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Detection of meteoric smoke particles in the mesosphere by a rocket-borne mass spectrometer

Scott Robertson [a], Shannon Dickson [a,*], Mihaly Horányi [a], Zoltan Sternovsky [a], Martin Friedrich [b], Diego Janches [c], Linda Megner [d], Bifford Williams [e]

[a] University of Colorado, Boulder, CO 80304, USA
[b] Graz University of Technology, 8010 Graz, Austria
[c] Goddard Space Flight Center, Greenbelt, MD 20771, USA
[d] Department of Meteorology, Stockholm University, 106 91 Stockholm, Sweden
[e] GATS-Inc., Boulder, CO 80301, USA

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ABSTRACT

In October 2011, two CHAMPS (Charge And Mass of meteoric smoke ParticleS) sounding rockets were launched into the polar mesosphere, each carrying an electrostatic multichannel mass analyzer for charged meteoric smoke particles (MSPs) that operated from 60 to 100 km and returned data on the number density of the charged MSPs in several ranges of mass. The payloads also carried Faraday rotation antennas and an array of plasma probes for determining electron and ion densities and the payload charging potential, thus providing a comprehensive picture of the distribution of charges over a wide range of altitudes that can be compared with models for the vertical distribution of MSPs and for the distribution of charge. The launches were from the Andøya Rocket Range, Norway, following the end of the noctilucent cloud season to avoid detection of ice. A night launch (11 October 21:50 UT) and a day launch (13 October 13:50 UT) helped to elucidate the role of solar ultraviolet in determining the charge state of the particles. The night data show a distinct change in the charge state of MSPs at the D-region ledge (~78 km) below which the density of free electrons is greatly reduced. Above the ledge, negative MSPs are detected at up to 92 km, have number densities reaching ~200 cm^{-3}, and positive MSPs are absent. Below the ledge, positive and negative MSPs are about equally abundant, each with densities of ~2000 cm^{-3} at 70 km and with slightly lower densities at 60 km. The MSPs are seen predominantly in mass bins spanning 500–2000 amu and 2000–8000 amu, with more massive particles (radii above ~1.2 nm assuming a smoke particle density of 2 g/cm^3) having number densities below the detection threshold (10 cm^{-3}) and less massive particles being indistinguishable from ions. The daytime launch data show positive MSPs present only below the ledge and their number density is reduced to below 300 cm^{-3}. The daytime data show negative MSPs both above and below the D-region ledge and their number density is also reduced, perhaps as a consequence of photodetachment. Modeling of the charge state of the MSPs shows that the total number density of MSPs, charged and uncharged, is approximately 20,000 cm^{-3} below the ledge and the model reproduces the absence of positive MSPs above the ledge.

1. Introduction

In the last decade, advances in instrumentation have made it possible to detect the meteoric smoke particles (MSPs) from the ablation of meteors in the upper atmosphere. The new methods include rocket-borne instruments, ground-based radar, and remote sensing by satellite. We report results from a 10-channel rocket-borne mass spectrometer that simultaneously records the number density of charged nanometer-sized particles in five mass ranges for both signs of charge. The design has sampled air flowing through the instrument thus allowing the detection of the smallest particles which might otherwise be carried around the instrument by aerodynamics. These measurements of the number density of MSPs are the first with mass resolution and they extend over a greater range of altitude (60–90 km) than previous in situ measurements. Number densities of positively and negatively charged particles are measured separately and the uncharged fraction is deduced from a charging model. Two nearly identical payloads, also carrying a variety of other instruments to aid in data interpretation, were launched from Andøya Rocket Range, Norway, one in daytime and one at night in order to help elucidate the role

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[*] Correspondence to: Center for Integrated Plasma Studies, University of Colorado, UCB 390, Boulder, CO 80309-0390, USA. Tel.: +1 303 735 4305.
E-mail address: Scott.Robertson@colorado.edu (S. Robertson).

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of photoelectron emission and photodetachment in determining the charge state of the particles.

Meteoric smoke particles are the likely condensation nuclei for noctilucent clouds (NLC) (Witt, 1969). Rosinski and Snow (1961) modeled the formation of meteoric smoke particles in the meteor trail. Plane (2003) has argued that smoke particles do not form in the meteor trails but form after the trail has dispersed by polymerization of reaction products with large dipole moments. Recent work on the ablation process includes detailed modeling (Vondrak et al., 2008) and observations (Janches et al., 2009) of differential ablation that show Na and K evaporating about 12 km higher (100–110 km) than the more refractory Si, Fe, and Mg. There have also been flow tube studies of the molecular species likely to be formed by chemical reactions of the metal atoms from ablation (Saunders and Plane, 2006). Regardless of composition, models (Hunten et al., 1980; Megner et al., 2006; Bardeen et al., 2008) have shown that there are several tens of thousands of nanometer-sized particles per cubic centimeter throughout the mesosphere and upper stratosphere. These results are strongly dependent upon assumptions that include an initial mean particle size of 0.2 nm and a vapor number density adjusted to be consistent with a mean flux of 44 t/day (Hughes, 1978; Megner et al., 2008a), which has a large uncertainty (Plane, 2012). These models suggest that the highest number densities occur at 80–90 km above which there is a sharp depletion in abundance. Since the ablation profile depends on uncertain properties such as the meteor velocity distribution, the altitude of this upper limit could be anywhere between 85 and 105 km (Kalashnikova et al., 2000; Megner et al., 2006). Below 80 km, the models show a decreasing number density due to coagulation and sedimentation as well as latitudinal and seasonal variations from atmospheric circulation.

Observations of meteoric material have been made by airborne instruments in the Arctic stratosphere below 14 km in winter, when mesospheric air is transported downward (Curtius et al., 2005). The transported particles have implications for polar stratospheric clouds, sulfate aerosols and ozone chemistry. Observations of Ir and Pt in Greenland ice cores are consistent with an origin in meteoric smoke particles (Gabrielli et al., 2004). The presence of meteoric smoke particles above 60 km altitude has been detected by measurements of optical extinction by the Solar Occultation for Ice Experiment (SOFIE) instrument on the AIM (Aeronomy of Ice in the Mesosphere) spacecraft (Hervig et al., 2009). These extinction data also placed constraints on the composition of the smoke particles (Hervig et al., 2012). Evidence for MSPs has also been seen in data from the incoherent scatter radar at Arecibo, Puerto Rico. The data had sufficient signal to noise ratio in the range 80–95 km to deduce particle characteristic radii and number densities. Strelnikova et al. (2007) found number densities rising from $\sim 10\ \text{cm}^{-3}$ at 85 km to $\sim 1000\ \text{cm}^{-3}$ at 90 km whereas Fentzke et al. (2009, 2012) found densities rising from $\sim 300\ \text{cm}^{-3}$ at 80 km to $\sim 20{,}000\ \text{cm}^{-3}$ at 94 km with little seasonal variation, as would be expected at midlatitudes. Both studies indicated a characteristic radius of approximately 1 nm.

While there is substantial evidence of MSP occurrence at NLC altitudes, atmospheric circulation models have recently shown a strong seasonal variation in the density of MSPs sufficiently large to be condensation nuclei for NLCs. MSPs less than 1 nm in radius are thought to be ineffective as nuclei because of the Kelvin barrier. Megner et al. (2006, 2008a, 2008b) coupled the Community Aerosol Radiation Model for Atmospheres (CARMA) for smoke production and sedimentation with the CHEM2D model for circulation and showed that at the summer pole the number density of particles greater than 1 nm in radius is reduced to below $10\ \text{cm}^{-3}$ as a consequence of meridional circulation. This seasonal reduction was also seen by Bardeen et al. (2008) who coupled the CARMA model with the three-dimensional Whole Atmosphere Community Climate Model (WACCM) for circulation. The predicted summer reduction in the density of MSPs above 60 km altitude has been seen in measurements of optical extinction (Hervig et al., 2009). The models suggest that the sufficiently large MSPs are too few to serve as condensation nuclei for NLCs or for the subvisual icy particles causing the radar returns called polar mesospheric summer echoes (PMSE) (Rapp and Lübken, 2004). Gumbel and Megner (2009) and Megner and Gumbel (2009) have pointed out that the Kelvin barrier is removed if the particles are charged; thus allowing the more numerous smaller particles to serve as condensation nuclei if charged. Plane (2011) has argued that metal silicates have sufficient dipole moments to remove the barrier in the absence of charge.

The altitudes at which MSPs and ice particles occur include the D region of the ionosphere where there are sufficient numbers of free electrons and ions for a significant fraction of these particles to be charged (Reid, 1990; Havnes et al., 1990; Jensen and Thomas, 1991). Initial modeling, which assumed a much greater number of free electrons than of particles, showed that nearly all of the particles would be negatively charged due to the greater rate coefficient for the attachment of electrons. Polar mesospheric winter echoes (PMWE), much weaker than PMSE, have been seen in disturbed conditions with high electron densities in winter at 55–80 km altitude. These have been attributed to the attachment of electrons to MSPs with particle radius near 3 nm (Kavanagh et al., 2006; La Hoz and Havnes, 2008; Havnes and Kassa, 2009; Havnes et al., 2011). Modeling for a wider range of conditions has shown that for low ionization rates and large numbers of particles both the electron and the ion from an ionization event would each attach to a MSP making the numbers of positive and negative particles more nearly equal (Reid, 1997; Rapp and Lübken, 2001).

The first in situ observations of charged meteoric smoke in the mesosphere were made using the rocket-borne Faraday cups that had been developed for the detection of charged NLC particles (Havnes et al., 1996). Modeling of the air flow in and around Faraday cups has shown that nanometer-sized particles (but not the larger NLC particles) are carried around the cup entrance by the air flow which results in reduced sensitivity to these particles (Hedin et al., 2007) that is dependent upon altitude and velocity. Measurements of MSPs were initially made at tropical latitudes (Puerto Rico) where temperatures in the mesosphere rule out the possibility of observed particles being ice (Gelinas et al., 1998) and above Alaska outside the season in which icy particles could occur (Lynch et al., 2005; Gelinas et al., 2005). Amyx et al. (2008), using a dust impact detector, found net positively charged particles with densities of $\sim 1000\ \text{cm}^{-3}$ at 80–85 km altitude above Scandinavia after the NLC season. Rapp et al. (2007) have reviewed in situ measurements including data from mass spectrometers and Gerdien condensers that had much earlier indicated charged species too massive to be identified as molecular ions.

Rapp et al. (2003) developed a rocket-borne instrument for detection of MSPs utilizing an ultraviolet flashlamp coupled with a Faraday cup. The lamp caused photodetachment of electrons from the negatively charged smoke particles and possibly photoemission from neutral particles. A fast burst of electrons from photodetachment was detected by the Faraday cup as well as a continuous (DC) signal from the charged smoke. The DC signal was attributed to smoke particles greater than about 2 nm in radius because the smaller particles would be carried around the instrument by aerodynamic effects. The instrument was flown on several rockets as part of the ECOMA (Existence and Charge state of Meteoric smoke particles in the middle Atmosphere) campaign from the Andøya Rocket Range, with some flights within the NLC season and some outside the season (Rapp et al., 2009, 2010, 2012; Rapp and Strelnikova, 2009; Strelnikova et al., 2009). Data from three flights in 2010 (before, during, and after the Geminid meteor shower) showed electron release from negative MSPs from 87 to