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A combined rocket-borne and ground-based study of the sodium layer and charged dust in the upper mesosphere

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ABSTRACT

The Hotel Payload 2 rocket was launched on January 31st 2008 at 20.14 LT from the Andøya Rocket Range in northern Norway (69.31° N, 16.01° E). Measurements in the 75–105 km region of atomic O, negatively-charged dust, positive ions and electrons with a suite of instruments on the payload were complemented by lidar measurements of atomic Na and temperature from the nearby ALOMAR observatory. The payload passed within 2.58 km of the lidar at an altitude of 90 km. A series of coupled models is used to explore the observations, leading to two significant conclusions. First, the atomic Na layer *and* the vertical profiles of negatively-charged dust (assumed to be meteoric smoke particles), electrons and positive ions, can be modelled using a self-consistent meteoric input flux. Second, electronic structure calculations and Rice–Ramsperger–Kassel–Markus theory are used to show that even small Fe–Mg–silicates are able to attach electrons rapidly and form stable negatively-charged particles, compared with electron attachment to O_2 and O_3. This explains the substantial electron depletion between 80 and 90 km, where the presence of atomic O at concentrations in excess of 10^{10} cm^{-3} prevents the formation of stable negative ions.

1. Introduction

It was first suggested more than half a century ago that nano-particles form in the earth's upper atmosphere as a result of the ablation of meteoroids and the subsequent condensation of gas-phase metal oxide and silicate species (Rosinski and Snow, 1961; Hunten et al., 1980). Meteoric ablation is also the source of the layers of metal atoms – Na, Fe, Mg etc. – which occur globally between 80 and 105 km in the mesosphere/lower thermosphere (MLT) (Plane, 2003). Below about 85 km, these metals are converted to reservoir species – mainly hydroxides and carbonates – through reactions involving O_3, O_2, CO_2 and H_2O. Chemical ablation modelling indicates that similar quantities of iron, magnesium and silicon – the bulk constituents of chondritic meteoroids – are injected into the upper atmosphere (Vondrak et al., 2008). Laboratory experiments have shown that Fe and Mg oxides spontaneously polymerize with SiO_2 vapour to form nano-particles, principally of olivine composition ($Fe_{2-2x}Mg_{2x}SiO_4$, $0 \le x \le 1$) (Saunders and Plane, 2006, 2011). In the mesosphere the formation of these so-called meteoric smoke particles (MSPs) occurs over several days, and is presumed to lead to the permanent removal of these metallic compounds from the gas phase.

MSPs can be measured directly above 70 km by rocket-borne particle detectors (e.g. Gelinas et al., 2005; Lynch et al., 2005; Rapp et al., 2007; Robertson et al., 2013). These measurements indicate typical particle numbers of a few thousand per cm^{-3} above 75 km. However, the detectors measure only those particles that are charged, so that the total MSP concentration has to be obtained by dividing the measured number by the fraction of charged particles in the plasma, which has to be estimated from a dusty plasma model. Because the plasma density in the region between 70 and 100 km varies from ~100–20,000 cm^{-3}, roughly similar to the number density of MSPs, the modelled fraction of charged MSPs depends on a number of parameters which are poorly known, such as electron-particle attachment rates and electron photo-detachment rates (Rapp et al., 2007).

In order to improve this situation, a new type of particle detector has been flown recently which contains a pulsed VUV lamp to photo-detach electrons from negatively charged particles (Rapp et al., 2010, 2012). This has been followed by the flight of an electrostatic multichannel mass analyzer, which can measure

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several different mass ranges and both negatively- and positively-charged particles (Robertson et al., 2013). The MSP number density and size have also been estimated by analysing the backscatter signals from high performance-large aperture radars (Fentzke et al., 2009), although this is a less direct technique. In addition, the first optical detection of MSPs between ~40 and 80 km has now been reported, using the SOFIE spectrometer on the AIM satellite (Hervig et al., 2009). Observations at several wavelengths (near-UV to near-IR) have been used to infer that MSPs are composed of amorphous metal silicates.

In this paper we will describe and then model a selection of results from the Hotel Payload 2 (HotPay 2) project, which are relevant to understanding the neutral metal layers in the MLT, the formation of meteoric smoke, and the effect of MSPs on the plasma in the upper mesosphere. HotPay 2 was a complex sounding rocket project managed and supported by the Andøya Rocket Range, Norway. The payload carried instruments from nine scientific institutes in different European countries, and one instrument from the US. The launch was supported by ground-based lidar, radar and airglow measurements (Enell et al., 2011). Although the payload was designed to study a number of upper atmospheric phenomena, including auroral physics, particle precipitation and the cosmic ray flux, in this paper we will focus on the experiments designed to study the MLT region.

There are two linked questions that we will address. First, can the atomic Na layer and the MSP size distribution be accounted for self-consistently by the same meteoric input flux? Second, is the attachment rate of electrons to very small MSPs large enough to explain the substantial depletion of electrons relative to positive ions, which is always observed between about 80 and 90 km (e.g. Friedrich et al., 2011)?

2. The HotPay 2 campaign

The HotPay 2 rocket was launched on January 31st 2008 at 20.14 LT from the Andøya Rocket Range in northern Norway (69.31°N, 16.01°E). The scientific conditions for the launch were excellent: a clear night for the ground-based optical instruments, and a stable auroral arc to the north. The payload reached an altitude of 380 km (target 342 km). The Na lidar at the ALOMAR observatory on a mountain behind the rocket range was successfully aimed to intersect the planned payload trajectory in the MLT region: the lidar was only 2.58 km from the payload as it passed through 90 km. The rocket was launched when the Na layer was observed to be relatively unperturbed i.e., close to an average Gaussian profile centred around 90 km (Fig. 1), and there were quiet auroral conditions overhead. Further details concerning the payload, launch conditions and ancillary ground-based observations are described in Enell et al. (2011).

2.1. Airglow measurements

The vertical profile of atomic O was measured using an on-board O_2 Atmospheric band photometer. O atoms, which are mostly produced in the upper atmosphere through O_2 photolysis during the day, recombine to form molecular O_2 in a number of metastable states which can then emit radiation. One of the strongest emission features in the night sky spectrum is the Atmospheric Band system ($b^1\Sigma_g^+ \rightarrow X^3\Sigma_g^-$) dominated by the (0–0) and (0–1) bands at 762 nm and 864 nm, respectively. The 762 nm nightglow emission was measured on HotPay 2 using a standard filter photometer which was one of three comprising the Night-Time Emissions from the Mesosphere and Ionosphere (NEMI) instrument on the top deck of the payload (Enell et al., 2011).

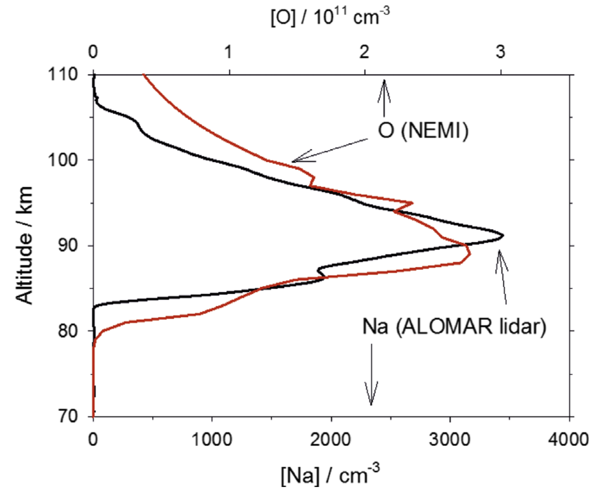

Fig. 1. Comparison of the atomic O profile measured by the NEMI instrument on HotPay 2, with the Na density measured by the ground-based ALOMAR Na lidar between 20:00 and 20:09 LT, immediately before the launch at 20:14 LT.

The resulting profile was then numerically differentiated to yield the volume emission rate of the emitting layer, which was converted into the absolute atomic O concentration using the formalism developed from the ETON (Energy Transfer in the Oxygen Nightglow) rocket campaign in 1982 (Greer et al., 1986). In that study the atomic oxygen density and O_2 Atmospheric band airglow intensity were measured simultaneously, from which a consistent set of reaction rates describing the O_2 nightglow excitation processes and quenching mechanisms could be derived (Murtagh, 1989; Hedin et al., 2009). Further details of the instrument and analysis procedure are described elsewhere (Enell et al., 2011). The derived O concentration density profile is shown in Fig. 1.

2.2. Plasma measurements

The payload carried two separate instruments for the determination of plasma constituent densities: a three-frequency radio wave propagation experiment to obtain electron densities by the Faraday rotation technique, and a gridded electrostatic probe to measure positive ions (Enell et al., 2011; Friedrich et al., 2012). The wave propagation experiment consisted of ground-based transmitters for each frequency (2.20, 3.88 and 15.01 MHz) radiating linearly polarised waves to the rocket payload. The payload carried receivers for these frequencies fed from a common linearly polarised antenna. For reasons of flight stability, HotPay 2 had a spin-rate of 3.3 rps, which also rotated the antenna. With this configuration the received signals have two maxima and two minima each spin period, i.e. whenever the antenna was parallel and perpendicular, respectively, to the transmitting antenna on the ground. In the presence of a magnetic field the electron density content between transmitter and receiver leads to a rotation of the polarisation i.e. Faraday rotation. This rotation (phase against an aspect sensor) is the raw data from which electron content and, in consequence, electron density is derived. The height resolution is limited by the rocket spin with which the wave polarisation is scanned, but the measurements are completely immune to payload charging or aerodynamic effects. This method is described e.g. by Bennett et al. (1972), and the choice of sounding frequencies was addressed by Jacobsen and Friedrich (1979).

The ion probe consisted of a gridded sphere at plasma/payload potential with a negatively biased collector inside. Such an arrangement measures a current primarily determined by the