Microphysical and turbulent measurements of the Schmidt number in the vicinity of polar mesosphere summer echoes

Franz-Josef Lübken and Markus Rapp
Physikalisches Institut der Universität Bonn, Bonn, Germany

Tom Blix and Eivind Thrane
Norwegian Defence Research Establishment, Kjeller, Norway

Abstract.
During the ECHO campaign in 1994 neutral and electron density fluctuations were measured together with charged aerosols on the same sounding rocket launched close to a VHF radar detecting polar mesosphere summer echoes (PMSE). For the first time this combination of measurements allows for an independent test of the microphysical and the turbulence interpretations of the Schmidt number (Sc). The Schmidt number characterizes the reduction of the electron diffusivity by charged aerosols, which leads to an enhancement of the electron density fluctuations at small spatial scales. In one of the flights charged aerosols were observed at ~83–89km together with correlated depletions in electron density ('biteouts'). We have applied a model of aerosol charging to the measured plasma profiles and determined a mean aerosol radius of ~8nm and a mean aerosol charge of $1e^-$. In the microphysical description of electron diffusion these parameters correspond to Sc~420. Spectral analysis of the electron density fluctuations showed enhancements of spectral densities at small scales suggesting likewise a Schmidt number much larger than unity. Using an energy dissipation rate of 67mW/kg as derived from neutral air turbulence measurements on the same rocket we get from the electron spectra Sc=385 which is in excellent agreement with the microphysical result. Apart from this turbulent layer we observe no significant disturbances in neutral air number densities below ~87km which confirms earlier indications that processes must exist to create PMSEs which are not directly coupled to neutral air turbulence.

Introduction

Very strong VHF radar echoes from the summer mesopause region at high latitudes were first reported in the early 1980's by *Ecklund and Balsley* [1981] and were later called 'polar mesosphere summer echoes' (PMSE). In the following years various radars operating at different frequencies confirmed that these intense echoes occur only during summer and mainly from a few kilometers below the mesopause (see the review by *Cho and Röttger* [1997]). The explanations given for PMSE were mostly related to neutral air turbulence which was believed to cause small-scale fluctuations also in plasma density and therefore could create refractive index variations at the Bragg scale of the radar waves ($\lambda/2$~3m for a VHF radar operating at 50 MHz). However, it was realized quickly that the power spectral density (PSD) at scales around 3 meters is too small by orders of magnitude to create PMSEs since the neutral density fluctuations created at these scales are quickly dissipated by molecular viscosity. This implies that $\lambda/2$ is located in the viscous subrange of the turbulent spectrum characterized by a steep decrease of PSD with wavenumber. The spectrum of turbulent fluctuations in the plasma will extend to significantly smaller scales, however, if the diffusion coefficient D of the plasma is smaller than the kinematic viscosity ν. The ratio of these two quantities $Sc = \nu/D$ is called 'Schmidt number' (Sc~1 for neutral gas). It was proposed by *Kelley et al.* [1987] that large cluster ions and charged aerosols will result in a reduced mobility of the electrons (since they are electrically bound to the 'heavy' aerosols), therefore to Schmidt numbers larger than unity, and to an increase of the plasma PSD at the 3m scales. These aerosols can only exist at the very low temperatures of the summer mesopause region and presumably consist of water ice.

In this paper we present new measurements and model calculations which elucidate the importance of negatively charged aerosols in modifying the turbulent spectrum thereby creating PMSEs. We will derive Sc from the microphysical properties of the charged aerosols, and then compare this result with the turbulent spectra of the electron and neutral density fluctuations.

Paper number 98GL50479.
0094-8534/98/98GL-50479$05.00

In situ measurements of neutral and plasma densities

The first unambiguous measurement of the Schmidt number in the vicinity of PMSEs was reported by *Lübken et al.* [1994]. Small scale fluctuations of neutral and electron number densities were observed by the rocket borne instrument CONE (COmbined Neutral and Electron sensor). The Schmidt number was obtained from an intercomparison of the spectra of neutral and electron density fluctuations, respectively.

In this paper we report similar measurements performed by CONE during the ECHO campaign (in which VHF radar echoes were studied) which took place from the Andøya Rocket Range (69°N) in summer 1994. We will concentrate on the sounding rocket flight labeled ECT2 which took place on July 28, 1994, at 22:39:00 UT, when the nearby

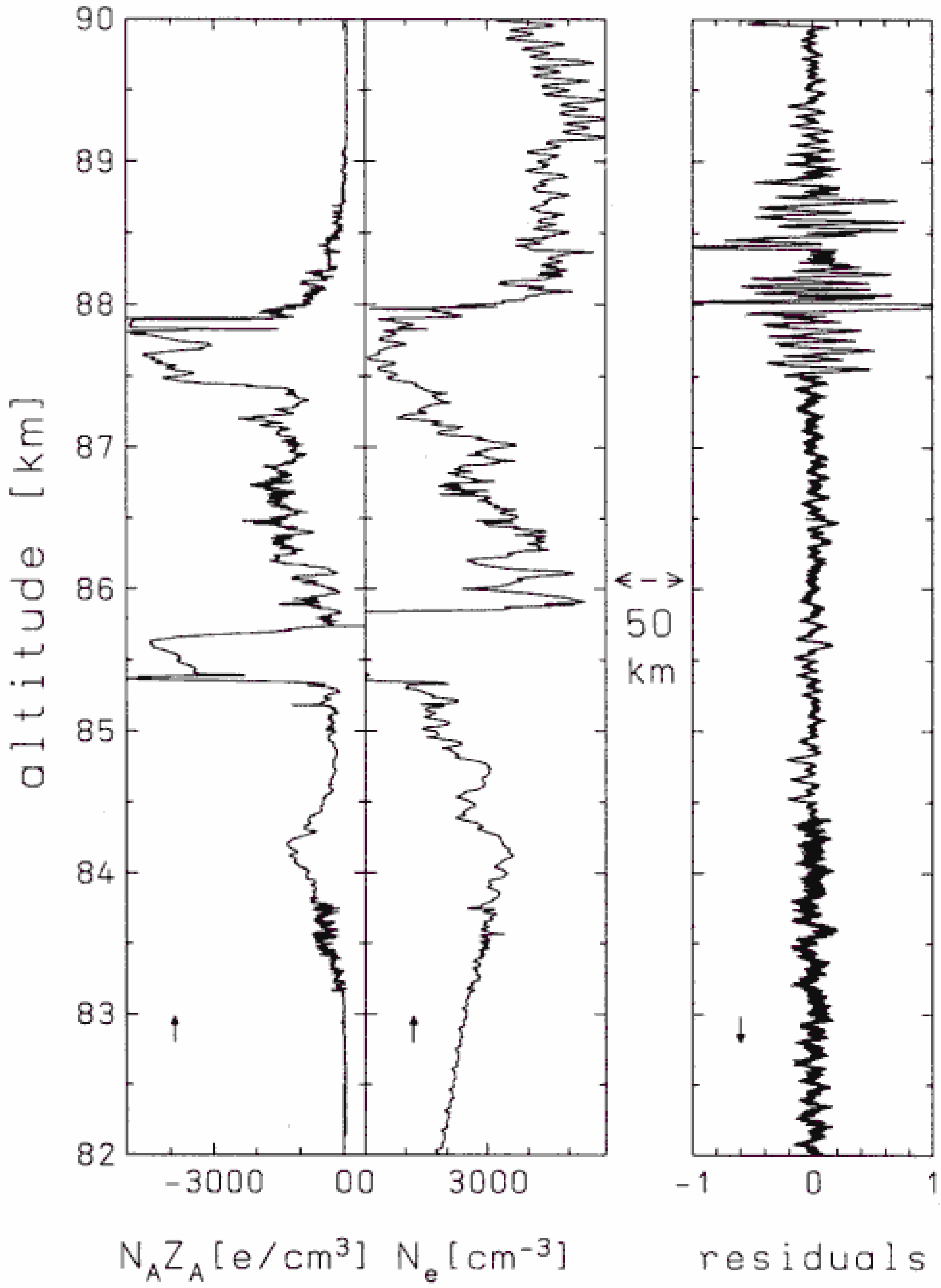

Figure 1. In situ measurements during the ECHO flight ECT2 in the vicinity of a VHF radar detecting a PMSE. Left panel: Aerosol charge density $N_A Z_A$, where N_A is the aerosol number density, and Z_A is the charge per aerosol. Middle panel: Electron number density. Right panel: Neutral density fluctuations ('residuals') relative to a smooth background. The aerosol and electron measurements were performed on upleg, whereas the neutral fluctuations were observed on downleg at a horizontal distance of ~50km.

ALOMAR-SOUSY radar observed strong PMSEs from 84 to 89 km [*Bremer et al.*, 1996,]. Two falling spheres were launched shortly before and after the ECT2 flight and gave density and temperature profiles in the upper atmosphere. CONE measured neutral densities on downleg and electron densities both on upleg and downleg. A dust probe (DUSTY) was flown on the same payload and measured charged aerosols on upleg (actually, DUSTY measures the product $Z_A \cdot N_A$ of aerosol number density N_A and aerosol charge Z_A). First results of the DUSTY instrument are presented in *Havnes et al.* [1996].

In Figure 1 aerosol and electron data are shown (both from upleg) together with relative neutral density fluctuations ('residuals') measured on downleg. Charged aerosols are present between ~83 and ~89km and coincide with depletions in the electron density profile. Such 'biteouts' in the electrons have frequently been observed in the vicinity of PMSEs [*Ulwick et al.*, 1988,]. In the next section we will show that these biteouts are caused by the capturing of electrons by aerosols.

Schmidt Number From Microphysics

The electron densities from the upleg are shown again in Figure 2. We have determined the mean particle radius, r_o, and charge applying the aerosol charging model of *Jensen and Thomas* [1991] to the conditions present during flight ECT2. We have taken the temperatures from the falling sphere flight, the aerosol data shown in Figure 1, and the undisturbed electron profile indicated in Figure 2. The ratio Q/α (Q=ion production rate ; α=ion-electron recombination coefficient) was chosen such that the model resembles the measurements above and below the biteout region with a linear altitude dependence of Q/α in between. This procedure gives Q/α numbers which closely match commonly accepted values [*Jensen and Thomas*, 1991,]. Model calculations are shown in Figure 2 for mean radii of r_o=1, 8, and 20 nm, respectively (the corresponding widths in the assumed log-normal distributions are σ = 1.2, 1.3, and 1.4, respectively). From the model we arrive at a mean charge of $1e^-$ for the 1nm and 8nm particles, and $1.8e^-$ for the 20 nm particles. The measured electron profile around 87.5km is reproduced by the model if a particle radius of r_o ~8nm is used, whereas the other radii (1 and 20nm) result in too small and too large electron depletions, respectively. In the lower biteout region at 85.6 km, however, the 20nm model profile more closely resembles the measurements. This suggests that the particles are larger at lower altitudes in agreement with the idea of particle sedimentation and growth.

In the biteout regions shown in Figure 1 negative charges

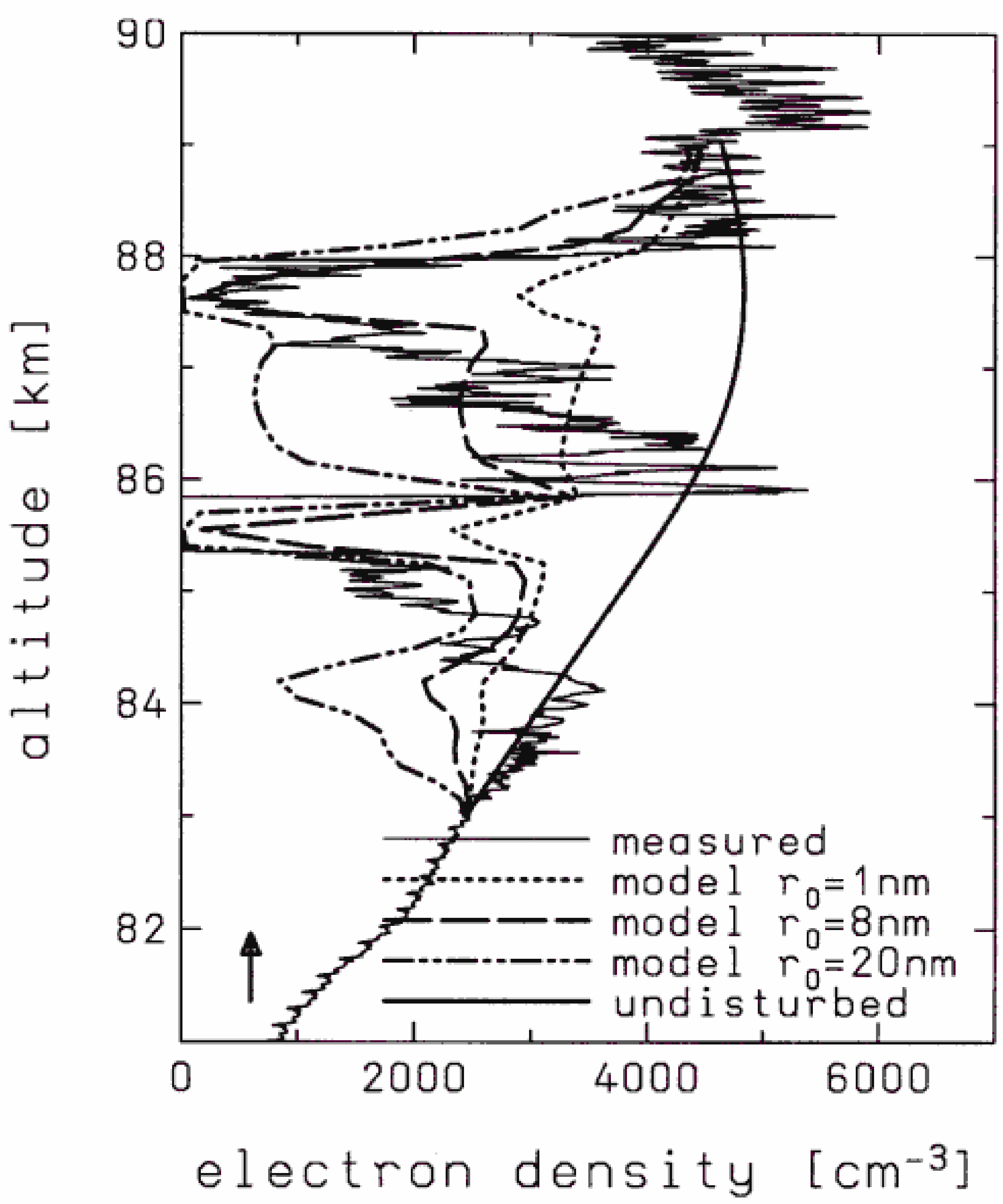

Figure 2. Electron density profile from the upleg of flight ECT2 (thin solid line). The 'undisturbed' profile (thick solid line) is extrapolated from the measured profile below and above the biteout region. Model calculations are shown for three radii: 1, 8, and 20 nm.

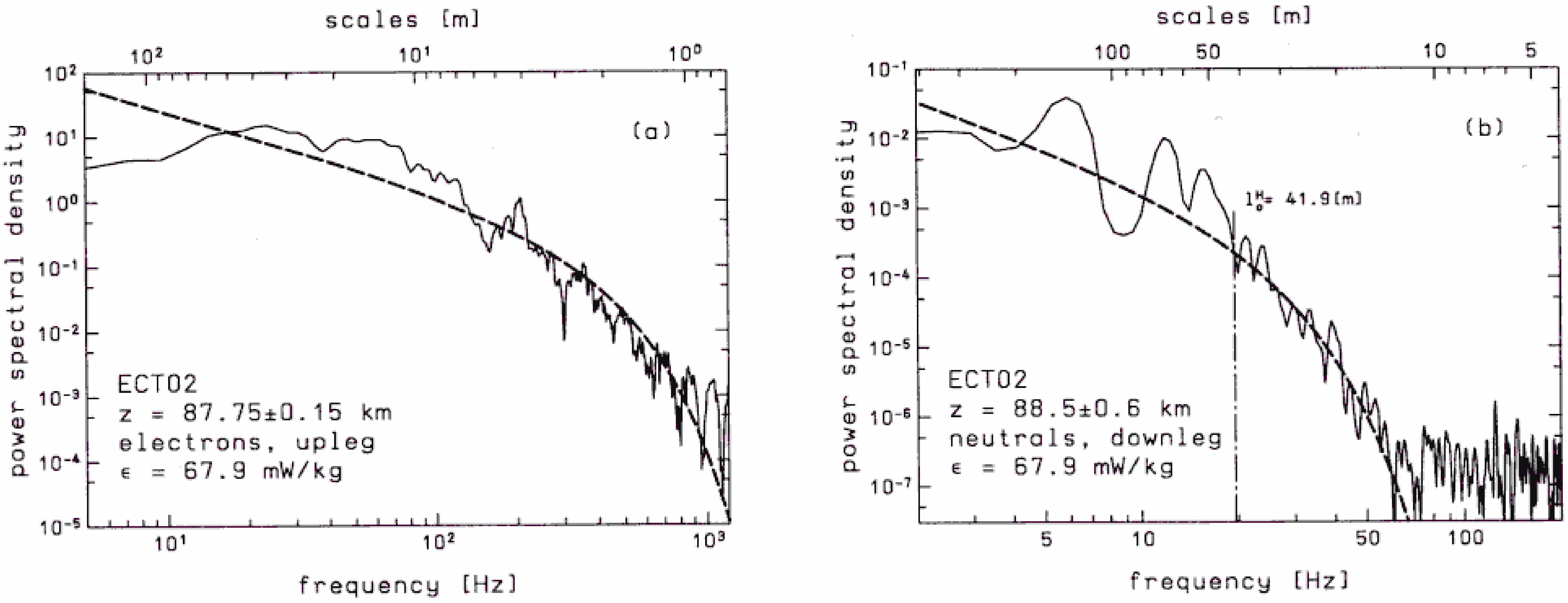

Figure 3. Spectrum of electron (a) and neutral density fluctuations (b) observed in the flight ECT2. Note the different frequency scales. The electron spectrum was measured on upleg whereas the the neutral PSDs were measured on downleg. The inner scale l_o^H is indicated in the neutral density spectrum (dotted-dashed line ; see *Lübken*, 1997, for a detailed description of l_o^H). Theoretical models were fitted to the measured spectra (dashed lines). From the fit to the neutral spectrum we derive ϵ=67mW/kg which was used to deduce Sc=385 from the electron spectrum.

are mainly located on the aerosols and are no longer present as free electrons. For example, at 87.5km the electron density is approximately N_e=500/cm^3, and DUSTY measured negatively charged aerosols of $Z_A \cdot N_A$ ∼−4000e/cm^3. *Cho et al.* [1992] have shown that under these circumstances the effective electron diffusion coefficient is similar to the diffusion coefficient of aerosols:

$$D_e \approx D_A \qquad \text{if} \quad Z_A \cdot N_A \gg N_e \qquad (1)$$

For proton hydrate ions of mass ∼100amu which are expected to dominate the ion composition around the summer mesopause the ratio of aerosol to ion diffusivity is given by (see *Cho et al.*, [1992] and references therein):

$$\frac{D_A}{D_+} = \frac{0.43}{r_A^2} \qquad (r_A \text{ in nm}) \qquad (2)$$

Using the definition of the Schmidt number and the expressions given in equations 1 and 2 we find

$$Sc = \frac{\nu}{D_e} = \frac{\nu}{D_+}\frac{D_+}{D_e} \approx \frac{\nu}{D_+}\frac{D_+}{D_A} = \frac{\nu}{D_+}\frac{r_A^2}{0.43} \qquad (3)$$

We have calculated ν from the measured temperatures, and D_+ from the polarization model (equation 7 in *Cho et al.*, [1992]) and arrive at $\nu/D_+ = 2.8$. With equation 3 we get:

$$Sc = 6.5 \cdot r_A^2 \qquad (r_A \text{ in nm}) \qquad (4)$$

For particles with a mean radius of ∼8nm we arrive at a Schmidt number of ∼420, i.e., much larger than unity.

Turbulent spectra of electron and neutral density fluctuations

Can we detect an effect of Sc≫1 also in the turbulence fields? The spectral analysis of the electron density fluctuations measured on upleg from 87.6 to 87.9 km is shown in Figure 3a. Let's assume for a moment that Sc is *not* enhanced, i.e. Sc=1. In this case electrons are passive tracers for neutral air turbulence and we can deduce the turbulent energy dissipation rate ϵ by fitting a theoretical turbulence model with Sc=1 but variable ϵ to the spectrum in Figure 3a (see *Lübken* [1997] for more details). We arrive at ϵ ∼19kW/kg which corresponds to a heating rate of approximately 1.6 million Kelvin per day. These are very unrealistic numbers which demonstrates that the small scale electron fluctuations must be enhanced relative to the neutrals, or, that the Schmidt number must be much larger than unity.

In order to determine Sc from the electron spectrum we derive ϵ from the neutral density fluctuations measured on downleg. (We note that there is a horizontal distance of ∼50km between upleg and downleg at ∼88km. However, the horizontal extent of the layer seems to be rather homogeneous since the electron biteouts and the small scale structure of the electron and aerosol densities are very similar on upleg and on downleg.) Indeed, the residuals shown in Figure 1 exhibit small scale fluctuations around 88 km indicating neutral air turbulence. A spectrum of the residuals at 87.9–89.1km is shown in Figure 3b. Applying the method described in *Lübken* [1997] we arrive at ϵ=67mW/kg.

We now assume that this ϵ value is also valid in the upleg part of the flight and deduce the Schmidt number from the electron spectrum in Figure 3a following the procedure presented in *Lübken et al.* [1994]. The main idea is to fit a Schmidt number dependent theoretical model to the electron spectrum by varying Sc and keeping ϵ constant (ϵ=67mW/kg from above). Applying this procedure to the PSD in Figure 3a gives a theoretical spectrum which nicely fits the observations. From the best fit model we get Sc=385 which is in excellent agreement with the microphysical result presented in the previous section.

What is the uncertainty of Sc caused by the fact that the ϵ value on the upleg may be different from that measured on downleg ? We have multiplied and divided ϵ by a factor of 2 and arrive at Sc=276 and Sc= 532 for the larger and smaller ϵ values, respectively. We conclude that the Schmidt number derived from the electron spectra is much larger than unity even if we anticipate the uncertainty in ϵ.

We note that small scale electron density fluctuations are present outside the main biteout regions, e.g., at 83.5, or just above 88km. These cases require special attention and will be dealt with in the near future. We also note that the neutral density fluctuations below ~87.5km are much smaller in magnitude compared to higher altitudes. Spectral analysis shows that no turbulence is present at these altitudes which confirms a conclusion presented earlier [*Lübken et al.*, 1993,], namely that there must exist mechanisms creating PMSEs which are not directly linked to neutral air turbulence.

Conclusion

We have analyzed in situ measurements of neutrals, electrons, and charged aerosols in the vicinity of PMSEs. The Schmidt number was deduced by two independent methods: First by the determination of the electron diffusivity from the microphysical properties of the aerosols, and second, by the comparison of the spectra of neutral and electron density fluctuations. Both methods give large Schmidt numbers (in fact the largest ever observed) which suggests that the enhancement of electron fluctuations observed at small scales is indeed caused by the low mobility of the charged aerosols. In this case neutral air turbulence in combination with negatively charged particles can account for the electron density fluctuations required to produce PMSEs.

Apart from this 'turbulent' case we have found strong aerosol enhancements, large electron depletions, and small scale plasma fluctuations at altitudes where no significant disturbance in the neutrals was observed. This indicates that there must exist other, non-turbulent physical processes to create PMSEs. Further observations are required to investigate the relative importance of these non-turbulent mechanisms and to select amongst the various theoretical speculations published in the literature.

Acknowledgments. We thank O. Havnes for providing the aerosol data, and W. Singer for the information regarding the PMSEs. The rocket flights were supported by the BMBF under DARA grant 01OE88027.

References

Bremer, J., P. Hoffmann, A. H. Manson, C. Meek, R. Rüster, and W. Singer, PMSE observations at three different frequencies in northern Europe during summer 1994, *Ann. Geophys.*, *14*, 1317–1327, 1996.

Cho, J. Y. N., and J. Röttger, An updated review of polar mesosphere summer echoes: Observation, theory, and their relationship to noctilucent clouds and subvisible aerosols, *J. Geophys. Res.*, *102*, 2001–2020, 1997.

Cho, J. Y. N., T. M. Hall, and M. C. Kelley, On the role of charged aerosols in polar mesosphere summer echoes, *J. Geophys. Res.*, *97*, 875–886, 1992.

Ecklund, W. L., and B. B. Balsley, Long-term observations of the Arctic mesosphere with the MST radar at Poker Flat, Alaska, *J. Geophys. Res.*, *86*, 7775–7780, 1981.

Havnes, O., J. Trøim, T. Blix, W. Mortensen, L. I. Næsheim, E. Thrane, and T. Tønnesen, First detection of charged dust particles in the Earth's mesosphere, *J. Geophys. Res.*, *101*, 10839–10847, 1996.

Jensen, E., and G. E. Thomas, Charging of mesospheric particles: Implications of electron density and particle coagulation, *J. Geophys. Res.*, *96*, 18,603–18,615, 1991.

Kelley, M. C., 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.

Lübken, F.-J., Seasonal variation of turbulent energy dissipation rates at high latitudes as determined by in situ measurements of neutral density fluctuations, *J. Geophys. Res.*, *102*, 13,441–13,456, 1997.

Lübken, F.-J., G. Lehmacher, T. Blix, U.-P. Hoppe, E. Thrane, J. Cho, and W. Swartz, First in-situ observations of neutral and plasma density fluctuations within a PMSE layer, *Geophys. Res. Lett.*, *20*, 2311–2314, 1993.

Lübken, F.-J., J. Giebeler, T. Blix, E. Thrane, W. Singer, and J. Bremer, In-situ measurement of the Schmidt number within a PMSE layer, *Geophys. Res. Lett.*, *21*, 1651–1654, 1994.

Ulwick, J. C., K. D. Baker, M. C. Kelley, B. B. Balsley, and W. L. Ecklund, Comparison of simultaneous MST radar and electron density probe measurements during STATE, *J. Geophys. Res.*, *93*, 6989–7000, 1988.

F.-J. Lübken and M. Rapp, Physikalisches Institut der Universität Bonn, Nussallee 12, D–53115 Bonn, Germany. e-mail: luebken@physik.uni-bonn.de

T. Blix and E. Thrane, Norwegian Defence Research Establishment, Division for Electronics, P. O. Box 25, N–2007 Kjeller, Norway.

(Received November 12, 1997; accepted January 23, 1998.)