MESOSPHERIC ELECTRIC FIELDS DUE TO METEORIC CHARGED DUST

Victoria V. Yaroshenko[(1)], Marcel Goossens[(2)], Alexander P. Nickolaenko[(3)],

[(1)]Max-Planck-Institut für Extraterrestrische Physik, D-85740, Garching, Germany
V.Yaroshenko@ipp.mpg.de

[(2)]Center for Plasma Astrophysics, K.U.Leuven, Belgium
Marcel.Goossens@wis.kuleuven.ac.be

[(3)]Usikov Institute for Radio-Physics and Electronics, Ukrainian National Academy of Sciences
sasha@ire.kharkov.ua

ABSTRACT

Gravitational sedimentation of charged dust and its subsequent discharging by ionospheric electrons and/or ions results in a peculiar plasma capacitor and a vertical polarization of electric fields within the upper mesosphere. This mechanism predicts the electric fields from several tens to a few hundreds of *mV/m* at altitudes 85-95 *km*.

INTRODUCTION

Since the late 1980s there is an increasing interest in the role of meteoric dust in the mesospheric plasma. Observations clearly show that dust layers are preset at mesospheric altitudes (85-95 km), where the meteoric stall and ablation occurs [1-4]. In addition, when dust particles are immersed in plasma and radiative environments, they inevitably become charged and thus introduce new features in the plasma electrodynamics. These particles have much larger masses than the plasma electrons and ions, can have multiple charges and introduce strong inhomogeneities on scales of the Debye length. Dust can act as a source or a sink for the electrons or ions introducing compositional changes. Moreover, dust particles are subject to non-electromagnetic forces (e.g. gravity, friction etc.). So one can expect meteoric dust to be especially important in the mesosphere, and first of all in view of its role in the generation of mesospheric vertical electric fields [5-8].

In this paper we present a simple model for the generation of electric fields in mesospheric plasmas. We build our treatment on the existence of a dust layer at upper mesospheric altitudes (85-95 km), and an assumption that the dust particles are electrically charged mainly by the same charging mechanism. We show that a charge separation in the Earth's gravitational field gives rise to a peculiar plasma capacitor and to a plasma polarization in the electric field. The latter is strongly dependent on the dust size and its density. By using reasonable parameters for the dust component, we found that the electric field strength is between several tens and a few hundreds of *mV/m*, which is comparable with the local plasma threshold field, $E_p = \sqrt{3\kappa T m_e \delta \nu^2 / e^2} \approx 10^{-4}\, V/m$. Here, κ is the Boltzmann constant, m_e and e denote the electron mass and charge, $\delta \le 10^{-3}$ is the fraction of energy lost by electron in a collision with a heavy particle, ν is the effective collisional frequency of electrons.

A MODEL OF THE ELECTRIC FIELD GENERATION

We assume that there is a dust layer of a thickness $d \sim 1 km$ located at the mesospheric altitudes between 85 -95 km. Of course, a very low-density dust component is present throughout the bulk of the ionosphere and atmosphere but some special conditions cause a concentration of the fine dust particles at fixed mesospheric altitudes. The dusty plasma layer is quasineutral, namely

$$eN_e + q_i N_i + q_d N_d = 0\,, \tag{1}$$

where q_i and q_d are the ion and dust charges; N_e, N_i and N_d are the equilibrium electron, ion, and dust densities of the layer (for simplicity the latter is characterized by a mono-sized grain population). We will specify the sign and values of q_d later, when considering particular regions of the mesosphere. The electron and ion plasma densities outside the dust layer are assumed to be equal: $N_e = N_i = N_0$.

Since the grains are so massive, the dust is essentially non-magnetized, and slowly sediments downward through the atmosphere, directly responding to gravity, whereas the magnetized electrons and ions move along the magnetic field lines. As a result, the ensuing charge separation and the arising electric field will be strongly dependent on the direction of the geomagnetic field. Having formulated these conditions, we can consider special cases corresponding to the horizontal and oblique geomagnetic field H_0 and to different signs of the dust charge.

Case A: Tropical Mesosphere. First of all, we start with a tropical mesosphere, assuming that H_0 is horizontal and parallel to the dust layer. The charged dust drifts to the Earth under the action of gravity and carries away its electric charges, while electrons and ions are not free to follow them. The charged dust particle cannot penetrate far away into the underlying ionospheric plasma because of the collisions with electrons or ions, whose number densities are much higher than those of the dust particles. The grain becomes a neutral particle by swallowing up electrons (ions) thus producing a charge imbalance ($N_e \neq N_i$) below the initial altitude. The distance D that the charged dust particle can travel depends on its velocity V_d and the neutralization time t_c and can be roughly estimated as $D \approx V_d \; t_C$. The dust velocity V_d for a spherical particle of radius *a* is given by [9]

$$V_d = \frac{ga}{2p} \rho_d \sqrt{\pi \kappa T / 2m_m} \,, \tag{2}$$

where p is the ambient pressure, ρ_d is the mass density of the grain, *g* the acceleration due to gravity, and m_m refers to the mass of a typical atmospheric molecule. The timescale t_c is just

$$t_C = \left(4\pi a^2 N_\alpha \; V_{T_\alpha}\right)^{-1}. \tag{3}$$

Here $\alpha = e$, when $q_d > 0$ and $\alpha = i$, for $q_d < 0$.

The spatial charge separation due to the dust motion in the gravitational field produces a peculiar "plasma capacitor", when the two parallel oppositely charged layers ("plates") are separated by some distance, which is of the order of either the thickness of the initial dust layer d (in the case when $d >> D$) or D (when $d << D$). The "upper plate" carries an excess of ionospheric particles having the opposite sign compared to the dust charges, whereas the «lower plate» has the charge of the same sign as the charged dust grains. As a result, the vertical electric field is polarized in the direction of the gravitation force for the negatively charged dust or in the opposite direction for the positive charged dust. The electric field between the "plasma capacitor plates" can be estimated as:

$$E = \sigma / \varepsilon_0 , \tag{4}$$

with an effective surface charge density given by either $\sigma = q_d N_d D$ (if $d >> D$) or $\sigma = q_d N_d d$ (for $d << D$).

To apply the analysis to real plasmas we use the observational data for the tropical region [3], which imply that the probability for acquiring the minimum excess charge by a dust particle is not very high. The meteoric dust model predicts dust sizes of a ~1-10 nm at a density of N_d ~10^3 cm^{-3} at the altitudes of about 90 *km*. In order not to overestimate the role of the charged dust, we assume that $N_d \sim 10 cm^{-3}$ and $q_d = -e > 0$. This case is relevant to the daylight hours, when the particles can be positively charged due to photoemission. The electron density and thermal velocity are about 10^4 cm^{-3} and 10^4 *m/s,* respectively and t_c ranges from a few seconds to a few minutes, depending on the particle size. Table 1 lists the vertical electric fields (4) corresponding to the grains of different size in daytime conditions. It turns out, that the dust grains with a size of a few *nm*, can easily generate local electric fields of several tens or even of hundreds of *mV/m*.

Table 1. Tropical mesosphere, the 90 ±2 *km* altitudes, $q_d = -e$

α, *nm*	t_C, *s*	V_d, *cm/s*	*D, m*	*E, V/m*
1	199	1.3	2.56	0.46
2	49.8	2.6	1.29	0.23
4	12.4	5.2	0.645	0.12
6	5.53	7.8	0.431	0.08
8	3.11	10.4	0.323	0.058
10	1.99	13	0.258	0.046

The situation can be totally different during the nighttime. Now, the dust charge is expected to be negative: $q_d = e < 0$. The neutralization time (3) is increased considerably reaching $t_c \sim 10^2$ - 10^4 s, mainly because of $V_{Ti} >> V_{Te}$. As a result, D increases and the resulting imbalance in charge densities causes electric fields, much stronger than in the daytime. The field is directed downward, to the Earth. The parameters and electric fields used are listed in Table 2.

Case 2: Polar Mesosphere. In the case of magnetic field oblique to the dust layer, the plasma electrons and ions, moving along the field lines, follow the sedimented charged dust particles till the split between their paths will not exceed the plasma Debye length. λ_D. It is easily to verify, that the charge separation starts, when the dust particles reach distances of $\Delta D = \lambda_D / \cos\chi$ that depends on the tilt of the geomagnetic field χ. Hence, the "plasma capacitor" may exist only inside the dusty layer. In contrast to the tropic case, the polar capacitor carries a smaller effective charge density $\sigma = eN_d[D - \Delta D]$, and thus the generated electric fields (4) are reduced. Obviously, the vertical electric field cannot be generated in the immediate vicinity of the magnetic pole where $\chi \to \pi/2$ giving $\Delta D \to \infty$, $\sigma \to 0$, and $E \to 0$.

We estimate the vertical electric field, generated in the polar mesosphere at the altitudes of 82-85 *km* by assuming that $\chi \sim 80^0$ and the ionosphere is characterized by $N_0 = 5 \times 10^3$ cm^{-3}, $V_{Te} = 2.15 \times 10^4$ *m/s*, and $V_{Ti} = 5 \times 10^2$ *m/s*. According to measurements in the polar mesosphere summer echoes (PMSE) conditions, the dust charge density is $N_d q_d / e \sim 10^2$ cm^{-3} [1,5], and $a \sim 10$-50 nm. The computed electric fields (4) are listed in Table 3 and Table 4.

Table 2. **Tropical mesosphere, the 90 ±2 *km* altitudes, $q_d = e$**

α, *nm*	t_C, *s*	V_d, *cm/s*	*D, m*	*E, V/m*
1	7.96×10^3	1.3	103.48	18.62
2	199×10^3	2.6	51.74	9.31
4	49.7×10^2	5.2	25.84	4.64
6	12.4×10^2	7.8	17.23	3.1
8	5.53×10^2	10.4	12.9	2.3
10	79.6	13	10.35	1.86

Table 3. **Polar mesosphere, the 82 - 85 *km* altitudes, $q_d = -e$**

α, *nm*	t_C, *s*	V_d, *m/s*	*D - ΔD, m*	*E, V/m*
8	12.44	0.1	1.12	0.43
10	7.96	0.13	0.93	0.33
20	1.99	0.26	0.31	0.13
30	0.88	0.39	0.25	0.08
40	0.5	0.52	0.15	0.06
50	0.32	0.65	0.1	0.03

Table 4. **Polar mesosphere, the 82 - 85 *km* altitudes, $q_d = e$**

α, *nm*	t_C, *s*	V_d, *m/s*	*D* - Δ*D*, *m*	*E*, *V/m*
10	636.8	0.13	82.69	14.87
15	282.67	0.195	55.01	9.91
20	159.2	0.26	41.29	7.43
30	70.76	0.39	27.48	4.94
40	39.8	0.52	20.59	3.69
50	25.47	0.65	16.45	2.92

CONCLUSIONS

The mesospheric plasma contains layers of charged grains whose motions can be responsible for the generation of mesospheric electric fields. Using reasonable parameters for the dust component, we have obtained values for the electric field strength between several tens and a few hundreds of *mV/m* as was frequently reported in experiments.
The simple approach outlined in this paper points to several effects. 1). The vertical electric field resulting from sedimentation of charged dust can substantially exceed the value of the plasma threshold field in the lower ionosphere. 2). The direction and magnitude of this field can vary with the time of day. Quite possibly, this may cause mesospheric electric currents flowing at relevant latitudes. Such electrification and the currents may be different at low and high latitudes.

ACKNOWLEDGEMENTS

VY thanks Catholic University, Leuven, for kind hospitality during a stay in which this work was initiated and Alexander von Humboldt Foundation for the financial support.

REFERENCES

[1] O. Havnes, J. TrØim, T. Blix, W. Mortensen, L.I. Næsheim, E. Thrane, and TØnnesen, "First detection of charged dust particles in the Earth's mesosphere", *J. Geophys. Res*., vol. 101, pp.10839-10847, November, 1996.
[2] O. Havnes, A. Brattli, T. Aslaksen, W. Singer, R. Latteck, T. Blix, E. Thrane and J. TrØim, "First common volume observations of layered plasma structures and polar mesospheric summer echoes by rocket and radar", *Geophys. Res. Lett*., vol. 28, pp.1419-1422, April, 2001.
[3] L.J. Gelinas, K.A. Lynch, M.C. Kelley, S. Collins, S. Baker, Q. Zhou, and J.S. Friedman, "First observation of meteoric charged dust in the tropical mesosphere", *Geophys. Res. Lett.,* vol. 25, pp. 4047-4050, August, 1998.
[4] M. Horanyi, S. Robertson, B. Smiley, J. Gumbel, G. Witt and B. Walch, "Rocket-borne mesospheric measurement of heavy (*m*>>10 *amu*) charge carriers", *Geophys. Res. Lett*., vol. 27, pp. 3821-3825, 2000.
[5] A.M. Zadorozhny, Tyutin, A.A., O.A. Bragin, and Y.N. Kikhtenko, "Recent measurements of middle atmospheric electric fields and related parameters", *J.Atm. Terr. Phys*., vol 56, pp. 321-335, 1993.
[6] Yu. A . Bragin,., A.A. Tyutin, and A.A. Kocheev, "Direct measurements of the atmospheric vertical electric field strength up to 80 km", *Cosmic Res*., Eng. Trans., vol. 12, pp. 279-280, February, 1974.
[7] N.C. Maynard, N.C., C.L. Croskey, J.D. Mitchel, and L.C. Hale, "Measurements of volt/meter vertical electric fields in the middle atmosphere", *Geophys. Res. Lett*., vol. 8, pp. 923 - 926, 1981.
[8] C.L. Croskey, L.C. Hale, J.D. Mitchel, D. Muha, and N.C. Maynard, "A diurnal study of the electrical structure of the equatorial middle atmosphere", *J.Atm. Terr. Phys*., vol. 47, pp. 835-844, 1985.
[9] E.Jensen, and G.E. Thomas, "Growth-sedimentation model of polar mesospheric clouds: comparison with SME measurements", *J. Geophys. Res*., vol. 93, pp. 2461-2473, October, 1988.