

A TIME CONSTANT OF RESPONSE OF PMSE TO IONOSPHERIC HEATING

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ABSTRACT

During July of 1999, experiments using the EISCAT VHF radar and the Heating facility were conducted to investigate the effects of ionospheric heating on polar mesosphere summer echoes (PMSE). It was shown that heating can dramatically reduce the backscattered echo power of PMSE. We re-examine the high temporal resolution data from three of the experiments. The response time of the PMSE to heating is estimated to be less than 30 ms. We consider that an increase of the Debye length up to one sixth of a radar wavelength due to electron heating might explain the observed heating effect on PMSE.

INTRODUCTION

Polar mesosphere summer echoes (PMSE) are abnormally strong radar returns that occur during summer months near the mesopause at high latitudes (for review see [1]). Several intensive campaigns involving lidar, rocket-borne measurements and complementary radar experiments have taken place during the past 20 years since PMSE was first discovered. The essential results have been obtained, but so far there is no clear understanding of the mechanism responsible for this strong echo. It seems that PMSE reflect a complicated process of coupling between neutral constituent and multi-component plasma consisting of electrons, ions (including cluster-ions) and charged aerosols [2].

In order to influence the electron component during PMSE events, we conducted, in summer 1999, a joint PMSE/Heating experiment using the EISCAT VHF radar and the EISCAT Heating facility. The idea was based on the following. Powerful HF radio waves transmitted by the Heating facility can reach mesospheric heights and increase the electron temperature there up to an order of magnitude [3]. This can modify the electron diffusivity and attachment/recombination coefficients and could be expected to influence PMSE.

During our experiment we demonstrated that PMSE were indeed affected by the heating pulses, with the back-scattered signal decreasing when the heater was on [4]. The PMSE power responded to heating in less than 2 seconds. Such a quick reaction of PMSE allows us to suggest that increased electron diffusion might be responsible for dissipation of PMSE. Irregularities in electron density, which we detect as PMSE, can dissipate due to enhanced diffusion caused by the electron temperature increase. Rapp and Lübken [5] have reported a theoretical study of diffusion in a multicomponent plasma under enhanced electron temperature conditions. According their calculations, for the case of $T_e=20 \cdot T_n$, where T_e and T_n are the electron and neutral temperature, respectively, and for a ratio of attached to free charge of 20, the diffusion decay time is about 0.1 s. In order to make more definitive conclusions further analysis of the experimental data is needed, with better time resolution.

EXPERIMENTAL CONFIGURATION AND DATA ANALYSIS

The joint PMSE/heating experiment reported here was conducted at the EISCAT site near Tromsø, Norway on July 9-11, 1999. The EISCAT VHF radar was used to detect PMSE and the EISCAT Heating facility to heat the ionosphere. A description of the experiment can be found in [4].

The backscattered powers during those time intervals and heights chosen for analysis have first been separated relative to the heater state at the time of the observations, that is, relative to whether the heater was on or off. Outliers in the time-series data for the power were identified as being those occurring beyond three standard deviations of the mean

calculated for every time interval chosen for analysis. The outliers were then removed from the time-series. Finally, the signals for all intervals corresponding to heater on or off states have been averaged in the following way. The first data point collected after the heater was turned on was averaged together with all of the other first data points. This is then likewise done for the subsequent points.

It is important to note that we collected the radar data in the following way: sampling was continuous during the first 1.88 s of each data-taking interval of 2 s. The remaining 0.12 s were used to transfer the samples to the computer. The intervals of heating we used were 10 s or 20 s, i.e. both proportional to the dump interval. Heating on/off were also synchronised to sampling interval start times. Later we will see that this was a disadvantage of the experiment arrangement.

RESULTS

The temporal behaviour of the PMSE power for exp01, exp04, and exp07 are presented in Figs. 1, 2 and 3, respectively. Here we use for convenience the original experiment numbering as given in [4] - all relevant experiment parameters are provided below. For each experiment there are 2 plots corresponding to the transitions of heater on to heater off and heater off to heater on. Time is shown along the abscissa and is measured in seconds from the beginning or from the end of a heater-on interval, depending on the sequence of the heater status. We show in the figure only 4-second intervals containing the most interesting region, i.e., when the heater is switched from on to off (or vice versa). Mean values and standard deviations obtained for the whole intervals of heater on and off are shown with solid and dashed lines, respectively.

Experiment 1 (exp01) was conducted on July 9, and we use the data for the interval 22:29 – 22:43 UT. The heater was operated in the extraordinary mode (the same for the other 2 experiments) at 4.04 MHz with an effective radiated power (ERP) of 194 MW, transmitted vertically. It was switched on for 10 s and then switching off for 10 s, and this modulation pattern was repeated many times.

Experiment 4 (exp04) took place on July 10, and data are used from the interval 01:04- 01:19 UT. The heater transmitted at 5.423 MHz frequency with an ERP of 629 MW, this being the highest for all the experiments. Beam direction was vertical, and the modulation pattern was 20 s on/ 20 s off.

Experiment 7 (exp07) was carried out on July 10, and we use the data for interval 22:32 – 22:37 UT. The heater was operated at 4.04 MHz with an ERP of 183 MW. The heater was left on all the time, and the modulation was accomplished by steering the heater beam 10 s in the vertical direction and then 10 s directed 16° off zenith towards the south. In the latter case the heater does not illuminate the same volume as observed by the radar, so the heater can be considered to be off.

The effect of heating on PMSE power is seen distinctly for all 3 experiments. The greatest reduction of PMSE power occurred as might be expected for exp04, when the heating was most powerful.

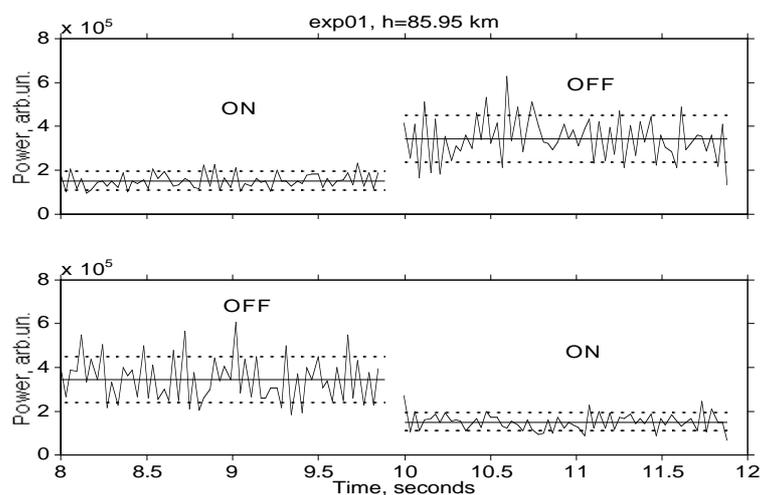


Fig. 1. Examples of the transition in averaged PMSE backscattered power as a function of electron heating for experiment 1. The state of the heater is indicated. Mean values and standard deviations of the measurements are shown with solid and dashed lines, respectively

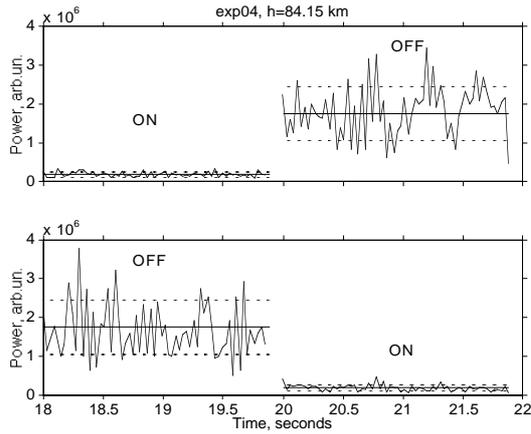


Fig. 2. The same as in Figure 1 but for experiment 4.

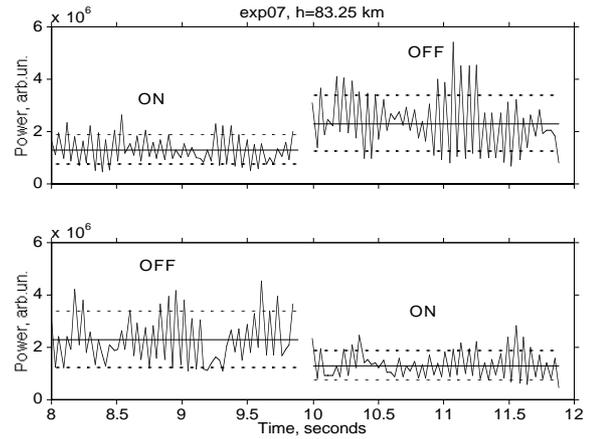


Fig. 3. The same as in Figure 1 but for experiment 7.

DISCUSSION

Let's consider the reaction time of the PMSE power to heating. Unfortunately, due to the data-sampling arrangement, there is a gap in the PMSE power data corresponding to the last 0.12 s of each heating-on or heating-off period. Consider, for example, exp04 and the sequence of heater on for 20 s and heater off for the next 20 s (Fig.2). A mean value of PMSE power for heater on interval is $1.9 \cdot 10^5$ (arbitrary units) with a standard deviation of $7 \cdot 10^4$. The corresponding quantities for the period when the heater was off are $1.8 \cdot 10^6$ and $7 \cdot 10^5$, respectively. One might reasonably expect that during the last 0.12 s of each 20 s period, the PMSE power would lie within the limits defined by the same mean and the same standard deviation as for the previous 19.88 s. The heater was switched off exactly at the time corresponding to the time mark of 20 s on the plot in Fig. 2. The first data point was obtained 30 ms after this time, and the corresponding PMSE power at this moment has already increased to the PMSE background level. One can conclude that the time for the PMSE to react to heater switch-off is close to or less than our time resolution, i.e., 30 ms or less. Similar considerations apply for the opposite sequence, heater off – heater on, for exp04, and for both switching directions for exp01. The situation is not so clear for exp07 due to the smaller heating effect and relatively high standard deviation.

The estimates of the time for PMSE to react to heating which we have obtained seem to be much less than were suggested in [5] for electron diffusion. Hypothetically, for an electron temperature 20 times higher than neutral temperature, the time scale for diffusion could be as small as 30 ms. For this, however, ratio of attached and free charge in the plasma-aerosol considered in [5] must be more than 100. If this ratio is instead equal to 10 then the characteristic diffusion time would be about 0.3 s, i.e. it should be an order of magnitude longer than the reaction time we obtain according to Figs. 1-3. It is very difficult to determine how high the ratio may be. The general assumption of current PMSE theories [2] is that the ratio be more than unity. However, rocket measurements inside of PMSE region summarised in [6] in Tables 2 and 3 give the ratio as ranging from 0.3 up to 30. Because there is no clear evidence for the ratio to be 100 or more under PMSE conditions, we need to consider whether some mechanism other than diffusion can explain the very fast reaction of PMSE to heating.

One of the important parameters for the scatter of radio waves is the Debye length, which can be determined by formula:

$$\lambda_D = (\epsilon_0 k_B T_e / N_e e^2)^{1/2} \quad (1)$$

or

$$\lambda_D(\text{cm}) = 6.9 [T_e(\text{K}) / N_e(\text{cm}^{-3})]^{1/2}, \quad (2)$$

where ϵ_0 is the permittivity of free space, k_B is the Boltzmann constant, N_e is the free electron density, and e is the electronic charge. We now consider the effects of having the probing radar wavelength be larger and smaller than the Debye length. If $1/(k\lambda_D) \ll 1$, where k is radar wave number (this corresponds approximately to $\lambda/6 \ll \lambda_D$, where λ is radar wave length), then in a volume illuminated by incident radio wave with about the same phase, the electrons can be considered as individual charged particles moving according to their thermal velocity distribution. Scattering

occurring under these conditions is that of the thermal fluctuations of the free electrons. This is termed Thomson scattering. In turn, if $1/(k\lambda_D) \gg 1$, then the electrons illuminated by the radio wave with the same phase have to participate in plasma screening and hence, to follow thermal ion fluctuations and to participate in collective plasma motions. In the latter case, scattering of radio waves occurs on plasma irregularities and is called coherent.

PMSE is an example of coherent scattering. This is confirmed by the strength of the echoes and narrowness of the Doppler spectra (e.g., for EISCAT observations [7]). At the summer mesopause for the case of thermal equilibrium $T_e = T_n \sim 130\text{K}$. Assuming $N_e = 500\text{ cm}^{-3}$ we get $\lambda_D = 3.5\text{ cm}$ which is much smaller than λ for the EISCAT VHF radar. However, when we heat electrons their temperature can increase by a factor as large as 20 [8] that leads to an increase of the Debye length. Let us estimate a critical electron temperature T_c and density N_c for which λ_D becomes equal to $1/k$ for the case of the EISCAT VHF radar. From (2) we get:

$$N_c (\text{cm}^{-3}) \approx 0.1 \cdot T_c (\text{K}) \quad (2)$$

So, for an electron temperature of 2500 K (roughly 20 times the thermal equilibrium value), and if N_e is less than 250 cm^{-3} , the Debye length exceeds one sixth of a radar wavelength which implies Thomson scattering on individual electrons rather than on electron plasma irregularities. This might be the reason for the sharp drop in the PMSE power when we heat electrons strongly enough.

CONCLUSION

We have analysed here measurements of PMSE power sampled with high time resolution using the EISCAT VHF radar during ionospheric heating experiments. We have been able to determine an upper limit for the time required for PMSE power to respond to switching the heater on or off. This characteristic time is less than 30 ms, which was the time resolution of the radar data recorded during the experiments. We believe that this time is too short to be accounted for by the effect of ionospheric heating on electron diffusion. Therefore, we propose another explanation for the heating effect on PMSE. During heating the electron temperature at PMSE heights is expected to grow significantly on a time scale of less than 1 ms [9]. Increased electron temperature leads to an increase of the Debye length in the plasma so that it can exceed one sixth of the radar wavelength if electron density is low enough. Then the radar wave scattering will change from being coherent scatter from plasma irregularities to Thomson scatter from the individual electrons, and the backscattered signal power falls.

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