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Electron temperature control of PMSE

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Abstract. Recently an artificially induced modulation of polar mesosphere summer echos (PMSE) was observed when the electrons at PMSE altitudes were heated by a ground based heating facility [*Chilson et al.,* 2000]. The PMSE disappeared within a few seconds when the heater was switched on and reappeared within a few seconds when the heater was switched off again. We explain these observations employing a model of electron diffusion in the environment of positive ions and negatively charged aerosols which takes into account enhanced electron temperatures. If the electron temperature equals the neutral gas temperature, electron diffusion is efficiently inhibited due to the multipolar electric field between the aerosols, positive ions, and electrons. If the electron temperature is enhanced, however, the electron diffusivity is increased which compensates the effect of charged aerosols such that spatial structures in the electron gas at scales as small as the radar half wavelength are efficiently destroyed by diffusion. Furthermore, an enhanced electron temperature increases the aerosol charge which supports the decay of electron disturbance through plasma interference effects. The heating experiment has demonstrated that the reduction of electron diffusivity by charged aerosol particles is the underlying physical mechanism for the existence of PMSE.

1. Introduction

Polar mesosphere summer echoes (PMSE) are extremely strong radar echoes from the polar summer mesopause which were first detected by VHF radars at 50 MHz [*Czechowsky et al.*, 1979; *Ecklund and Balsley*, 1981]. Significant scattering at this frequency only takes place if the refractive index in the plasma exhibits structures at the radar half wavelength $\lambda/2$ [*Tatarskii*, 1961]. It was soon realized that neutral air turbulence alone can not account for the scattering because spatial scales of $\lambda/2$=3 m are efficiently destroyed by molecular diffusion. *Kelley et al.* [1987] pointed out that a large enough amount of small charged ice particles or cluster ions can decouple the electron diffusion from the diffusion of the neutral gas due to the multipolar electric field between the different plasma constituents. This situation is often described by the Schmidt number Sc which is the ratio of kinematic viscosity and the effective diffusion coefficient of the electrons: $Sc = \nu/D_e^{eff}$. Without aerosols $Sc \approx 1$, but with the existence of charged aerosols the diffusivity is significantly reduced leading to Sc values much larger than 1 [Lübken et al., 1994]. In fact all current PMSE theories require the presence of charged aerosol particles to account for scattering structures in the electron gas at $\lambda/2$ [*Cho and Röttger*, 1997]. The existence of these charged aerosol particles has only recently been proven by direct observations [*Havnes et al.*, 1996]. Until now there has been no direct experimental proof that it is indeed the reduction of electron diffusion by charged aerosols which allows for the existence of scattering structures at very small scales.

In this paper we will interpret experimental results of electron heating in the presence of PMSE observed with the 224 MHz EISCAT radar ($\lambda/2$=0.67 m) at Tromsø [*Chilson et al.*, 2000]. These authors observed a more or less instantaneous fade out (time scale $\leq$ 2 s) of PMSE when the electrons were heated to $\sim$ 3000 K by a ground-based heating facility (Belova, private communication). Furthermore, the PMSE reappeared within a few seconds when the heater was switched off. To explain these observations we will first discuss which physical processes depend on electron temperature and which of these take place on a short enough time scale to be compatible with the observations. We will then present a model of electron diffusion to show that an increase in electron temperature compensates the effect of charged aerosol particles on electron diffusion. Finally we will give some recommendations for future heating experiments.

2. Influence of electron temperature on PMSE

How does the electron temperature influence the atmosphere and the aerosols at PMSE altitude? We can exclude a heating of the aerosols by electrons since the energy of the electrons is too small to significantly affect the aerosols or the background neutral atmosphere. This is to a certain extent proven by the EISCAT observations since typical time scales for evaporation and condensation of aerosols in the upper mesosphere are on the order of minutes and hours, respectively, [*Turco et al.*, 1982] which is much larger than the time constant observed for the fade out and recovery of PMSE.

We note that the fade out/recovery of the PMSE cannot be due to advection of somehow modulated air parcels through the beam of the VHF-radar: The heater enhances the electron temperature in its entire field of view defined by its beam width of 14.5°. The beam width of the VHF-radar, however, is much smaller, namely 0.6 × 1.7° and overlays with the heater beam at PMSE altitudes. This implies that even a very strong horizontal wind of 100 m/s would require more than 100 s to transport 'un-heated' air masses into the field of view of the radar.

We conclude that the observed modulation of the PMSE signal must be due to an effect in the plasma. There are basically two physical processes related to PMSE which depend on electron temperature and which take place on short enough time scales, namely electron diffusion and charging of aerosols. In the next two subsections we will discuss these two processes in more detail.

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2.1. Electron diffusion model

Hill [1978] developed a theory of multipolar diffusion which was later applied by *Cho et al.* [1992] to investigate the influence of charged aerosol particles on electron diffusion. They considered a simplified D-region plasma with only one type of positive ions, and aerosol particles of only one radius and charge and then calculated an effective electron diffusion coefficient as a function of $\Lambda = |Z_A|N_A/n_e$, where Z_A is the number of charges captured on the aerosol particles, N_A is the number density of aerosols, and n_e is the electron number density in the gas phase.

We have extended this model by including the possibility that the electron temperature is different from the neutral temperature. We have followed the procedure described in *Hill* [1978] to derive the continuity equations for a system consisting of electrons (n_e), positive ions (n_i), and singly negatively charged aerosols (N_A). Since only two of these three constituents diffuse independently (because of charge neutrality) negatively charged aerosols and positive ions have been grouped to $n_\oplus = n_i + N_A$ for reasons of algebraical convenience. The continuity equations then read:

$$\frac{\partial n_{\overset{\oplus}{e}}}{\partial t} = \frac{D^+ \pm D^-}{2}\Delta n_\oplus + \left[\frac{T_e}{T_n}D^+ + \frac{D^+ \mp D^-}{2}(1 + 2\Lambda\frac{T_e}{T_n})\right]\Delta n_e \qquad (1)$$

where $D^\pm$ is the diffusion coefficient of positive ions and negatively charged aerosols, respectively [*Cho et al.*, 1992]. These equations have been implemented in a numerical code employing a Dufort-Frankel-algorithm [e.g., *Potter*, 1977, p.78-79].

We have determined the temporal evolution of a disturbance in the electron profile with an initial Gaussian shape, i. e. $n_e(x, t = 0) = n_e(0, 0) \cdot \exp(-x^2/2\sigma^2)$. Charge neutrality requires $n_\oplus(x, 0) = n_e(x, 0) \cdot (1 + 2\Lambda)$. We have tested our algorithm by calculating the temporal evolution of electrons, positive ions, and aerosol particles for the 'normal' case $T_e = T_n$ and comparing the results with the analytical solutions presented by *Hill* [1978]. In Figure 1 we show the temporal evolution of an electron and aerosol disturbance with a width σ=0.67 m for a plasma with Λ=2.0 and aerosols with a radius of 10 nm. There is perfect agreement between the numerical and analytical results. Furthermore, Figure 1 demonstrates how negatively charged aerosols influence the diffusion of electrons: The electrons are thrust out of the region around x=0 (where the aerosols are located) and leave a negative electron disturbance, i. e. the background electron density becomes depleted. The positive electron disturbance moves out of the central region towards higher x-values ($x \approx$2–4). At the same time the aerosol disturbance hardly changes due to the very small aerosol mobility.

We define the decay time of the electron disturbance by the condition that the difference between the maximum and the minimum of the disturbance has decayed to 10% of its initial value. The maximum at x-values of ∼2–4 decays rapidly. The minimum is bound to the aerosols and decays with the time constant of aerosol diffusion. This implies that disturbances in the plasma decay more and more slowly with increasing number of charged aerosols, i. e., with $\Lambda \gg 0$. So far we have assumed $T_e = T_n$.

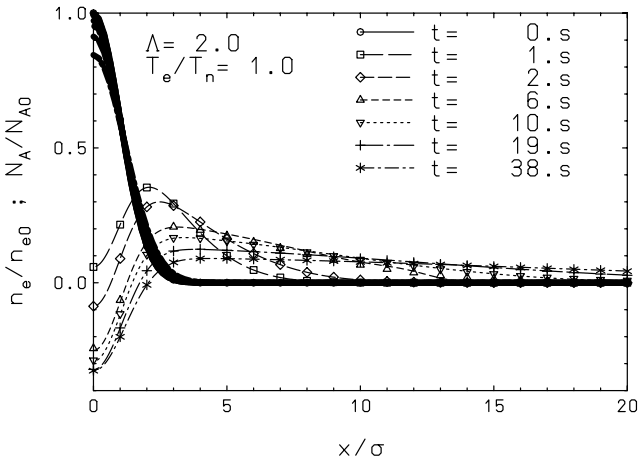

Figure 1. Electron (thin lines) and aerosol concentrations (thick lines) for different times of diffusion for $\Lambda = |Z_A|N_A/n_e$=2. Results for the electrons plotted with lines have been calculated numerically, the results indicated with symbols have been determined from the analytical solution of *Hill* [1978].

The situation changes, however, if the electron temperature is larger than the neutral air temperature. In Figure 2 we present decay times of electron disturbances in the presence of aerosols with a radius of 10 nm as a function of Λ for different ratios of electron to neutral temperature, T_e/T_n. As explained above we see that the decay time increases with increasing Λ if $T_e = T_n$. However, with increasing electron temperature the increase of decay times is shifted towards larger Λ-values until finally the decay time decreases for all reasonable values of Λ if T_e/T_n >10. To elucidate the physical processes involved in electron diffusion and to further understand the fast recovery of the PMSE signal after the heater is off we have studied a 10 s-period time sequence of an electron and aerosol disturbance for Λ=2.0, i.e. from t-5 s to t+5 s. We have assumed T_e/T_n=20 for t <0, and T_e/T_n=1 for t >0. In Figure 3 it is clearly seen how the electron depletion caused by the presence of negatively charged aerosols (see Figure 1) decays during the first second of heating and has more or less completely vanished after 5 s. Remenber, that during the same period the aerosol disturbance merely changes at all. However, when the heating is switched off (t >0) the aerosols quickly force a new depletion in the background electron density due to the Coulomb repulsion between electrons and aerosols. Only 1 s after the heater is off the total electron disturbance has again reached a value of ∼ 40%, i.e. close to the level before the heater was switched on.

In summary, increasing electron temperature compensates the effect of negatively charged aerosols on the diffusion of electrons. Increasing T_e enhances electron diffusion and destroys PMSE. In terms of the Schmidt number this means that the effective electron diffusion coefficient defined by $D_e^{eff} \propto \sigma^2/t_{10\%}$ increases and Sc decreases as a complicated function of T_n/T_e. Note that we have performed the model calculations presented above for particles with a radius of 10 nm since aerosol particles of this size are presumably typical for PMSE [*Cho and Röttger*, 1997]. Varying the particle radius inside reasonable limits (factor of 2 or so) does not change any of the qualitative staements made above.

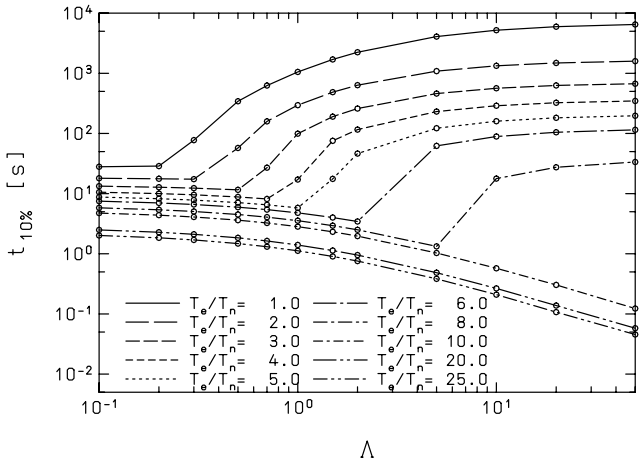

Figure 2. Decay times of a Gaussian electron perturbation as a function of Λ for the case of positive ions and singly negatively charged aerosol particles with a radius of 10 nm and different values of T_e/T_n.

2.2. Influence of $T_e \neq T_n$ on aerosol charging

We must further consider that the aerosol charging mechanism itself is affected when the electron temperature changes since the diffusional flux of electrons (and positive ions) to the aerosols is temperature dependent [e.g., *Natanson*, 1960; *Rapp*, 2000]. We have calculated the capture rates of electrons by differently charged aerosols with a radius of 10 nm as a function of electron temperature using equations 3-5 of *Rapp* [2000]. For an electron temperature of 3000 K we get a rate of $\approx 3 \cdot 10^{-4}$ cm^3/s. A rough estimate of the time constant for the capture process is given by $\tau = 1/(\nu \cdot N_A)$ where ν is the electron capture rate. Using the capture rate from above and asking for τ=1 s gives $N_A \approx 3300/\text{cm}^3$ which is a quite reasonable number [*Cho and Röttger*, 1997]. Thus particle charging occurs on time scales of a few seconds only.

What is the effect of an increased electron temperature on the mean particle charge? Using the particle charging model of *Rapp and Lübken* [2000] we find that an electron temperature increase leads to an enhanced charging of the aerosols. Some of the aerosol particles acquire a second or even a third electron while for 'normal' electron temperatures they are singly negatively charged. This implies that the total number of charges on the aerosol (thus Λ) increases whith increasing electron temperature. Increasing the aerosol charge, however, should support PMSE [*Cho et al.*, 1992] contrary to the observation that PMSEs vanish when the heater it turned on. We conclude that the time constant for aerosol charging can well be on the order of seconds but that an enhanced electron temperature leads to an increased charging of aerosols which should support, not destruct, PMSE.

Although increased charging due to electron temperature enhancement alone would support, not weaken PMSE (opposite to observations), this mechanism is still important since an enhanced aerosol charge supports the electron diffusion described in the section 2.1 in case that $T_e/T_n \geq 10$. Referring to Figure 2 we see that e.g. for T_e/T_n=20 the decay time decreases with increasing Λ. While for fixed Λ=1.2 the decay time would decrease from $t_{10\%} \sim 1000$ s at $T_e = T_n$ to $t_{10\%} \sim 2$ s at $T_e = 20T_n$, for Λ=10 it decreases to ~ 0.2 s.

Note that in principal it would be necessary to couple the aerosol charging model with the diffusion model. However, we have treated both processes separately in order to avoid mixing up different physical processes. Furthermore, our results suggest that for large values of T_e/T_n an increase in Λ is of minor importance compared to the effect of enhanced electron temperature: e.g. for Λ = 2 the decay time decreases from 2400 s for T_e/T_n=1 to 0.8 s for T_e/T_n=25. For fixed T_e/T_n=25 it only decreases from 0.8 s for Λ=2 to 0.1 s for Λ=20.

3. Conclusion and outlook

We have presented an explanation for the fast fade out and recovery of PMSE signals when the electron temperature was artificially enhanced [*Chilson et al.,* 2000]. We conclude that the observed fade out of the PMSE signal within a time of less than 2 s is due to an enhanced electron diffusion which compensates the effect of negatively charged aerosols. Furthermore, in case that $T_e/T_n \geq 10$ enhanced electron diffusivity leads to a larger charging of the aerosol particles which indirectly supports electron diffusion. The fast recovery of the PMSE after the heater is off is explained by the fact that the aerosol disturbance has not decayed like the electron disturbance and causes a depletion in the background electron density as soon as T_e/T_n=1.

The EISCAT heating experiment proves that PMSE are indeed observed due to the existence of charged aerosols which reduce the electron diffusivity. If this effect is balanced by an enhanced electron temperature the PMSE disappears. The explanation presented above is independent of the mechanism which creates the small scale structures in the aerosol number densities. The heating experiment therefore does not allow to test the PMSE theories which are currently discussed in the literature.

Finally, we suggest some interesting studies based on the measurements made so far and also some potential future experiments with the EISCAT heating facility: *Chilson et al.* [2000] have varied the heating power and thus the electron temperature. Measuring the decay time of the PMSEs and the degree of PMSE weakening as a function of the

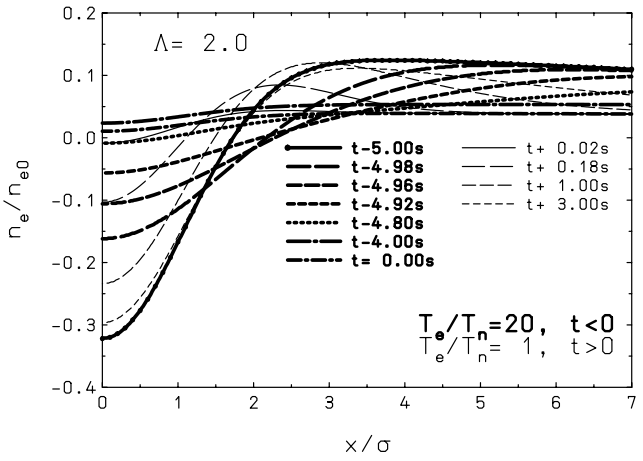

Figure 3. Electron disturbances at different times for the case Λ=2. For t <0 we have assumed T_e/T_n=20 (thick lines) and for t >0 T_e/T_n=1 (thin lines).

heating power will give detailed information on electron diffusivity and on aerosol properties. Since the decay time is proportional to the square of the spatial scale involved a joint heating/PMSE experiment should be repeated where the PMSE is observed with a radar operating at larger or smaller wavelengths. From this we could learn more about the diffusion of electrons in the presence of charged aerosol particles and the physical processes leading to PMSE.

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