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On the signature of positively charged dust particles on plasma irregularities in the mesosphere

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ABSTRACT

Recent rocket payloads have studied the properties of aerosol particles within the ambient plasma environment in the polar mesopause region and measured the signature of the positively charged particles with number densities of (2000 cm^{-3}) for particles of 0.5–1 nm in radius. The measurement of significant numbers of positively charged aerosol particles is unexpected from the standard theory of aerosol charging in plasma. Nucleation on the cluster ions is one of the most probable hypotheses for the positive charge on the smallest particles. This work attempts to study the correlation and anti-correlation of fluctuations in the electron and ion densities in the background plasma by adopting the proposed hypothesis of positive dust particle formation. The utility being that it may provide a test for determining the presence of positive dust particles. The results of the model described show good agreement with observed rocket data. As an application, the model is also applied to investigate the electron irregularity behavior during radiowave heating assuming the presence of positive dust particles. It is shown that the positive dust produces important changes in the behavior during Polar Mesospheric Summer Echo PMSE heating experiments that can be described by the fluctuation correlation and anti-correlation properties.

1. Introduction

Polar Mesospheric Clouds PMCs have been investigated by radar, lidar, satellite and rocket. Remote sensing techniques such as lidar as well as in situ sounding rocket measurements have been implemented to measure the size and possible charge of dust (ice) particles associated with PMCs. A main objective of the past works was to measure the density of positively and negatively charged dust particles as well as plasma densities. First detection of charged dust particles was reported by Havnes et al. (1996). Both positive and negative particles were observed in this experiment. Another sounding rocket experiment was carried out in 2002 when both Noctilucent cloud NLC and PMSE were present (Blix et al., 2003; Smiley et al., 2003). Positive and negative particles were detected in the PMSE source region which proves the relationship of positive particles and electron fluctuations (Blix et al., 2003; Smiley et al., 2003). This had been also observed in another experiment and in the absence of NLC conditions (Gelinas et al., 1998). Observations made during the DROPPS program also indicate the presence of positively charged aerosols/dust at PMSE/NLC altitudes (Croskey et al., 2001).

The ECOMA project (Existence and Charge state Of Meteoric smoke particles in the middle Atmosphere) was conducted in 2007 and aimed to measure in situ the number densities of both charged and uncharged aerosol particles in the mesosphere and lower thermosphere (Brattli et al., 2009). Total negative charge density consisting of negatively charged dust particles and electron density measured by the ECOMA and Faraday instruments, respectively, was $4-5\times10^9\ m^{-3}$. The negative charge density was more than the positive density measured by the positive ion probe which violates the charge quasi-neutrality condition. A computational model developed by Lie-Svendsen et al. (2003) was incorporated to study under what conditions both the reduction in positive ion density and formation of positively charged smoke particles can be expected. It turns out that both processes need circumstances that may be perceived to be out of the ordinary to happen which either implies the presence of dust particles larger than 30–40 nm in the PMSE source region or evaporation of dust particles of the order of 100 nm at the bottom of PMSE layer (Lie-Svendsen et al., 2003). This argument also has been made by Brattli et al. (2009) that positively charged, small (<2 nm) particles must have existed and been undetected by all the charged particle instruments. To solve the problem of the ECOMA campaign and measure smaller charged particles, a new instrument called MASS (Mesospheric Aerosol Sampling Spectrometer) which is a multichannel mass spectrometer for charged aerosol particles was incorporated and used in the 2007

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ECOMA/MASS campaign. Positive dust particles in the mesosphere were detected in these in situ measurements. Significant numbers of positively charged aerosol particles of any size measured in the recent experiment are unexpected from the standard theory of aerosol charging in plasma (i.e. Lie-Svendsen et al., 2003). Considering that the negative dust particles observed in the experiment had a radii less than 3 nm and coexisted with small positive particles (0.5–1 nm), this charge distribution is not consistent with the theory of plasma charging, since the positive ion capture by larger negative dust particles is more likely than the attachment of positive ions to the small neutral particles (Robertson et al., 2009). The first possibility proposed by Robertson et al. (2009) to justify the presence of positive dust particles is an enhanced photoemission current. But, the photoemission process for the nanometer sized particles is very small due to small absorption cross section and large work function of ice (Robertson et al., 2009). The second possibility for positive dust particle formation is that the icy particles may be contaminated by Na or Fe that can significantly lower the work function (Rapp and Lubken, 1999). It has been shown that even enhanced photoelectron emission rate is much lower than the electron capture rate however (Robertson et al., 2009). The third possibility for the positive particles is that the particles grow from small molecular ions or cluster ions (Arnold, 1980; Turco et al., 1982; Sugiyama, 1994, 1995; Gumbel et al., 2003) and become neutral by capturing electrons as they grow (Robertson et al., 2009). The particle may later charge negatively by collecting two or more additional electrons. Condensation on meteoritic smoke particles has also been proposed as an alternative scenario for nucleation which requires a minimum particle radius near 0.5 nm (Megner et al., 2008; Gumbel and Megner, 2009; Winkler et al., 2008). But low meteoritic smoke densities in the summer and high possibility of charging negatively for small particles formed on these condensation nuclei impose a restriction on this hypothesis to account for the observation of positively charged particles (Bardeen et al., 2008; Megner et al., 2006, 2008).

The nucleation process of ice particles in the mesosphere was studied in more detail by Gumbel and Megner (2009). It turns out that nucleation on the smoke particles has two major restrictions. Smoke particles should be larger than the critical radius which is near 0.5 nm for typical conditions (Keesee, 1989; Megner et al., 2008; Gumbel and Megner, 2009; Winkler et al., 2008). Surface parameter is another factor which determines the capability of the smoke particle surface to absorb water vapor and form water ice particles. It has been shown that problems which arise for the ice particle formation on the smoke particles can be avoided by the nucleation on cluster ions (Gumbel et al., 2003). The only limitation attributed to this process is the competition step between particle growth (the addition of water vapor) and recombination with the surrounding electrons. This is because the neutral particle formed by the recombination of ion clusters with a surrounding electron implies the neutral critical radius condition and impacts the growing ice embryos. Therefore for the nucleation on the cluster ion, growth must lead to a particle size beyond the critical radius before the recombination with electrons occurs which takes seconds to hours depending on the local electron density (Gumbel and Megner, 2009). It should be noted that the word ''positive dust particles'' is used throughout the paper for the dust particles formed on the cluster ions and dust for the ice-covered dust grains which usually charge up negatively due to larger size.

This work is based on the experimental data observed during the 2007 ECOMA/MASS campaign and the conclusion made by Robertson et al. (2009) that the positive dust particles observed were possibly formed by nucleation on the cluster ions. First, a computational model with a continuous charging model based on the Orbital-Motion-Limited (OML) approach (Bernstein and Rabinowitz, 1959) and also a quantized stochastic charging model based on a modified Natanson model (Natanson, 1960; Robertson and Sternovsky, 2008) is introduced. The correlation and anti-correlation of electron, ion, and dust density fluctuations are investigated using the proposed hypothesis for the presence of positive dust particles observed during the 2007 ECOMA/MASS campaign (Robertson et al., 2009). The important similarities between the simulation results and experimental data are discussed. Afterwards, as an application, the effect of positive dust particles on the electron irregularity amplitude during PMSE radiowave heating is studied. Finally a summary and conclusion are provided.

2. Computational model

A one-dimensional hybrid computational model is incorporated to study time evolution of the fluctuations in the electron and ion density for growing ice embryos at mesopause altitudes. In this model electrons and ions are treated as fluid and dust particles are treated as Particle In Cell (PIC) which allows for a range of dust particle mass and charges (Scales, 2004; Chen and Scales, 2005; Mahmoudian et al., 2011). Two charging models are adopted in this work for comparison. Dust particles are considered to charge up by collecting electrons and ions embodied by the dynamical charging equation which is given by

$$\frac{dQ_d}{dt} = I_e + I_i, \tag{1}$$

where I_e and I_i are the currents onto each individual dust particle by electron and ion flux, respectively, and Q_d denotes time-varying charge on the dust grain.

For the first model, continuous charging is considered and the electron and ion current on the negative and neutral dust particles ($Z \leq 0$) based on the Orbital-Motion-Limited (OML) model are given by Bernstein and Rabinowitz (1959), Shukla and Mamun (2002), Cui and Goree (1994):

$$I^{\mathrm{OML}}_{e,Z\leq 0} = \sqrt{8\pi} r_d^2 q_e n_e \nu_{te} \exp(-q_e\phi_d/KT_e), \tag{2}$$

$$I^{\mathrm{OML}}_{i,Z\leq 0} = \sqrt{8\pi} r_d^2 q_i n_i \nu_{ti}(1-q_i\phi_d/KT_i). \tag{3}$$

For positive dust particles ($Z>0$), the ion and electron currents are given by Shukla and Mamun (2002)

$$I^{\mathrm{OML}}_{e,Z>0} = \sqrt{8\pi} r_d^2 q_e n_e \nu_{te}(1-q_e\phi_d/KT_i), \tag{4}$$

$$I^{\mathrm{OML}}_{i,Z>0} = \sqrt{8\pi} r_d^2 q_i n_i \nu_{ti} \exp(-q_i\phi_d/KT_e). \tag{5}$$

Here, r_d is the dust radius, $\nu_{te}(i)$ electron (ion) thermal velocity, and ϕ_d dust floating potential. The currents for capture of electrons and ions by aerosol particles are derived by Orbital-Motion-Limited (OML) theory (Bernstein and Rabinowitz, 1959) and Natanson (1960).

The second model considered is the modified Natanson model. The Natanson model has recently been modified by Robertson and Sternovsky (2008) where they adopted the effect of the induced-dipole force for the case of attractive aerosol particles. It has been shown that the induced-dipole force increases ion collection rates by about a factor of 2 for the smallest aerosol particles (Brattli et al., 2009). Electron and ion currents for neutral aerosol particles ($Z=0$) could be represented as follows (Natanson, 1960; Rapp, 2000; Lie-Svendsen et al., 2003;