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ELECTRON TEMPERATURE DEPENDENCE OF PMSE POWER: EXPERIMENTAL AND MODELLING RESULTS

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ABSTRACT

Joint PMSE - ionospheric heating experiments using the EISCAT VHF radar and the Heating facility were conducted at the EISCAT site near Tromsø during the period July 9-14, 1999. Height profiles of backscattered power for four different combinations of heating parameters and ionospheric conditions are presented and analysed with the help of an ionospheric heating model. The decrease of PMSE power during heating has a height dependence and varies from one case to another. This variability of the heating effect on PMSE power may be related to height-dependence and case-to-case variation of the electron temperature enhancements due to the ionospheric heating as well as to differing undisturbed levels of PMSE power. The possible relation of electron recombination, diffusion, and aerosol charging to the observed reduction of PMSE power during heating is discussed. An increase of electron diffusivity due to the temperature enhancement seems to be the most likely factor affecting PMSE during the experiments.

1. INTRODUCTION

Polar Mesosphere Summer Echoes (PMSE) are abnormally strong radar backscatter from mesopause heights observed during summer in the polar regions. Several intensive campaigns involving lidar sounding, rocket-borne measurements and complementary radar experiments have taken place during the past 20 years since PMSE was first discovered. Many results have been obtained, and the general consensus is that the necessary factor for PMSE formation is the coldness of the summer mesopause region (e.g. Balsley and Huaman, 1997). This leads to the formation of sub-visible ice crystals, which might scavenge free electrons and reduce electron diffusivity (Kelley et al., 1987) and hence, increase the Schmidt number, which is defined as the ratio between the kinematic viscosity of the neutral gas and the electron diffusion coefficient. Consequently, electron density fluctuations at such a small scale as a radar half-wavelength can persist longer before being dissipated by diffusion, unlike the case for neutral density fluctuations, e.g. generated by turbulence. So, the role of low neutral temperatures in the vicinity of the summer mesopause is clear, at least theoretically. But how can electron temperature influence the characteristics of PMSE? How effectively is the existence of PMSE controlled by electron diffusivity? We have tried to address such questions with the help of a new joint PMSE - electron heating experiment (Chilson et al, 2000).

In the mesosphere the electron temperature is normally equal to the neutral temperature due to a high rate of collisions. One simple way to raise the electron temperature is by the action of a powerful HF radiowave. To do this we have used the EISCAT Heating facility located near Tromsø (69.58°N, 19.22°E), with the co-located EISCAT VHF radar being used for the PMSE measurements. The first task was to show that PMSE are indeed affected by heating and that we can measure this effect. This has been successfully achieved and has been reported by Chilson et al. (2000). The electron heating was found to lead to a reduction of PMSE power, with this process taking less than 2 seconds. The echo power reduction during heating was further found to vary with height, and from one case to another. In this paper we concentrate on a detailed study of the heating using estimates of enhanced electron temperature profiles computed by a model. Then we consider those physical processes relevant to PMSE, which could be affected by enhanced electron temperature. We consider such important processes as aerosol charging, electron-ion recombination and electron diffusion. We apply the theoretical results obtained recently by Rapp and Lübken (2000) on electron diffusivity, to explain the results of the experiments.

2. EXPERIMENTAL SETUP AND ELECTRON TEMPERATURE MODELLING

2.1 Experiment Description

During the period July 9-14, 1999 joint PMSE/Heating experiments were conducted for a total of 10 hours at the EISCAT site near Tromsø. The experiments took place near midnight from 2200 UT to 0200 UT. The VHF radar operated at 224 MHz, and was used for detection and measurement of PMSE. The operation, sampling and data processing are described by Chilson et al. (2000). We mention only that we here use backscattered power determined from the radar data with a time resolution of 2 seconds and a height resolution of 300 m.

The EISCAT Heating facility was used for ionospheric modification (for description of the facility see Rietveld et al., 1993). It transmitted at two frequencies of 4.04 and 5.423 MHz, in ordinary (O) and extraordinary (X) modes, and with different effective radiated power (ERP) in the range of 194-629 MW (determined by the antenna array). We have used mostly 2 modulation patterns: switching heating on for 10 or 20 seconds and then off for 10 or 20 seconds, respectively.

2.2 Model of Ionospheric Heating

A model of electron temperature during ionospheric heating has been developed and described by Belova et al. (1995). It includes an electron energy balance equation for the steady state case and an equation describing propagation and absorption of the radio wave. As input parameters it uses background electron density and temperature profiles from 60 km up to 150 km, the parameters of the heating wave, and a model of the neutral atmosphere.

The most important item is the electron density in the lower part of the ionosphere because it is there that most of the absorption of the heating wave takes place. The dependence of the electron temperature profile on the initial profile of the electron density has been investigated by Pashin et al. (1995). It could be shown that the influence of the initial electron density in the lower ionosphere on enhanced electron temperature can be substantial. Thus, information about electron density during our heating experiments is of great significance for successful modelling. Unfortunately, we do not have exact information about the electron density. The only available data are from the IRIS imaging riometer, which measures integral ionospheric absorption of cosmic radio noise above our experiment site. Radio noise absorption varied from one experiment to another but not strongly, i.e. it remains inside the range of 0-0.4 dB. We have used the riometer absorption data to derive D region (60-90 km) electron density profiles using the method described by Osepian and Kirkwood (1996) and Osepian et al. (1999). We combine this with an upper part (90-150 km) which is taken from the empirical model proposed by Friedrich and Kirkwood (2000).

The initial electron temperatures have been chosen to be equal to the neutral temperatures, which have been recently published in a summary of in situ measurements of the thermal structure of the polar summer mesosphere by Lübken (1999). The upper part of these profiles above 93 km was taken from the MSIS-E-90 model (Hedin, 1991).

3. EXPERIMENTAL AND MODELLING RESULTS

We will present data in the following way. Backscattered powers for intervals when the heater was on (P_{on}) and off (P_{off}) have been averaged over the duration of each heating experiment. We will present height profiles for the P_{on} to P_{off} ratio as well as profiles of the undisturbed power P_{off}, and computed height profiles of the disturbed electron temperature for each heating experiment.

3.1 Dependence of Heating Effect on Height

In Figure 1 the upper panel shows the results for experiment 1. Here and later we follow the original experiment numbering as given in Chilson et al. (2000). On the left side of the panel the undisturbed PMSE power (P_{off}) as well as power on/off ratio profiles are plotted. PMSE in this case exhibit a double layered structure which is a rather common situation for PMSE. Layers are centered at approximately 85.5 and 90 km. As mentioned above, heating causes a reduction of the PMSE power, and we see the ratio is less than unity for all heights where PMSE exist. The ratio reaches a minimum, implying that the heating effect reaches a maximum, at the heights where maximum undisturbed PMSE powers were observed. This could mean that the heating effect depends on the background PMSE level. On the right-hand side, the computed profile of the disturbed electron temperature with respect to the undisturbed one is presented, calculated for the heating configuration specified on the plot. The riometer absorption was near 0 dB, which corresponds to the quiet ionospheric conditions with low electron density in the D region. Therefore the heating wave passed through the lower part of this region without substantial absorption and heated electrons significantly in the upper part of the D-region. As seen from the left part of the figure the undisturbed PMSE powers were approximately the same for the two peak heights, but the effect of heating is obviously larger at 85.5 km than that at 90 km; the PMSE power drops to less than half at the former height. The electron temperature is also more enhanced at 85.5 km than at 90 km, i.e. Te/Tn=19 and Te/Tn=12, respectively. We can conclude that, for experiment 1, a stronger decrease of PMSE power is achieved where the electron temperature is higher.

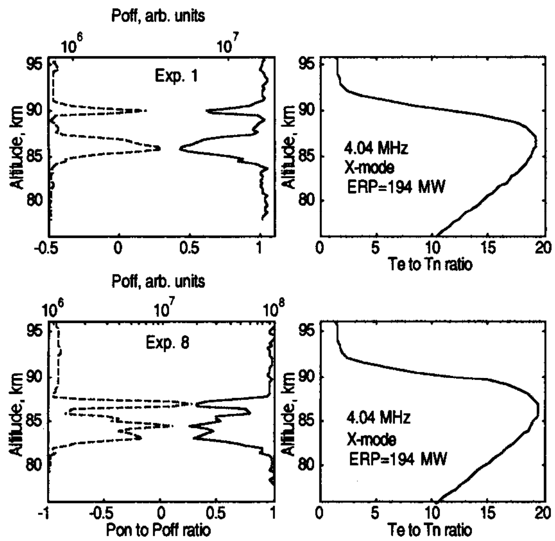

Fig. 1. (left panel) Height profiles of the P_{on} to P_{off} ratio (solid lines), P_{off} (dashed lines); (right panels) height profiles of the T_e to T_n ratio for experiment 1 (top) and 8 (bottom).

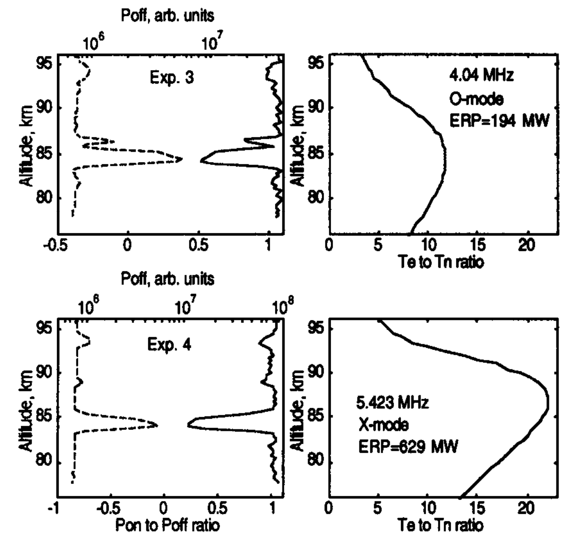

Fig. 2. The same as in Fig. 1 but for experiment 3 (top) and 4 (bottom).

3.2 Dependence of Heating Effect on PMSE Background Level

The lower panel of Figure 1 presents the results for experiment 8. It was conducted with the same heating configuration as experiment 1 and under similar ionospheric conditions (according to the riometer data). This results in the same enhanced electron temperature profile as shown on the right side of the figure. However, the initial PMSE level was higher for experiment 8 than for experiment 1, and we get a stronger decrease of PMSE power (falling to about one third) due to heating for experiment 8. However, any dependence of the heating effect on electron temperature is not so evident in this case as in the case of experiment 1.

3.3 Dependence of Heating Effect on the Parameters of Heating

Experiments 3 and 4 were conducted during two consecutive hours. However, the mean level of the riometer-measured absorption was slightly higher for experiment 3 than for experiment 4. But most important was that we used very different heating configurations: frequency, mode and transmitted power. For experiment 3 we used O-mode heating to interact with the ionospheric electrons, which is not so efficient as X-mode heating. Therefore we achieved electron temperature enhancements of up to a factor 12 only, spread over a wide altitude range, as shown in Figure 2 in the right upper panel. For experiment 4 the ERP was extremely high, 629 MW, which gives a rise in electron temperature by more than 20 times compared to the undisturbed level. It seems likely that this large electron temperature enhancement governed the PMSE power behaviour: the decrease of PMSE level was much stronger for experiment 4 than that for experiment 3, as is clear comparing the upper and the lower left panels in Figure 2. We can conclude also that we have here direct correlation between the heating effect on PMSE power and the electron temperature disturbance, similar to the case for experiment 1. The higher the temperature the higher the decrease of PMSE power due to heating that is observed. However, this dependence is not linear. At peak power heights the electron temperature for experiment 4 increased 1.8 times more than that for experiment 3, but PMSE power decreased 2.5 times more for experiment 4 compared to experiment 3.

4. DISCUSSION AND INTERPRETATION OF RESULTS

To understand what factors determine the behaviour of PMSE during heating and why PMSE power is reduced we should consider every electron temperature dependent process relevant to PMSE. A first attempt of this kind of analysis has been undertaken by Rapp and Lübken (2000), and we proceed further in this direction and discuss a contribution of several processes.

During heating, electron density in the D-region can change significantly due to temperature dependence of the electron recombination coefficient (Itkina and Krotova, 1981). This could influence PMSE strength. However, the time constant of this process can be roughly estimated as $(\alpha_{eff} \cdot N_e)^{-1}$, where α_{eff} is an effective electron recombination coefficient, and N_e is electron density. Taking into account cluster ions (Kirkwood and Osepian, 1995) and an electron density of 10^4 cm^{-3}, we get about 100 s for the recombination time constant, which is much longer than the heating impulse duration of 10-20 s. The process of electron attachment, leading to negative ion formation, has a shorter time constant of about 1 s, but it is important only at the heights less than 80 km (Kirkwood and Osepian, 1995). We can conclude that electron density at heights of PMSE is not significantly changed by recombination during our heating experiments.

Aerosols, as mentioned above, play an important role in PMSE formation due to the fact that they capture electrons and reduce electron diffusivity. The capture rates of electrons by aerosols are temperature dependent (Natanson, 1960) and change during heating. This in turn can alter aerosol charging and hence, free electron density and electron diffusivity. Rapp and Lübken (2000) have analysed this matter qualitatively. Here we use a numerical calculation of electron density disturbance due to heating based on the aerosol charging model by Rapp and Lübken (2001).

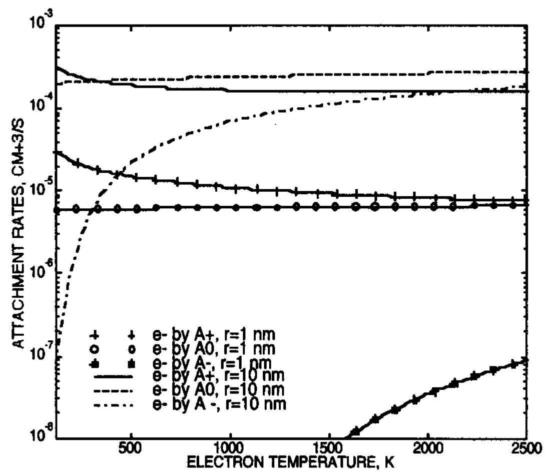

Fig. 3. Capture rates of electron by aerosols of two radii: 1 nm and 10 nm, as function of the electron temperature. Legend signs A-+0 denote singly negatively, positively charged, and neutral aerosol, respectively, e marks an electron.

In Figure 3 the capture rates of electrons by aerosols as a function of electron temperature are presented. The calculations were made for aerosols of two radii of 1 nm and 10 nm, and three sorts: singly negatively and positively charged, and neutral. The behaviour of other capture rates is in general similar to those shown in Figure 3. The capture rates by neutral and negatively charged aerosols, which are most important for the PMSE case, increase with temperature. The physics of this is that heated electrons get more energy to overcome the Coulomb barrier of the repulsive part of an aerosol-electron potential. The capture rates for the positively charged aerosols exhibit the opposite effect.

To use the aerosol charging model one needs to specify input parameters such as an effective electron recombination coefficient α_{eff}, a production rate Q or an initial electron density N_{e0} as well as an aerosol density N_{a0}, and an aerosol radius r_a. We chose r_a=10 nm, $\alpha_{eff} = 6 \cdot 10^{-6}$ cm^3 s^{-1}, N_{e0} = 300 cm^{-3} which is the model estimate at height of 85 km for riometer absorption of 0 dB and gives Q = 0.54 $cm^{-3}s^{-1}$. First we have run the model for an undisturbed temperature of 130 K, and for N_{a0} = 300 cm^{-3}. Then we have taken into account the temperature dependence of the capture rates in order to calculate disturbed plasma concentrations. The results are shown in Figure 4 (upper panel). For an electron temperature of 130 K there is an electron depletion because the electrons are captured by initially neutral aerosols. As the electron temperature increases some of the aerosols capture a second or even a third electron. Thus the electron depletion becomes deeper and the aerosol net negative charge shows a growth. We have further calculated the variable $\Lambda = |Z_a| N_a/N_e$, i.e. the ratio between tied and free charge (see lower panel of Figure 4). This quantity will be useful later for consideration of electron diffusion. As the free electron density decreases and thus the aerosol charge increases the value of Λ rises to values as large as 35 for an electron temperature of 2000 K.

The model calculations were repeated for an even larger aerosol number density of 1000 cm^{-3}. The results are presented in Figure 5. The main features of the plasma concentration behaviour are similar to those obtained for lower aerosol concentration. Values of Λ rise from 90 to as much as 180. Thus, electron heating leads to increase of the aerosol charge and parameter Λ. Cho et al. (1992) considered electron diffusion in the presence of charged aerosols and demonstrated that higher Λ values result in the larger Schmidt numbers. Hence, according to the Cho et al. (1992) heating should increase rather than suppress PMSE.

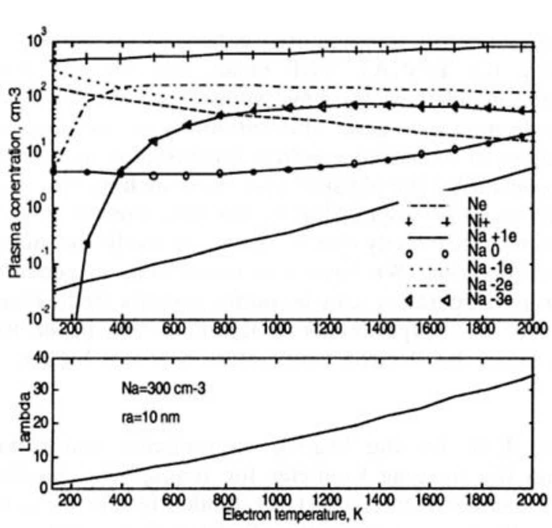

Fig. 4. (top) Dependencies of concentrations of different plasma constituents on the electron temperature for initial aerosol density of 300 cm^{-3}. Denotations are described in the legend. (bottom) Electron temperature dependency of Λ (Lambda).

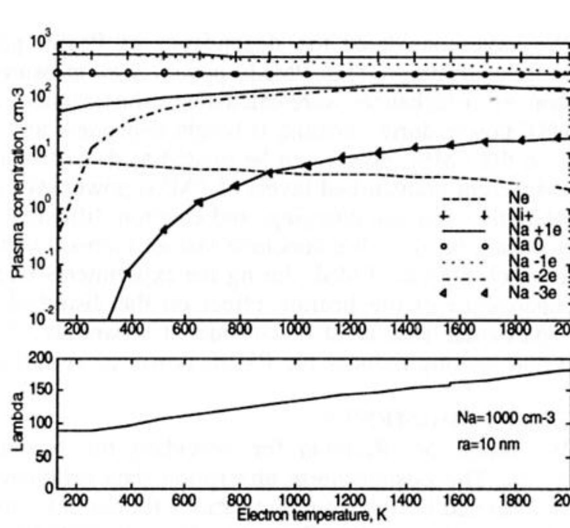

Fig. 5. The same as in Figure 4 but for initial aerosol density of 1000 cm^{-3}.

However, the electron diffusion during heating differs strongly from that for undisturbed conditions (Rapp and Lübken, 2000). Heating changes the electron diffusion in a very complicated way as demonstrated in Figure 2 of Rapp and Lübken (2000). For an electron temperature equal to the neutral temperature, there is a steady growth of the characteristic electron diffusion time (decay time) with an increase of Λ, i.e. with increase of N_a and/or aerosol charge. This implies that the electron diffusivity decreases with increase of Λ. For Λ = 1.2 the decay time is as much as 10^3 seconds. This result supports to some extent Cho et al. (1992)'s result that, to reach a Schmidt number of 100, Λ must be greater than 1.2. But we cannot use the same threshold for Λ marking the PMSE existence in case of enhanced electron temperature. As we conclude from the above mentioned Figure, for enhanced electron temperature the diffusivity first increases with Λ, which can lead to the disappearance of PMSE, but for high enough Λ values the electron diffusivity starts to decrease with Λ. The critical value of Λ when the tendency in diffusivity changes depends on electron temperature: the higher the temperature the larger becomes the critical value of Λ. For strong electron temperature enhancements ($T_e/T_n>8$) to reach long enough decay time (e.g. 10^2 seconds) the values of Λ must be much more than 100, which is an unrealistic high level. For very powerful heating, i.e. $T_e/T_n>20$ the aerosol influence on electron diffusion does not compensate the growth of diffusivity due to heating. As a simple picture, there are two factors driving the electron diffusivity: the first one is that the presence of aerosol particles leads to a decrease of diffusivity, and the second counteractive one is that heating raises diffusivity but also aerosol charge and hence, Λ - that in turn can suppress diffusivity. Because of this negative feedback the behaviour of diffusivity during heating becomes complicated.

Let's turn to the experimental results discussed in section 3. For experiments 1, 3 and 4 we obtained the result that the PMSE signal strength decreases more strongly as the electron temperature becomes higher. This effect could be explained by electron diffusivity altered due to heating. These are cases of powerful heating where T_e/T_n becomes more than 10. According to our aerosol charging model calculations, this corresponds to enhanced Λ values from 17 to 150. The higher T_e the higher is Λ, and according to Figure 2 by Rapp and Lübken (2000) the decay time can vary from 0.05 s to 0.5 s. The higher the temperature the shorter becomes the decay time and hence, the faster the structures in electron density which might be responsible for PMSE are destroyed. However, for the case of not so powerful heating the dependence of PMSE power on electron temperature might be more ambiguous and complicated. Perhaps, experiment 8 is a candidate, which represents this case.

5. SUMMARY

We have considered the dependence of PMSE power on electron temperature, enhanced by means of ionospheric heating. The PMSE power was measured using the EISCAT VHF radar, and the electron temperature disturbances were calculated using a model of electron heating. We have shown that the decrease of PMSE power during heating is height dependent and varies from case to case. This variability of the heating effect on the PMSE power can be related to the different degrees of enhanced electron temperature as well as to the different undisturbed levels of PMSE power. We have considered the physical processes such as electron recombination, aerosol charging, and electron diffusion, which might be responsible for the reduction of PMSE power during heating. We conclude that an increase of the electron diffusivity due to heating is likely the main factor which affected PMSE during the experiments under consideration. We have also found that, in general, the dependence of the heating effect on the disturbed electron temperature can be rather complicated. Thus every particular case must be considered separately. For 3 out of 4 experiments analysed in this paper we found that heating reduces the PMSE power more efficiently when the electron temperature becomes higher.

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