 30$ nm [5]. Here, T is the electrons temperature detected by the sounding rocket flight ECT02, and the ion temperature is equal to the electron temperature [21].

The dust plasma is considered as being layered and homogeneous in every layer, the reflection coefficient of a wave propagating from a layer boundary situated at z_i with a complex dielectric constant $\varepsilon(z_i)$ to a layer boundary situated at z_{i+1} with a complex dielectric constant $\varepsilon(z_{i+1})$ is [22]

$$\Gamma(z_{i+1}) = \frac{\frac{\varepsilon(z_{i+1})}{\varepsilon(z_i)} \cos\theta_i - \left(\frac{\varepsilon(z_{i+1})}{\varepsilon(z_i)} - \sin^2\theta_i\right)^{1/2}}{\frac{\varepsilon(z_{i+1})}{\varepsilon(z_i)} \cos\theta_i + \left(\frac{\varepsilon(z_{i+1})}{\varepsilon(z_i)} - \sin^2\theta_i\right)^{1/2}}. \tag{2}$$

The total reflection coefficient Γ_T is deduced by the sum of the partial reflection coefficients at each layer boundary, multiplied by their corresponding attenuation factors. Thus Γ_T is given as

$$\Gamma_T = \sum_{i=1}^{N} \Gamma(z_i)(q(z_i))^2. \tag{3}$$

The attenuation factor, $q(z_i)$, is $q(z_i) = 1-\exp(-\alpha(z_i)z_i)$. $\alpha(z_i)$ is the attenuation coefficient of layer i. The total reflected power factor is obtained by

$$\frac{P_{\mathrm{R}}}{P_{\mathrm{IN}}} = |\Gamma_T|^2. \tag{4}$$

The total transmitted factor can be deduced by

$$\frac{P_{\mathrm{T}}}{P_{\mathrm{IN}}} = \prod_i \exp(-\alpha(z_i)d), \tag{5}$$

where, d is the corresponding layer height. Then the total absorbed power factor is written as [10]

$$\frac{P_{\mathrm{A}}}{P_{\mathrm{IN}}} = 1 - \frac{P_{\mathrm{R}}}{P_{\mathrm{IN}}} - \frac{P_{\mathrm{T}}}{P_{\mathrm{IN}}}. \tag{6}$$

In this study, the polar mesopause between 82 km and 90 km is divided into 300 layers. The data of the temperature and charge number of a dust particle in Fig. 2 are utilized to analyze the radio propagation characteristics in layered space dusty plasma.

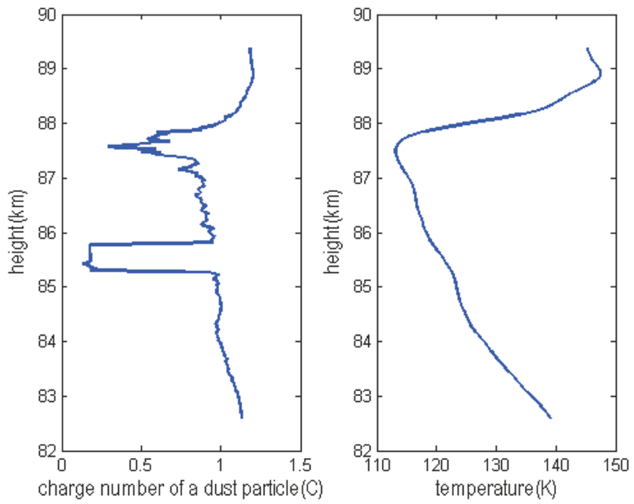

Fig.2 Left panel: profiles of charge number of a dust particle measured during sounding rocket flight ECT02. Right panel: profiles of electron temperature measured during sounding rocket flight ECT02

PMSE have been observed at frequencies ranging from 2.78 MHz to 1.29 GHz [23]. However, the active modulation experiments of PMSE are mainly detected at VHF and UHF bands. In order to account for the experiment phenomenon easily, the simulation results are calculated ranging from 50 MHz to 1300 MHz [16]. Considering the vertical incident wave, the variation of reflected power fraction with frequency at different temperatures is shown in Fig. 3.

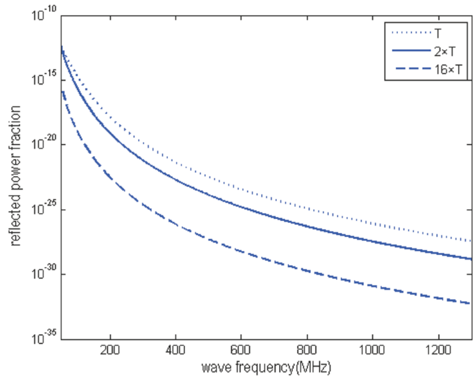

Fig.3 Variation of reflected power per unit incident power with frequency, (1) the dot curve represents electron temperature at T, (2) the solid curve represents electron temperature at double of T, and (3) the broken curve represents electron temperature at sixteen times of T

The dot curve in Fig. 3 shows that the reflected power decreases greatly for increasing incident frequency at normal atmospheric temperature, which agrees with the statistical survey. Solid and broken curves show the same tendency, which is expected according to the theory. It can be seen that the reflected power greatly decreases for increasing temperature from the three curves in Fig. 3. It is indicated from Fig. 3 that the reflected power greatly decreases for increasing incident frequency and temperature.

The transmitted power fraction versus frequency for three values of temperature is shown in Fig. 4. It is seen that the transmitted power is reduced sharply with the rising of incident frequency from the left panel of Fig. 4. However, the variation range of transmitted power in right panel of Fig. 4 is small. In order to compare with the variation clearly, the frequency band is divided into two parts. So it is clear that the transmitted power decreases with increasing of temperature from the two panels in Fig. 4. In addition, every curve shows that the transmitted power greatly decreases with increasing incident frequency.

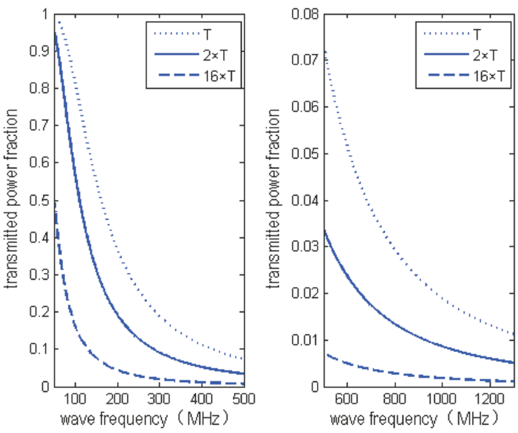

Fig.4 Variation of transmitted power per unit incident power with frequency, (1) the dot curve represents electron temperature at T, (2) the solid curve represents electron temperature at double of T, and (3) the broken curve represents electron temperature at sixteen times of T

Fig. 5 shows the absorbed power normalized with respect to the incident power versus frequency for three values of temperature. Here, the frequency band is also divided into two parts. Each curve shows that the absorbed power greatly increases with increasing incident frequency. In addition, we can observe from Fig. 5 that absorbed power greatly decreases with increasing electron temperature.

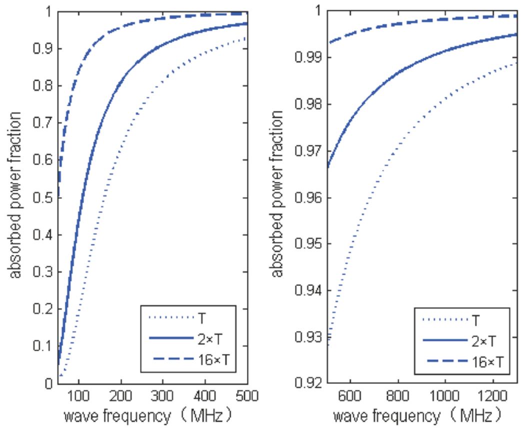

Fig.5 Variation of absorbed power per unit incident power with frequency, (1) the dot curve represents electron temperature at T, (2) the solid curve represents electron temperature at double of T, and (3) the broken curve represents electron temperature at sixteen times of T

4 Conclusion

Based on the theory of dusty plasma permittivity, radio wave propagation characteristic in layered space dusty plasma can be used to analyze the active modulation experiment results in this study. Several significant results are obtained by simulation research about the reflection, absorption, and transmission when an electromagnetic wave propagates in space dusty plasma at local summer polar mesopause. Comparing experimental results observed by EISCAT radar with calculated results, it is clearly seen that the electron temperature and observation frequency greatly affect radar echoes about PMSE. The radar echoes intensity of PMSE is reduced with the enhancement of electron temperature and the increase of radio frequency, which almost agree with the experiment results.

However, there are still tiny differences between the calculated and observed results. Comparing the echoes intensity detected by radar, calculated results show the echoes were weaker. The main reason is that the nonlinear phenomenon exists in the dust plasma and the equation of dusty plasma permittivity in this simulation needs modifying from HF to UHF bands. Besides, the overshoot phenomenon cannot be explained by the present permittivity, because dusty plasma in the polar mesopause does not meet the condition of electric neutrality at the moment when radar power is on and off. So the new equations of dusty plasma permittivity under the condition of non-equilibrium should be deduced in the future. When the non-equilibrium permittivity is given, the active modulation model will be set up and the calculated results will be close to the observed in the dust plasma.

Acknowledgments

We thank Professor M. RAPP and Professor O. HAVNES for providing the data of ECT-02.

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(Manuscript received 23 June 2015)
(Manuscript accepted 9 October 2015)
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