Meteoric dust particles are the primary charge carriers in the lower ionosphere

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Abstract

The CHAMPS (CHarge And Mass of meteoric smoke ParticleS) rocket campaign consisted of two sounding rockets with one launched at night 11 October and one launched in daytime 13 October 2011 from the Andøya Rocket Range, Norway. These dates are after the noctilucent cloud season to avoid the detection of icy cloud particles. The rockets carried instruments including a mass spectrometer for meteor smoke particles that from 60 – 100 km altitude measured the number density of positively and negatively charged particles in 5 logarithmically spaced mass ranges from about 10 – 10^5 amu. Meteoric smoke particles with number densities of several thousand per cc were detected in mass ranges up to 8,000 amu but not heavier, indicating an upper bound of about 1.2 nm on the radius of meteoric smoke particles. Recent numerical modeling of ionization, recombination of ions with electrons, and recombination on the smoke particles gives a distribution of charge among the species that is consistent with the nighttime observations. The model explains the unusual observation of equal numbers of positive and negative dust particles at 60 – 70 km altitude. In this altitude range, the positive and negative charges reside primarily on the smoke particles and charge-neutrality requires an equal number of positive and negative particles. In the past, the ionization rate in this region of the ionosphere has been calculated by assuming that the ionization rate is equal to the electron-ion recombination rate; however, our model shows that the recombination is in fact primarily on the dust particles. The daytime data indicate that photodetachment reduces the number of negatively charged particles in the daytime and that photoemission is not an important process, probably as a result of a higher energy threshold for photoemission than for photodetachment.

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Summary the CHAMPS rocket data

The CHAMPS rocket carried a multichannel mass spectrometer (Knappmiller et al., 2008) with channels sensitive to meteoric dust particles with mass in the ranges <500 amu, 500 – 2,000 amu, 2,000 – 8,000 amu, 8,000 – 20,000 amu and >50,000 amu. The spectrometer recorded the charge number density as a function of altitude for both positively and negatively charged particles. The signal was negligible in both the daytime and the nighttime data for positive and negatively charged particles in the 8,000 – 20,000 amu and >50,000 amu mass ranges (not shown) indicating few meteor smoke particles (<10 cm^{-3}) in this range and suggesting an upper limit in the radius of ~1.2 nm if a mass density of 2 g/cm^3 is assumed. Particles with masses greater than 500 amu were identified as meteor smoke particles and the particles with masses <500 amu were assumed to be a mixture of "ordinary" light molecular ions, cluster ions and meteor smoke particles. The spectrometer was not sensitive to electrons as a consequence of the payload floating potential being negative.

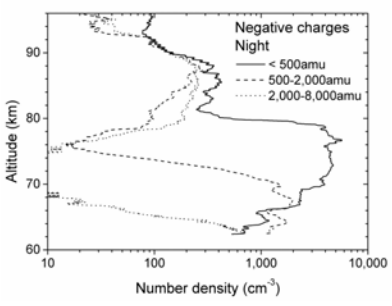
Knappmiller, S., Robertson, S., Sternovsky, Z., Friedrich, M., 2008. Rev. Sci. Instrum. 79, 104502.

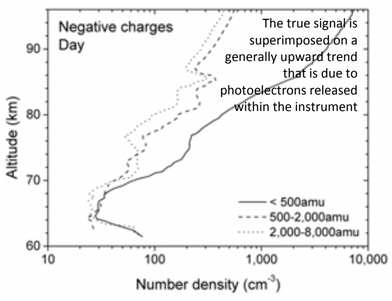
Nighttime data

11 October 21:50 UT, SZA 117 degrees

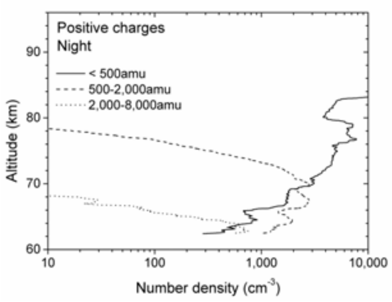
Daytime data

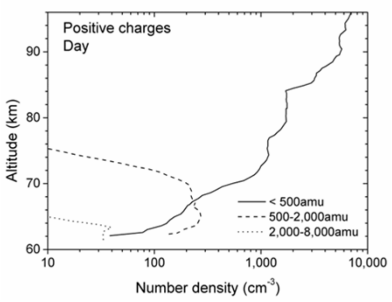
13 October 13:50 UT, SZA 83.5 degrees

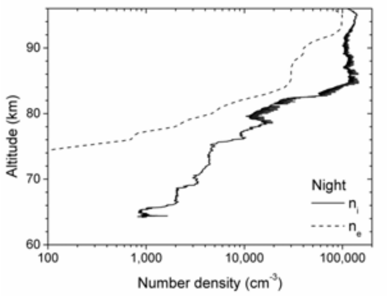


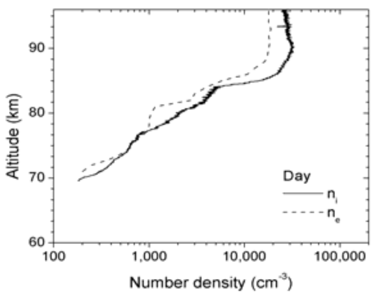


The true signal is superimposed on a generally upward trend that is due to photoelectrons released within the instrument









The Motivation

The motivation is to explain unexpected features of the rocket data . These are

1. Simple charging theory says that the dust particles should be predominately negative. Why are equal numbers of positive and negative particles observed at 60 – 70 km altitude?
2. The daytime data show both the positive and negative meteor smoke particles reduced in density from nighttime values. Photodetachment directly affects only the negatively charged meteor smoke particles. Why are the positive particles also reduced in density in the daytime?

The Model

We have extended Reid's model *(Reid, G.C., 1997 Geophys. Res. Lett. 24, 1095–1098)* by adding photodetachment of electrons from the negatively charged meteor smoke particles. The independent parameters are an ionization rate Q and a photodetachment rate β that are assumed independent of altitude. The model is dependent upon altitude only through the ionization rate. The model is simplified by assuming that the meteor smoke particles have a single radius of 0.8 nm and a single (homogeneous) number density. This model reveals the effect of photodetachment on the number densities of electrons, ions, and both positively and negatively charged meteor smoke particles. The meteor smoke particles are sufficiently small, <0.8 nm radius, that the particles can be assumed to be singly charged.

Publications about our work:

1. "Detection of Meteoric Smoke Particles in the Mesosphere by a Rocket-borne Mass Spectrometer," Scott Robertson, Shannon Dickson, Mihaly Horanyi, Zoltan Sternovsky, Martin Friedrich, Diego Janches, Linda Megner, and Bifford Williams, Journal of Atmospheric and Solar-Terrestrial Physics 118B, p. 161 – 179, October 2014 (special issue on Smoke and Ice in the Mesosphere) (doi:10.1016/j.jastp.2013.07.007).
2. "Charge balance in the mesosphere with meteoric dust particles, H. Asmus, S. Robertson, S. Dickson, M. Friedrich, and L. Megner, Journal of Atmospheric and Solar Terrestrial Physics 127, 137 – 149, May 2015 (doi:10.1016/j.jastp.2014.07.010).

Model equations

The adjustable parameters in the model are the ionization rate Q, the total number density of meteor smoke particles N_{tot}, and the photodetachment rate β. The altitude dependence enters only through the altitude dependence of Q. The outputs of the model are the number densities of the electrons, of a single species of positive ions, of positively charged meteor smoke particles, and of negatively charged meteor smoke particles. The number of uncharged meteor smoke particles (MSPs) is the total number N_{tot} reduced by the number that are charged. The data from the nighttime flight, for which photodetachment is inactive, are used to find the likely value for the N_{tot} given the measured numbers of charged meteor smoke particles.

Electrons

$$\frac{d}{dt} n_e = Q - \alpha_{ie} n_e n_i - n_e \sum_Z \alpha_e(Z) N_{MSP}(Z) + \beta N_{MSP}(-1)\,,$$

Ions

$$\frac{d}{dt} n_i = Q - \alpha_{ie} n_e n_i - n_i \sum_Z \alpha_i(Z) N_{MSP}(Z),$$

MSPs, Z = 1

$$\frac{d}{dt} N_{MSP}(1) = \alpha_i(0) N_{MSP}(0) n_i - [\alpha_e(1) n_e + \alpha_i(1) n_i] N_{MSP}(1)\,,$$

MSPs, Z = 0

$$\frac{d}{dt} N_{MSP}(0) = \alpha_i(-1) N_{MSP}(-1) n_i - [\alpha_e(0) n_e + \alpha_i(0) n_i] N_{MSP}(Z) + \alpha_e(1) N_{MSP}(1) n_e + \beta N_{MSP}(-1)\,,$$

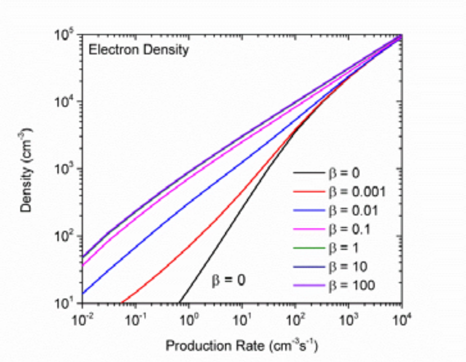
MSPs, z = -1

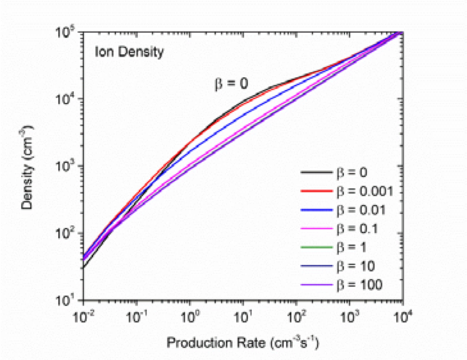
$$\frac{d}{dt} N_{MSP}(-1) = -[\alpha_e(-1) n_e + \alpha_i(-1) n_i] N_{MSP}(-1) + \alpha_e(0) N_{MSP}(0) n_e - \beta N_{MSP}(-1)\,.$$

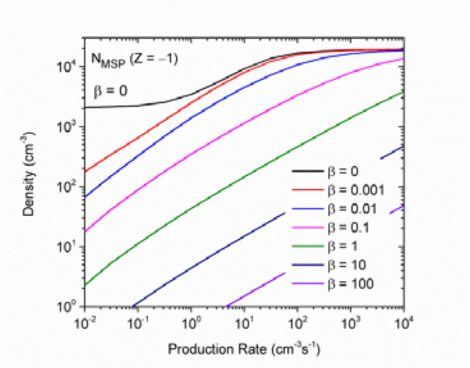
where n_e is the electron number density, n_i is the ion density, α_{ie} is the electron-ion recombination rate coefficient, Z is the charge number which can have values 1, 0, and –1, $N_{MSP}(Z)$ is the number of meteor smoke particles with charge number Z, $\alpha_e(Z)$ is the rate coefficient for attachment of electrons to meteor smoke particles with charge number Z, $\alpha_i(Z)$ is the coefficient for ion attachment, and t is time.

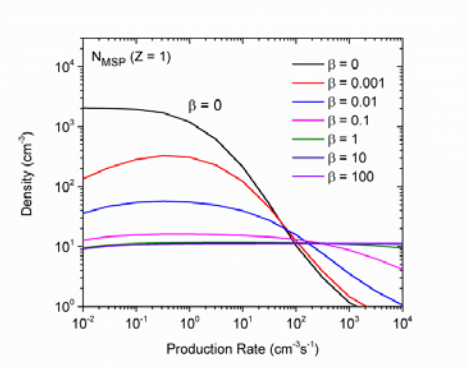
Model Results Plotted

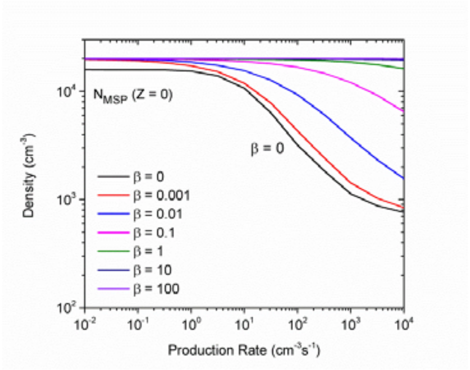
as a function of the ionization rate *Q*
and the photodetachment rate β (in s^{-1})











The most interesting result is the graph above for Z = +1 particles which shows that positive particles are reduced by photodetachment. The electrons created by photodetachment from negative meteor smoke particles recombine with the positive meteor smoke particles reducing their number.

Discussion of model results

Model results are plotted at left with a range of β values. Rapp (2009), using Mie scattering theory, has shown that β can have values as large as 100 s^{-1} for a radius of 1 nm for hematite. The electron number density is increased by increasing photodetachment for all values of *Q*. In the absence of meteor smoke particles and negative ions, the production is balanced by recombination (α_{ie}) of electrons with ions and the expected electron density is $n_e=\sqrt{(Q/\alpha_{ie})}$. For the highest photodetachment rates the electrons attach to meteor smoke particles and then are immediately removed; hence the electron density approaches the value without meteor smoke particles at altitudes where there are no negative ions.

The ion number density is decreased by increasing photodetachment for *Q* values greater than about 1 s^{-1}. This is likely a result of their being more electrons available for recombination. For the lower values of *Q*, the electrons from photodetachment are likely to attach to meteor smoke particles rather than recombine with ions and the effect of photodetachment on ions is less easily interpreted.

Rapp, M., Ann. Geophys. 27, 2417-2422 (2009)

Further discussion

The number density of negatively charged meteor smoke particles is reduced by photodetachment for all Q values. At 65 km, the numbers of negatively charged meteor smoke particles in the 500 – 2,000 amu mass range is reduced from ~2,000 cm^{-3} at night to less than 30 cm^{-3} in the daytime, indicating β greater than about 0.3 s^{-1}. For sufficiently high photodetachment rates, attachment of an electron to a neutral MSP occurs at the same rate as photodetachment from negative meteor smoke particles, if loss of charge by attachment of ions to negative meteor smoke particles can be ignored which should be the case for sufficiently low Q. The simplified expression for negative MSP density is $\alpha_e(0)N_{MSP}(0) = \beta\, N_{MSP}(-1)$ or $N_{MSP}(-1) = \alpha_e(0)N_{MSP}(0)/\beta$. This implies that the number of negatively charged meteor smoke particles should vary inversely with β, which is seen in the plot of the density of $N_{MSP}(-1)$. The number density of positively charged meteor smoke particles is reduced by increasing photodetachment for all values of Q as a result of recombination with the electrons from photodetachment. The number density of uncharged meteor smoke particles is increased by photodetachment for all Q values and approaches N_{tot} for the highest values of Q and β.

Conclusions

1. Positive and negative meteor smoke particles are about equally abundant at lower altitudes (low Q values) as required by quasineutrality when the charge on electrons and ions is less than the charge on the dust particles.
2. Recombination at low Q values is primarily on the dust particles, indicating that ionization rates cannot be inferred using the electron-ion recombination rate.
3. Photodetachment in daytime decreases both the number density of negative meteor smoke particles and positive meteor smoke particles because the photodetached electrons neutralize the positively charged meteor smoke particles.
4. Negative dust charging by photoemission is not indicated by the day/night differences, indicating that photoemission is not an important process.

The daytime launch, October 13, 2011.