IN SITU STUDIES OF METEOR SMOKE PARTICLES IN THE MIDDLE ATMOSPHERE DURING THE ECOMA-ROCKET CAMPAIGNS

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ABSTRACT

The ECOMA-project is dedicated to the study of the 'Existence and Charge state Of Meteoric smoke particles in the middle Atmosphere'. The project is led by the Leibniz Institute of Atmsopheric Physics, Germany, and the Norwegian Defence Research Establishment, Norway, and utilizes rocket borne in situ measurements as well as ground based observations with radars and lidars to characterize meteor smoke particles and their atmospheric and ionospheric environment.

In the present paper results from the campaigns conducted in September 2006 and in August 2007 are presented. We show that the ECOMA particle detector allows to detect meteor smoke particles throughout the mesosphere and that our measurements in autumn 2006 basically confirm expectations regarding the abundance of meteor smoke particles in the mesosphere from microphysical models. We further compare measurements from autumn and summer conditions, and we further demonstrate that the instrument is well suited for quantitatively determining microphysical parameters of mesospheric ice particles.

Key words: ECOMA; Meteor Smoke Particles.

1. INTRODUCTION

Meteor smoke particles (MSPs) are thought to be formed by the recondensation of metal- and silicon-containing molecules originating from the ablation of meteoroids in the 70-120 km altitude range [Pla03]. Starting with the 1960s, model studies suggested that MSPs should exist in the mesosphere/lower thermosphere with number densities of up to 10^4 particles/$cm^3$and corresponding radii ranging from the sub-nanometer range to a few nanometers [RS61, HTT80]. Despite these tiny dimensions, it has been suggested that MSPs are involved in a variety of atmospheric processes such as the nucleation of mesospheric ice clouds, heterogeneous chemistry, and the formation of nitric acid trihydrate (NAT)-particles in polar stratospheric clouds which are involved in ozone destruction in the polar spring [e.g., RT06, SS99, VSL05]. Despite obvious interest in MSPs, measurements of such particles have proven difficult so that today only a few measured altitude profiles are available from charged particle measurements on sounding rockets [SA92, GLK98, CMF01, LGK05, RHS05, SRS09b] and from incoherent scatter radar experiments [RSG07, SRR07].

Most of these previous in situ measurements used Faraday-Cup-based instruments based on the original design of [HTB96] who was the first to detect charged (ice) particles in the polar summer mesopause region. For this type of detector, however, it has become clear in the meantime that it possesses a severely limited detection efficiency for the smallest sizes (i.e., below $\sim$ 2 nm) and for which the smallest detectable radius even varies with altitude as a consequence of aerodynamics [HGW99, RHS05, HGR07]. Measurements with incoherent scatter radars, on the other hand, have so far only proven to be feasible with the most powerful incoherent scatter radar, i.e., the Arecibo radar, whereas measurements with even the EISCAT UHF radar were only indicative of the existence of MSPs [RSG07]. In addition, even with the Arecibo radar, measurements could only be performed at altitudes with sufficient D-region ionization, i.e., above $\sim$85 km [SRR07]. Hence, it is obvious that new measurements which should cover a larger altitude range and which should be able to detect MSPs of all sizes are highly desirable.

In the current manuscript, we present the concept and first results of a new particle detector which combines a classical Faraday cup-design with a xenon-flashlamp for the active photoionization of mesospheric aerosol particles and the subsequent detection of corresponding photoelectrons. In section 2.1 we introduce the basic design of this detector. Initial results from a rocket flights during the ECOMA-2006 and ECOMA-2007 campaigns (ECOMA = Existence and charge state of meteor smoke particles in the middle atmosphere) are presented in section 3.

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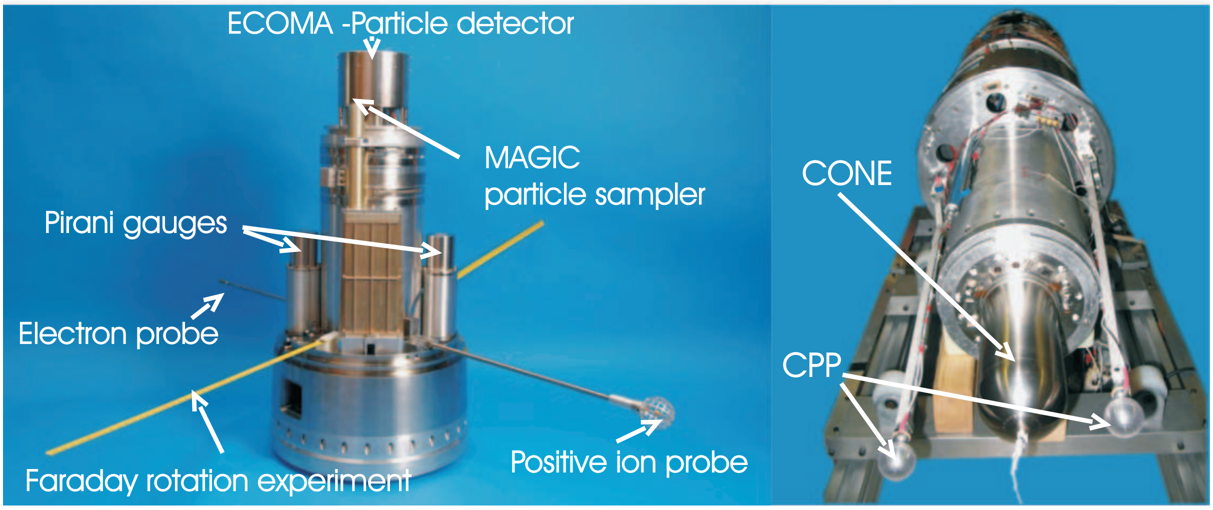

Figure 1. The photograph of the ECOMA payload: The front deck on the left panel and the rear deck on the right panel. (The pictures were taken by A. Brattli, University of Tromsø, Norway)

Results obtained from these both flights are discussed in section 3.3.

2. INSTRUMENTS ONBOARD OF ECOMA PAYLOAD

A foto of the ECOMA payload is shown in Figure 1. The main instrument, the ECOMA particle detector, is mounted on the front deck of the payload, and is designed to measure MSP number densities (2.1).

The other instrument directly dealing with the meteoric smoke onboard the ECOMA payload was the MAGIC particle sampler. This instrument is designed for the in-flight collection of MSPs and return to the ground for later analysis in the laboratory [GWG05].

On the front deck were mounted also: the radio wave propagation experiment, which yields a high precision electron density measurement. Two fixed biased probes on short booms to measure positive ions and electrons number densities, respectively. Two Pirani gauges for low-cost density and temperature measurements.

On the rear deck the Cold Plasma Probe (CPP) and CONE (=COmbined measurement of Neutrals and Electrons) instrument were mounted. CPP yields electron densities and temperatures as well as the payload potential. CONE is a combination of an ionization gauge for the measurement of neutral density and a fixed biased Langmuir probe to measure electron number density. CONE yields measurements with very high spatial resolution and allows to detect small scale fluctuations in both species (neutrals and electrons) that arise due to processes like neutral air turbulence [LRH02] or plasma instabilities [see e.g. BTK94].

In 2007, the ECOMA payload also carried a NLC photometer from the University of Stockholm for the optical in situ detection of mesospheric ice particles ([e.g. GSM01]).

2.1. The ECOMA particle detector

The new particle detector is a combination of a Faraday-cup and a xenon-flashlamp for the photo-ionization of meteor dust particles (Fig. 2).

The design of the Faraday cup comprises a collecting electrode (held at the payload potential by a negative feedback loop of the electrometer) for the measurement of charged particles and two grids (biased at $\pm$3-6 V relative to payload potential) to shield the collector against electrons and ions. This classical design of the Faraday Cup is combined with a xenon-flashlamp (in the center of the cup) which emits UV-photons for the active photoionization of particles. The flash lamp is operated at a repetition rate of 15.6 Hz.

Briefly, this technique can be summarized as follows. Directly after the flash photoelectrons are assumed to be isotropically emitted from MSPs in all directions (solid angle of $4\pi\ sr$). The volume where the ionization rate is larger than $\sim$1 % only extends to about 1 m ahead of the detector because of the beam divergence. Additionally, the probability of the electron to hit the detector's electrode decreases with the distance. Thus, the electrons released from the MSPs after the flash originate from the conically shaped nearby volume with an opening angle of 30° and can be measured as a current. Because of the high electron velocity (typical kinetic energy of few eV), the response on the flashing is shorter than 50 μs with the maximum during the first 10 μs.

The sensitive electrometer has two measurement channels with sampling rates of 1 and 100 kHz. This corre-

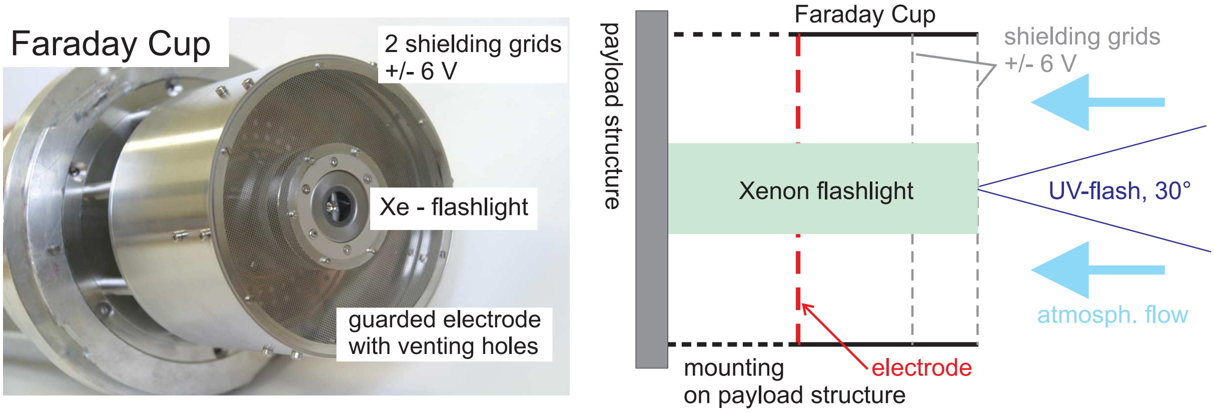

Figure 2. Photo and schematic of the ECOMA-particle detector.

sponds to the classical Faraday Cup and the new measurement technique, respectively.

The 100 kHz channel yields information about the total particle number density multiplied by the photoionization cross section (which is proportional to particle volume density if the prevailing Rayleigh regime). For the interpretation of these measurements an additional modelling is required. This new measurement technique is discussed in detail in [RS09] where the relation between MSPs' number density, their photoionization cross section, and measured current is introduced. It was shown that currents detected below ∼85 km height are due to photoionization of MSPs since other potential contributions from species with low work function create currents that are orders of magnitude smaller.

The 1 kHz channel (classical Faraday Cup) obtains 64 samples between two subsequent flashes. Because the duration of the flash-produced photocurrent is shorter than the time sampling interval of this channel (1 ms), only the first sample after the flash measurement point is affected by the photoelectrons and needs to be eliminated. During the next 63 samples the electrometer measures the net natural charge of the particles (either negative or positive), if there is any. Hence, the measurements by this channel yield the information about the charge number density of the meteor smoke particles. This current can be compared with other measurements provided by similar instruments.

3. MEASUREMENTS OF METEORIC DUST BY ACTIVE PHOTOIONIZATION

3.1. Results from September-flight (ECOMA01)

The first rocket sounding using the new method for MSPs detection by active photoionization was done on September 8, 2006 at 22:17:00 UT (ECOMA01).

Some initial results from this campaign are published in [RS09] and [SRS09b]. The main results are summarized

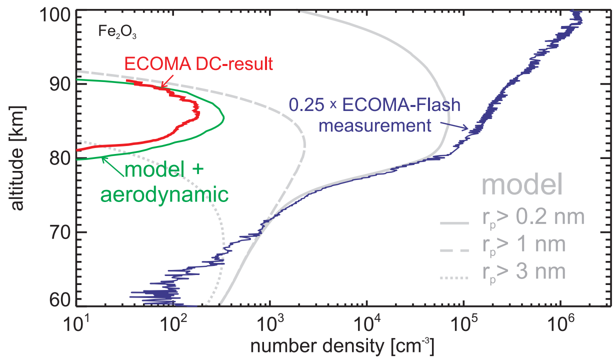

Figure 3. Results obtained during ECOMA01 campaign. The red and blue curves show the number densities obtained by 1 and 100 kHz channels respectively. The grey lines show the modeled number densities for different radii. The green line represents the combination of modeled MSPs with aerodynamical model.

in Fig. 3 where the simultaneous measurements of MSPs by two measurement techniques in comparison with theoretical estimates are presented. To convert the measured flash-current to the number density we assumed that the particles are Fe_2O_3-spheres with a quantum yield for photoionization of Y=1.0. The size distribution needed for cross section estimation was taken from the model of [MRG06].

The flash method (100 kHz channel), which measures the entire MSP population, observed a broad altitudinal dust distribution, i.e. from 60 to ∼90 km (Fig. 3, blue line). Whereas the 1 kHz channel only measured a layer of the charged dust between 80 to 90 km. Note, that ice particles cannot exist at those heights at the time of the ECOMA01 launch. Fig. 3 demonstrates that the *"layering"* observed by the classical Faraday cup technique (1 kHz channel), that is the dust layer confined to the heights 80 to 90 km, is not a geophysical feature but an instrumental limitation. This conclusion is also valid for all other similar dust detectors.

Quantitatively, the measured dust density exceeds the

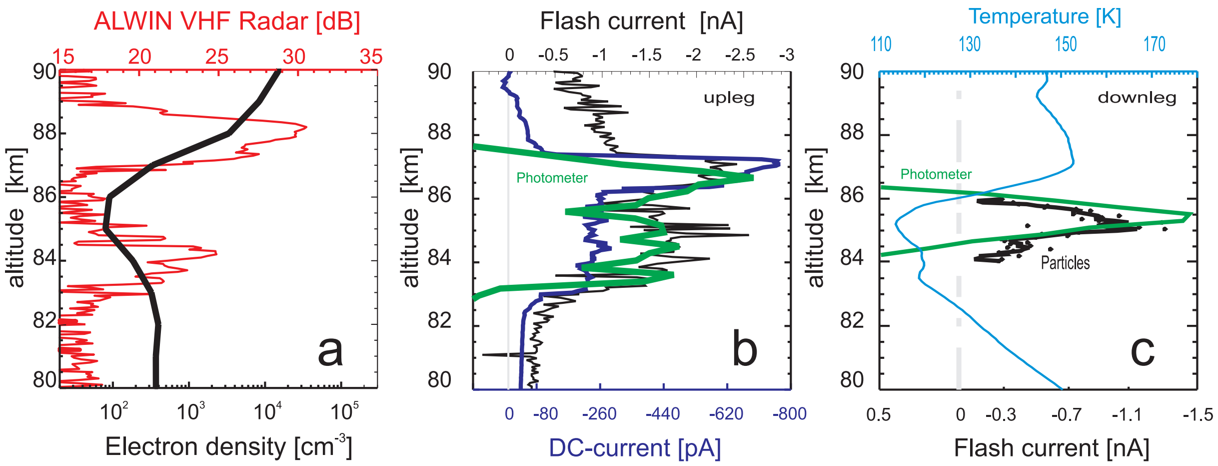

Figure 4. Overview of measurements with the ECOMA-particle detector in comparison to ***a****: ALWIN VHF-radar measurements of PMSE (red line) and absolute electron densities from the Faraday propagation experiment (black line).* ***b****: DC- (blue) and Flash- (black) currents measured by the ECOMA-particle detector on upleg compared to photometer measurements indicating the presence of "visible" ice particles (green line), i.e., ice particles with radii in excess of ≫20 nm.* ***c****: the same as* ***b****-plot, but for downleg. DC-measurements during downleg are impossible because of the wake conditions for the instrument. Also temperature profile measured by the CONE-instrument (sky-blue) is shown.*

model prediction by a factor of 4. This can be due to underestimation of the photoelectron yield, photoionization cross section, or meteoroid influx assumed in the model of [MRG06]. However, qualitatively, the model predictions and the measurements by the flash channel show good agreement. The importance of these measurements is that they were the first experimental confirmation of the existence of MSPs in the entire height range of the winter mesosphere.

3.2. Measurements of mesospheric aerosols in a PMSE/NLC event (ECOMA03)

The ECOMA03 sounding rocket was launched on 3 August 2007, at 23:22 UT from the Andøya Rocket Range (69° N). The detailed description of the results obtained during this flight can be found in [RSS09]. The special feature of the ECOMA03 flight is that this was the first flight of the ECOMA instrument under PMSE/NLC conditions.

An overview of the measurements obtained during this flight is shown in Fig. 4. In the left panel ALWIN radar measurements with the 7° North-West-beam are shown for the time of the rocket launch. Note that the rocket passed through the edge of the volume illuminated by this beam on the upleg part of the rocket trajectory. In the same panel we show electron density measurements by the Faraday rotation experiment [FTS09]. Interestingly, this shows that the PMSE disappeared exactly at the altitudes where the electron density was significantly diminished. This is in line with results of a previous study by [RGL02] who showed that PMSE require a minimum ambient electron number density of a few hundreds of electrons/cm^3. Hence, it appears that the decaying D-region ionization was, at least partly, responsible for the decay of the PMSE-layer.

The middle panel of Fig. 4 shows the ECOMA measurements for the upleg and, in the right panel, for the downleg. The measurements obtained by the flash channel are shown as black lines. This method allows to measure during both upleg and downleg (see [RS09] for details).

The DC-measurements (the classical Faraday cup, blue line in Fig. 4, panel b) are only available on the upleg and show a layer of net negatively charged particles in the altitude range 82 to 88 km. The same layer was also detected by the flash method and by NLC photometer of the University of Stockholm for the optical in situ detection of mesospheric ice particles [GSM01]. Comparing the in situ measurements of ice aerosols with the radar PMSE observations, we clearly see that the lower edges of the ice layer and of the PMSE signal are at the same altitude. The upper edge of PMSE signal is ∼1 km higher than the ice layer. Note that the radar detected a double-layer PMSE structure, i.e. there was no detectable signal between ∼85 and 86.5 km, whereas the ice layer detected by in situ measurements does not change between ∼83 and 86 km. This clearly shows that the presence of charged ice particles alone is not a sufficient condition for the existence of PMSE. Rather, PMSE additionally require a mechanism creating small scale structures at the radar Bragg scale which is commonly assumed to be neutral air turbulence in the presence of charged aerosol particles [e.g. KFR87, RL04] and sufficient ionization, as suggested by the comparison of the PMSE with the electron densities discussed above. For the present case [SRS09a] have shown that small scale structure at the radar Bragg scale occurred in the entire altitude range with ice particles. Hence the absence of sufficient numbers of free electrons is here responsiblefor the absence of PMSE at ∼83-86 km.

As shown in [RSS09], the measured photoelectron currents are a unique function of the ice particle volume density (and hence ice mass) within an uncertainty of only 15 % and the derived values are in the range $2 - 8 \times 10^{-14}\ cm^3/cm^3$ and are in general agreement with independent estimates from either satellite instruments [HGS09] or lidar measurements [BFv08] even though we note that our values are somewhat at the large side of those previous observations.

The downleg data (Fig. 4c) show only a thin layer of ice particles between ∼84 and 86 km. Note that the ECOMA flash method cannot distinguish between ice and meteoric smoke particles, whereas the photometer is only sensitive to the ice particles. Thus, because of the coexistence of the layers measured by both instruments, we can conclude that the current measured by the ECOMA-flash channel represents the ice particles. The other, although indirect, confirmation that the layer measured by the ECOMA-flash channel is the icy particles is due to overlapping of the temperature minimum measured in the same volume by the CONE instrument (sky-blue line in Fig. 4c). The large difference between the upleg and the downleg data, that are ∼50 km spaced, indicates of that the ice cloud was extremely inhomogeneous.

3.3. Comparison of September 2006 and August 2007 results

An interesting feature observed during ECOMA03 flight is the low photoelectron current outside the PMSE/NLC layers. The noise level of the 100 kHz channel is ∼300 pA. For comparison, the currents measured during the ECOMA01 flight rise from ∼2 nA at 60 km to ∼15 nA at 70 km and drop to ∼7 nA at 90 km [RS09, SRS09b]. Thus, the currents from the MSPs measured in September and discussed above were well above the detection limit. During the ECOMA03 flight in August, there was no detectable signal below the ice layers. On upleg above the ice layer the flash current slowly drops to ∼0.5 nA. The downleg data only show a thin layer of ice particles. Currents measured during these both flight are shown in Fig. 5. The large discrepancy between ECOMA01 and ECOMA03 can be explained by differences either in the underlying MSPs concentration or in the photoelectric properties of the particles. An in-depth analysis of this discrepancy is presented in [RSB09], where the other three ECOMA-flights from summer 2008 also was taken into consideration.

4. CONCLUSIONS

In the current paper we have presented rocket-borne observations of MSPs from two different sounding rocket campaigns, conducted under different geophysical conditions. During the first campaign (in September) the broad altitudinal distribution of MSPs was detected. Also

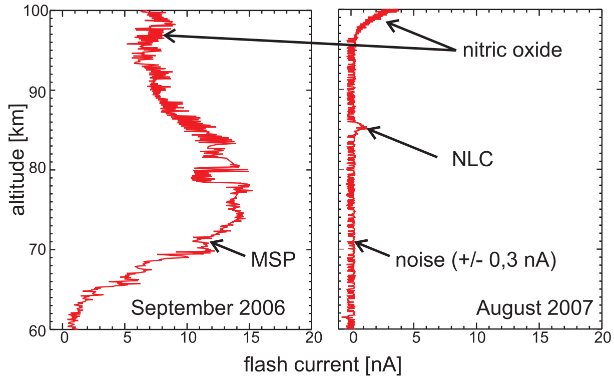

Figure 5. Photocurrents measured during ECOMA01 and ECOMA03 campaigns. Above ca. 95 km measurements are contaminated by photoelectrons from NO.

results from this flight confirmed that aerodynamical effects influence the classical Faraday cup measurements. Results from the second campaign (conducted in August) only showed a layer of ice particles (confirmed by photometer measurements on the same payload). The signal from MSPs was below the detection limit of the instrument.

By comparison of these flights, we see that the maximum signal, e.g. from flight ECOMA01 compared to ECOMA03, was reduced by a factor of 50. For explanation of this discrepancy the detailed knowledge of MSPs number densities and photoelectric properties are required.

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REFERENCES

[BFv08] G. Baumgarten, J. Fiedler, F. J. Lübken, and G. von Cossart. Particle properties and water content of noctilucent clouds and their interannual variation. *J. Geophys. Res.*, 113:6203–+, March 2008.

[BTK94] T. A. Blix, E. V. Thrane, S. Kirkwood, and K. Schlegel. Plasma instabilities in the lower E-region observed during the DYANA campaign. *JATP*, 56:1853–1870, 1994.

[CMF01] C. Croskey, J. Mitchell, M. Friedrich, et al. Electrical structure of PMSE and NLC regions during the DROPPS program. *Geophys. Res. Lett.*, 28:1427–1430, 2001.

[FTS09] M. Friedrich, K. M. Torkar, W. Singer, et al. Signatures of meteoric particles in ionospheric data. *Ann. Geophys.*, accepted, 2009.

[GLK98] L. J. Gelinas, K. A. Lynch, M. C. Kelley, et al. First observation of meteoritic charged dust in the tropical mesosphere. *Geophys. Res. Lett.*, 25:4047–4050, 1998.

[GSM01] J. Gumbel, J. Stegman, D. P. Murtagh, and G. Witt. Scattering phase functions and particle sizes in noctilucent clouds. *Geophys. Res. Lett.*, 28(8):1415–1418, April 2001.

[GWG05] J. Gumbel, T. Waldemarsson, F. Giovane, et al. The magic rocket campagn: an overview. *Proceedings of the 17th ESA Symposium, Sandefjord, Norway (ESA SP–590)*, pages 139–144, 2005.

[HGR07] J. Hedin, J. Gumbel, and M. Rapp. On the efficiency of rocket-borne particle detection in the mesosphere. *Atmos. Chem. Phys.*, 7:37013711, 2007.

[HGS09] M. E. Hervig, L. L. Gordley, M. H. Stevens, et al. Interpretation of SOFIE PMC measurements: Cloud identification and derivation of mass density, particle shape, and particle size. *JASTP*, 71:316–330, March 2009.

[HGW99] M. Horanyi, J. Gumbel, G. Witt, and S. Robertson. Simulation of rocket-borne particle measurements in the mesosphere. *Geophys. Res. Lett.*, 26:1537–1540, 1999.

[HTB96] O. Havnes, J. Trøim, T. Blix, et al. First detection of charged dust particles in the Earth's mesosphere. *J. Geophys. Res.*, 101:10839–10847, 1996.

[HTT80] D. M. Hunten, R. P. Turco, and O. B. Toon. Smoke and dust particles of meteoric origin in the mesosphere and stratosphere. *J. Atmos. Sci.*, 37:1342–1357, 1980.

[KFR87] M. C. Kelley, D. T. Farley, and J. Röttger. The effect of cluster ions on anomalous VHF backscatter from the summer polar mesosphere. *Geophys. Res. Lett.*, 14:1031–1034, 1987.

[LGK05] K. A. Lynch, L. J. Gelinas, M. C. Kelley, et al. Multiple sounding rocket observations of charged dust in the polar winter mesosphere. *J. Geophys. Res.*, 110, A03302, doi:10.1029/2004JA010502, 2005.

[LRH02] F.-J. Lübken, M. Rapp, and P. Hoffmann. Neutral air turbulence and temperatures in the vicinity of polar mesosphere summer echoes. *J. Geophys. Res.*, 107(D15):ACL 9/1–10, August 2002.

[MRG06] L. Megner, M. Rapp, and J. Gumbel. Distribution of meteoric smoke - sensitivity to microphysical properties and atmospheric conditions. *Atmos. Chem. Phys.*, 6:4415–4426, 2006.

[Pla03] J. M. C. Plane. Atmospheric Chemistry of Meteoric Metals. *Chem. Rev.*, 103:4963–4984, 2003.

[RGL02] M. Rapp, J. Gumbel, F.-J. Lübken, and R. Latteck. D region electron number density limits for the existence of polar mesosphere summer echoes. *J. Geophys. Res.*, 107(D14), July 2002.

[RHS05] M. Rapp, J. Hedin, I. Strelnikova, et al. Observations of positively charged nanoparticles in the nighttime polar mesosphere. *Geophys. Res. Lett.*, 32, L23821, doi:10.1029/2005GL024676, 2005.

[RL04] M. Rapp and F.-J. Lübken. Polar mesosphere summer echoes (pmse): Review of observations and current understanding. *Atmos. Chem. Phys.*, 4:2601–2633, 2004.

[RS61] J. Rosinski and R. H. Snow. Secondary particulate matter from meteor vapors. *J. Atmos. Sci.*, 18:736–745, December 1961.

[RS09] M. Rapp and I. Strelnikova. Measurements of meteor smoke particles during the ECOMA-2006 campaign: 1. Particle detection by active photoionization. *JASTP*, 71:477–485, March 2009.

[RSB09] M. Rapp, I. Strelnikova, B.Strelnikov, et al. Rocket-borne in-situ measurements of meteor smoke: charging properties and implications for seasonal variation. *J. Geophys. Res.*, 2009. *subm.*

[RSG07] M. Rapp, I. Strelnikova, and J. Gumbel. Meteoric smoke particles: evidence from rocket and radar techniques. *Adv. Space Res.*, doi:10.1016/j.asr.2006.11.021, 2007.

[RSS09] M. Rapp, I. Strelnikova, B. Strelnikov, et al. First in situ measurement of the vertical distribution of ice volume in a mesospheric ice cloud during the ECOMA/MASS rocket-campaign. *Annales Geophysicae*, 27:755–766, February 2009.

[RT06] M. Rapp and G. E. Thomas. Modeling the microphysics of mesospheric ice particles: Assessment of current capabilities and basic sensitivities. *J. Atmos. Sol. Terr. Phys.*, 68:715–744, 2006.

[SA92] P. Schulte and F. Arnold. Detection of upper atmospheric negatively charged microclusters by a rocket-borne mass spectrometer. *Geophys. Res. Lett.*, 19:2297–2300, December 1992.

[SRR07] I. Strelnikova, M. Rapp, S. Raizada, and M. Sulzer. Meteor smoke particle properties derived from Arecibo incoherent scatter radar observations. *Geophys. Res. Lett.*, 34:15815–+, August 2007.

[SRS09a] B. Strelnikov, M. Rapp, I. Strelnikova, et al. Small-scale structures in neutrals and charged aerosol particles as observed during the ECOMA/MASS rocket campaign. *Ann. Geophys.*, 27:1449–1456, April 2009.

[SRS09b] I. Strelnikova, M. Rapp, B. Strelnikov, et al. Measurements of meteor smoke particles during the ECOMA-2006 campaign: 2. Results. *Journal of Atmospheric and Solar-Terrestrial Physics*, 71:486–496, March 2009.

[SS99] M. E. Summers and D. E. Siskind. Surface recombination of O and H_2 on meteoric dust as a source of mesospheric water vapor. *Geophys. Res. Lett.*, 26:1837–1840, July 1999.

[VSL05] C. Voigt, H. Schlager, B. P. Luo, et al. Nitric acid trihydrate (NAT) formation at low NAT supersaturation in polar stratospheric clouds (PSCs). *Atmos. Chem. Phys.*, 5:1371–1380, 2005.