ON THE SIZES, CHARGES AND EFFECTS OF DUST PARTICLES IN POLAR MESOSPHERIC WINTER ECHOES.

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ABSTRACT

Heating observations of PMWE indicate that dust particles are present and that those active in creating overshoot effects most likely have sizes from 3 to ~ 4 nm. For small nanometer sized particles the photodetachment effect, where photons of energy less than the workfuction of the dust material can remove excess electrons, can be dominant at sunlit conditions. A large population of very small dust of 1 nm or less may have a profound influence on the PMWE by being mainly neutral at sunlight conditions but having -1e charges at night condition. This will create a large difference in the electron density from day to night, and may be part of the explanation for why PMWE are predominantly observed when the PMWE region is sunlit. Disturbed conditions are needed to create substantial electron densities in the PMWE layers and charge a sufficient number of the larger dust particles.

1. INTRODUCTION

The layers of radar echoes in the height region 55-85 km which are observed during the winter months ~ September to April in the polar regions [1,2] have been given the name PMWE (Polar Mesospheric Winter Echoes) . Their occurrence rate at around 70 deg north, as observed with present radars, is only a few percent [3]. This is much lower than the occurrence rate of ~ 80-90% [4] in midsummer for the much stronger polar mesospheric summer echoes (PMSE) [5,6] which occur in the coldest part of the summer mesosphere [7,8] near the mesopause between ~80 and 90 km height. PMWE are observed during periods of enhanced ionization caused by solar proton events or geomagnetic activity leading to precipitation into the lower mesosphere. The diurnal occurrence rate is strongly dependent on the mesosphere being illuminated by the sun with a maximum near local time 12 LT and a minimum during the night [3].

Due to similarities in the appearance of the PMSE and PMWE layers it has been discussed whether dust particles are present in the PMWE layers, as we know that they are for PMSE. Since the temperature in the winter mesosphere is too high for water vapour to condense to form ice particles, as happens near the summer mesopause when Noctilucent clouds (NLC) and PMSE clouds are formed, dust particles in PMWE cannot be icy but can be of meteoric nature. Several investigations, using lidars [9] rocket in situ measurements [10,11], radar and artificial electron heating experiments [12,13,14] show that dust either cannot be excluded or, that the presence of dust is indicated. Probably the strongest indications for the presence of dust come from radar observations together with artificial heating of electrons in the PMWE region. An immediate weakening of the PMWE radar backscatter is observed when the heater is switched on, as for PMSE [15]. This in it self does not necessarily indicate that dust is present since the increased electron temperature will cause any electron density gradient, independent of its cause, to be smoothed resulting in a weakening of the radar backscatter. However, the total behaviour of PMWE strength during the heating cycle from the time the heater is switched on, and after it is switched off, will be dependent on the existence of dust particles [16].

In the most extensive of heating experiments on PMWE [14] observed PMWE with a new 56 MHz MORRO radar at the EISCAT site at Ramfjordmoen. The EISCAT heating facility [17] was run with a heating cycle of 20 sec on and 100 sec off. The layers were weak and variable and much influenced by noise. One of the stronger layers was relatively stable over a period of ~ 45 min and the effect of the heater was clearly seen. Averaging over 20 heating cycles, each showing PMWE over 1 to 5 range gates (of 300 m each), and including range gates and heater cycles where the (signal+noise) had a strength above a given level, yielded a weak but convincing overshoot of ~ 1.1 and also a weak recovery during the time the heater was on. Reference [18] found that the weak overshoot indicated a dust size of around 3 nm. Another series of observations of much stronger PMWE [19] (with the same radar and heating cycle, confirmed the results of [14] that weak overshoots where consistently present. Height dependence of the heating as found from observations [19] and compared

Proc. '19th ESA Symposium on European Rocket and Balloon Programmes and Related Research,
Bad Reichenhall, Germany, 7–11 June 2009 (ESA SP-671, September 2009)

with theory [20], require electron densities in the PMWE layers of several times 10^9 m^{-3}, which is consistent with disturbed conditions, while deviations from the theoretical heating curves indicate that the total dust density in the strongest PMWE layers must be high enough to substantially influence on the electron density.

1. CHARGES ON PMWE DUST PARTICLES.

Most attention has been given to the charges of PMSE particles [e.g 21] in the upper part of the mesosphere while the charging of the smaller nanometer (smoke) particles has only recently received similar attention. Reference [18] studied the effect of photodetachment, based on the work by [25], and found that this effect which is size dependent and largest for small dust particles, could have a potentially large effect for the PMWE and possibly be the clue to some of its special properties such as the requirement of disturbed conditions for PMWE and the very much larger probability of PMWE being observed during the day than during the night [3]. The charging of nanometer particles at PMSE conditions has also been considered in efforts to explain the observations of positively and negatively charged dust [22,23].

For the very small dust particles which appear to be dominant in PMWE, the relatively short relaxation time of their overshoot curves [14] show that relaxation of the dust charges by ion collisions, as is most likely dominant in the PMSE [24], cannot be the major effect since this decharging process, which is proportional to the cross section of the dust, is slow for nanometer particles. However, in principle the apparent relaxation could be due to that the ~6 km wide radar beam, which is approximately of the same width as the heater beam, can be emptied of heated dusty plasma if the horizontal wind speed is high. With relaxation times of the order of 50-80 sec this requires winds in the range of 75 – 120 m/s. We therefore find that photodetachment, where excess electrons on a dust particle can be removed by solar photons of energies less than the work function of the dust particle, normally is the explanation for the relatively fast relaxation time. At sunlight conditions photodetachment can dominate over electron collisions in charging of the smaller PMWE dust particles. It can effectively remove electrons from small dust with negative charges and lead to that they stay mainly neutral if the ambient electron density is not very large. Reference [25] presents an approximation to a measured photo detachment cross section of C_6F_6 [26], which we will use as an illustration of how this effect can influence on the charge of mesospheric dust. If we consider dust charges of Z_d=-1 the model by [25] give that the lower limit in photon energy E_{phd} to produce photodetachment can be approximated by $E_{phd} = W-E_{bg}-0.72/r_{nm}$ This expression, where W is the bulk workfunction and E_{bg} the band gap in eV, is an approximation to experimental values which also include the energy shift due to small particle effects. The band gap E_{bg}=0 for metals and semimetals while it can be several eV for other materials. Reference [25] use E_{bg}= 5 eV for small silicate particles. If the photodetachment effect is reasonably strong we will show that this will lead to that the smallest particles will be mainly neutral in sunlight, while larger particles with a smaller photodetachment effect and a larger electron impact flux, are still mostly charged with Z_d= -1. Whether or not the photoionization effect is large enough to charge a substantial fraction of the particles positive [23] depends on their workfunction, sizes and also on the refractive index. The lower limit in photon energy for photoinization of a dust particle with Z_d=0 is given by $E_{phi} = W+(1+0.12/r_{nm})0.72/r_{nm}$ [25]. We see that for particles of size 1 nm or smaller there may be a difference in the onset of the photodetachment and the photoionization of at least 1.5 to 2 eV and if the bandgap energy is larger than zero this difference wil be larger. It is therefore not improbable that we can have a situation where photodetachment is important but that photoionization is not. In such a case the PMWE dust charges will be mainly distributed between Z_d = 0 and -1. References [22, 23] argue that photoionization must be important for the PMSE conditions to explain the observations of positive dust particles by various rocket probes. Reference [27] find that in at least some cases the apparent observations of positive dust charges are caused by secondary charging effects where impacting dust rub of electrons.

We have made calculations of the charge distribution for cases where we use the model of [25] for the photodetachment. We use a workfunction of 8 eV and a bandgap of 4 eV, close to the values for silicates used by [25] and consider a dusty plasma with two sizes of dust particles. With these values the photoionization is not important. We use two sizes of dust particles partly to simulate that we most probably will have a distribution of sizes for the PMWE dust particles, and also because this is apparently required by the observed heating profile, as a function of height, for PMWE conditions [19]. We vary the density of the smallest dust, which we give a radius 1 nm, to see the effect on the electron density of this background of small particles. The smaller dust particles are more affected by the photodetachment effect than the larger dust particles, which we give a radius 3 nm in accordance with [18]. We include production of ions and electrons at a rate which would have led to an ion and electron density of 5×10^9 m^{-3} if dust was not present, and we also calculate the effect of the dust particles on the background plasma density [28]. The high pair production rate will require that there is magnetospheric disturbed conditions with strong ionizing precipitation down into the PMWE region. This is also normally a requirement for PMWE [3]. In Figure 1 we show the charge distribution for the small and large dust for day and night conditions where we have varied the density of the small dust from a small value to a large value compared to the electron density. We see that the larger particles are not very much affected by the presence or absence of the photodetachment effect although there will be some increase of its neutral fraction at night when the small particle population is very high. The small particle charging is strongly affected being mostly neutral during day conditions and with nearly all or a major fraction charged to Z_d=-1 during night conditions. In all examples we have kept the 3 nm size particles at a density of 5×10^8 m^{-3} and the electron density (without dust) at 5×10^9 m^{-3}.

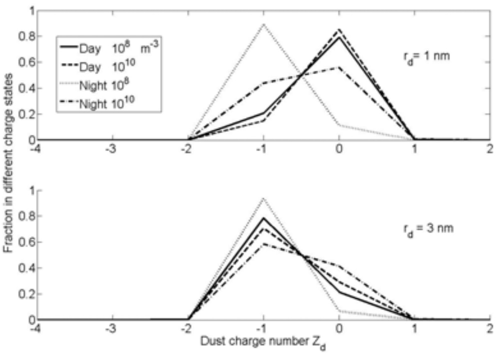

Figure 1. The charge distribution for a low and high value of the background 1 nm sized dust at day and night conditions. The legend apply to both figures.

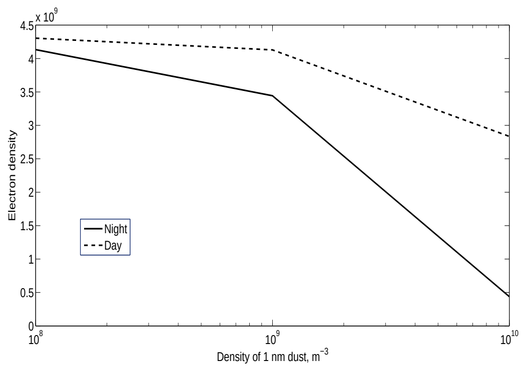

Figure 2. The electron density at day and night as function of the density of the background 1 nm dust particles.

In Figure 2 we show how the electron density at day and night conditions is affected by the density of the small dust, when we keep the density of the larger dust constant at 5×10^8 m^{-3}. We see that at night conditions the electron density, for a high value of the small dust density, is much lower than the electron density at daylight conditions when the small dust is mostly neutral.

3. CONCLUSIONS

The results shown in Figures 1 and 2 should have several important consequences for the PMWE and PMSE phenomenon:

1. For winter conditions where the sunlight and photodetachement process will be absent for parts of the PMWE season and part of the day, there should be a considerable difference in electron density between day and night. As Figs 1 and 2 show, even at disturbed conditions with high electron densities in the PMWE region, the electron density at night conditions can be several times less than at day conditions if the background density of the smallest smoke particles is high. This may lead to that there should be lower probability to observe PMWE at night than at day, as observed.

2. The PMWE dust population model which we have deduced from our observations, with a large population of small, possibly more or less uniformly distributed dust which regulates the day-night difference in electron density in the PMWE layers, and a much smaller number of larger (~ 3-4 nm) particles, can also answer why disturbed conditions are required to produce PMWE. If we repeat the calculations leading to Figure 1, choosing a value 5×10^9 and 5×10^8 m^{-3} for the small and larger dust but where we reduce the electron-ion production rate to give an electron density from 10^8 to 5×10^8 m^{-3} without dust, which we take to represent undisturbed conditions [32], the larger particles will also be mainly neutral as the smaller ones. A lack of charging of the larger dust particles and a lower electron density at quiet conditions may be a major reason why PMWE are not likely to appear then, and why disturbed conditions are required.

3. During the PMSE summer conditions the meteoric smoke particles [29, 30, 31] which should be present also in the PMSE region, will most likely be mainly neutral unless the electron density is very high. This should have consequences for their collision rate and attachment to larger icy PMSE/NLC particles, and favour a process where the neutral meteoric smoke particles become attached to, and eventually embedded in water ice condensing on the dust/aerosol

particles [27]. If a fraction of the smoke particles charge positively [22,23] this process would be more effective since the larger ice particles should have negative charges. This supports that the PMSE icy dust model consisting mainly of water ice with a large number of embedded meteoric smoke particles as suggested by [27], can be correct.

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