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In situ mass spectrometry during the Lutetia flyby

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ABSTRACT

During the Rosetta flyby at asteroid Lutetia the ROSINA instrument tried to detect a thin exosphere of the asteroid. Although the instrument is sensitive enough to detect even very tenuous gases at a density level of $1\ \mathrm{cm}^{-3}$ the Lutetia exosphere could not be unambiguously detected due to spacecraft outgassing, which was not constant because of the changing solar aspect angle. An upper limit for a water exosphere density at the flyby distance of 3160 km of $(3.5\pm 1.0)\times 10^{3}\ \mathrm{cm}^{-3}$ was deduced from the measurements.

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1. Introduction

Prior to the Rosetta flyby the asteroid (21) Lutetia was hard to classify, sometimes being named as M-type asteroid (e.g. Barucci et al., 1987) because of its quite high density and flat IR spectrum, sometimes being called as C-type asteroid (e.g. Barucci et al., 2005) or even an X-type asteroid. A recent analysis of Lutetia spectra before the flyby suggests that metal-rich carbonaceous chondrites seem to be the most plausible analog materials (Lazzarin et al., 2009). Because of their relatively small size, asteroids are not able to retain an atmosphere. Unlike comets their outgassing rate is also very less for most asteroids. Therefore, solar wind sputtering is the most important exospheric supply process on the sunlit side of an asteroid. In this case the most abundant species in the asteroidal exosphere are the most abundant refractory elements in the surface regolith. An exosphere dominated by solar wind sputtering was simulated for the two flyby targets of Rosetta by Schläppi et al. (2008). Carbonaceous chondrites can contain several percent of water (Mason, 1962). For the case that (21) Lutetia is indeed a C-type asteroid, thermal release of water could also play an important role. In the case of a solar wind sputtering dominated exosphere the most promising species to detect with in situ mass spectrometry would be oxygen, since it is the most abundant element in many of the expected minerals. In the case of thermal release one could expect to detect a very thin water exosphere (Schläppi et al., 2008).

The ROSINA instrument on Rosetta with its two mass spectrometers DFMS (Double Focusing Mass Spectrometer) and RTOF (Reflectron type Time of Flight mass spectrometer) and the pressure sensor COPS (Comet Pressure Sensor) has the necessary sensitivity to detect even very tenuous atmospheres (Balsiger et al., 2007). DFMS in low resolution mode (mass resolution $m/\Delta m = 500$) easily detects neutral densities down to $1\ \mathrm{cm}^{-3}$ in less than 20 s measurement time per mass line. The drawback of this sensor is that it measures only one mass at a time and has to step through the mass range by switching the ion acceleration voltage. Therefore this measurement is slow, and it takes about 20 min to measure a full mass spectrum from 12 to 150 amu/e. This is of minor consequence for measurements of the comet, but for a fast asteroid flyby it is mandatory to limit its mass range to just one or two integer masses. The field of view is $20^{\circ}\times 20^{\circ}$ aligned with the spacecraft z-axis (Fig. 1). The pressure sensor COPS has a lower detection limit of $10^{5}\ \mathrm{cm}^{-3}$ with a field of view of almost 4π. The third sensor, RTOF has a higher sensitivity to detect species with a density of $100\ \mathrm{cm}^{-3}$

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during its 200 s integration time and always measures over the full mass range from 1 amu to ~300 amu. The field of view is $10^\circ \times 40^\circ$ aligned with the spacecraft z-axis (Fig. 1). It is therefore well suited to look for the faint signals of a possible asteroid exosphere during a flyby. However, this sensor was operated only for a very limited time prior to the Lutetia flyby due to partial discharges in its high voltage electronics resulting from internal outgassing. Only 2 months before the Lutetia flyby RTOF became operational again, using a new way of operating the sensor. At the time of the flyby the RTOF sensor parameters were by far not yet optimized leading to a decreased mass resolution and sensitivity. In addition, due to the RTOF problems the time span with all three ROSINA sensors operating simultaneously was very short leading to operational problems during the Lutetia flyby (see below).

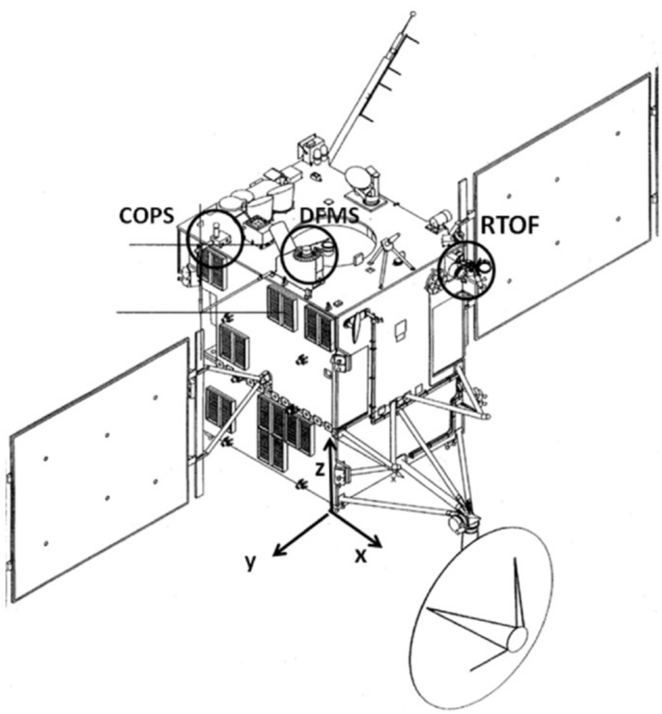

Fig. 1. Rosetta spacecraft with the three ROSINA sensors (COPS, DFMS, and RTOF). The +z-panel (the instrument panel) is on top in this picture. DFMS and RTOF field of views are co-aligned with the field of view of the cameras.

2. Spacecraft outgassing

There are two facts that complicate the measurements during the Lutetia flyby. The bore sights of the field of view DFMS and RTOF are co-aligned with the OSIRIS camera and with the navigation cameras. Due to the fixed mounting of the cameras Rosetta had to slew during the flyby, thus turning the field of view of the two mass spectrometers from the initial ram direction to a direction perpendicular to the Rosetta velocity vector at closest approach and then to an anti-ram direction for the time after a closest approach in which case no gas from the asteroid can enter the mass spectrometers. Any asteroid exosphere signal therefore has to be detected before closest approach.

Furthermore, both mass spectrometers and the pressure sensor were detected during the Rosetta cruise phase that the spacecraft is still outgassing after 6 years in space with a total neutral density in the vicinity of the spacecraft around $10^5\ cm^{-3}$. The contaminants represent the spacecraft composition with water being the dominant molecule (Schläppi et al., 2010). This background is not constant with time but depends strongly on the solar aspect angle. It changes by several orders of magnitude during flips and slews of the spacecraft, and also upon payload and subsystem operation.

During the Steins flyby it was decided to measure the oxygen density as being the most promising candidate species for detection of an exosphere (Schläppi et al., 2008). Due to flip and slew during the flyby the solar aspect angle changed quite rapidly exposing shadowed parts of the spacecraft to the Sun (Fig. 2). The total particle density measured by COPS changed by several orders of magnitude while the DFMS oxygen countrate changed only by approximately a factor of 6. COPS measurements reacted strongly to the flip around the spacecraft z-axis by 180° (see Fig. 2, arrow 1); the response of DFMS was delayed relative to the start of the flip by almost 20 min. This is most probably due to the different fields of view. Both sensors did not reach the background pressure before the spacecraft started

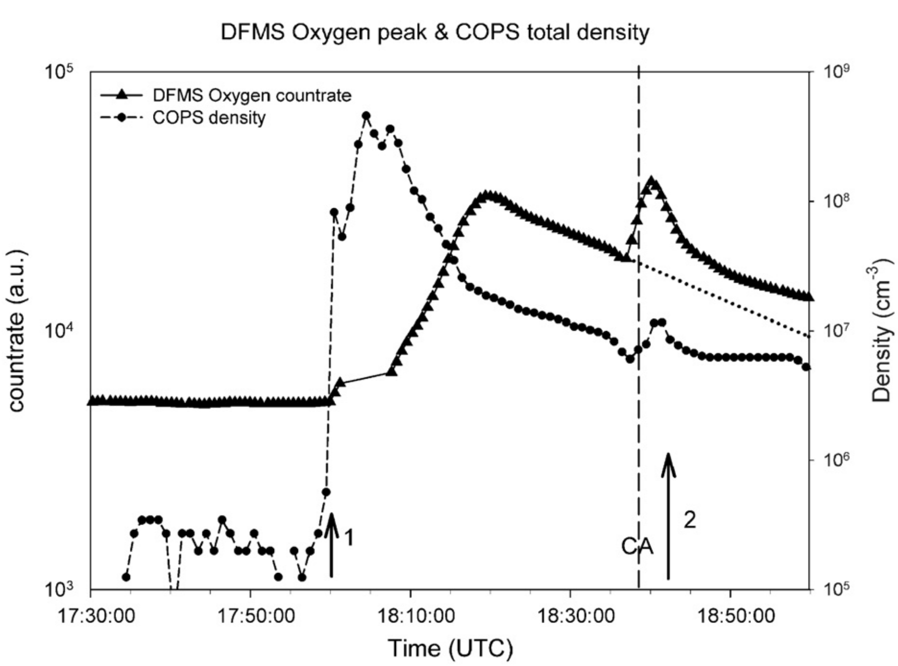

Fig. 2. Data from the asteroid Steins flyby. Total density measured by COPS and Oxygen countrate measured by DFMS are shown.

to slew during the asteroid flyby. The large outgassing signal during the flip is due to the exposure of the $-x$ panel to the Sun. This panel, with the Philae lander of Rosetta, is normally in shadow and very cold, which leads to a large reservoir of water.

During the slew around the y-axis both sensors showed a pronounced peak (Fig. 2, arrow 2) just after closest approach of Steins. This peak cannot be easily understood but has to be due to a relatively narrow cavity on the spacecraft, which is normally also shadowed and only exposed to sunlight for very distinct solar aspect angles. The fact that the peak appears almost simultaneously for COPS and DFMS points to a location for outgassing on the $+z$ panel.

All peaks were attributed to additional spacecraft outgassing and not to an asteroid exosphere. The same effects were observed later in the mission at different times during spacecraft slews (Schläppi et al., 2010).

It was therefore clear that for the Lutetia flyby special measures had to be taken to improve the chances to observe an asteroid exosphere. It was decided to perform the necessary spacecraft flip around the z-axis as early as possible to allow the background pressure to drop to its original level before the actual flyby. Due to thermal reasons it could not be performed earlier than 4 h before the time t_0 of the "closest approach". The spacecraft performed a Lutetia rehearsal in March 2010; that is all flips and slews were performed exactly as during the Lutetia flyby but without Lutetia present. The heliocentric distance was 1.7 AU compared to 2.5 AU for the Lutetia flyby. At this time RTOF was not yet operational. However, DFMS measured mass 18 amu/e (water) and COPS measured the total pressure (Fig. 3).

The result of this rehearsal can be seen in Fig. 3. Again there was a big pressure increase observed by COPS during the spacecraft flip

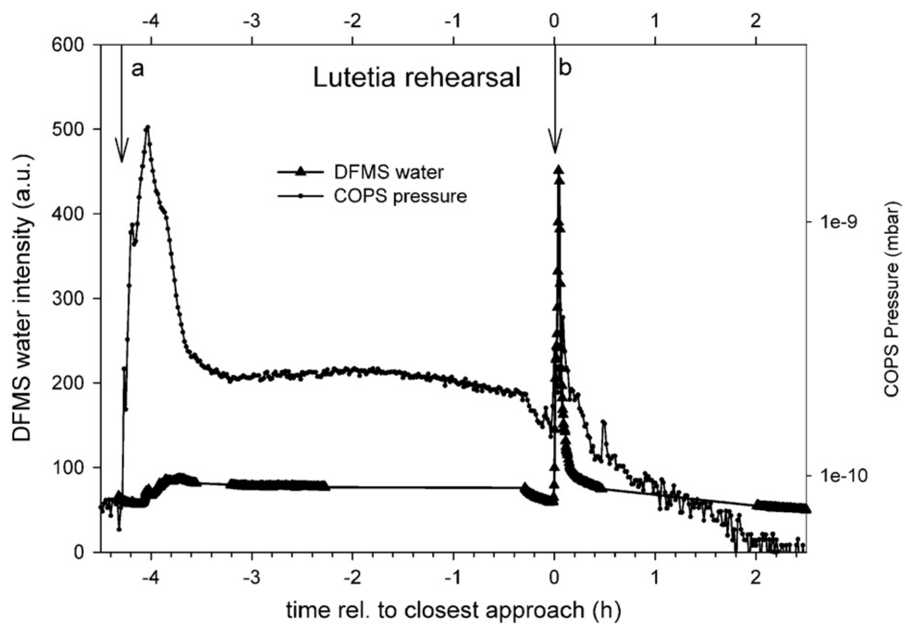

Fig. 3. Water intensity recorded by DFMS and pressure, recorded by COPS during the Lutetia rehearsal. (a) Denotes the start of the spacecraft flip around its Z-axis, (b) denotes the time of the "closest approach" with the spacecraft Z-axis perpendicular to its velocity vector.

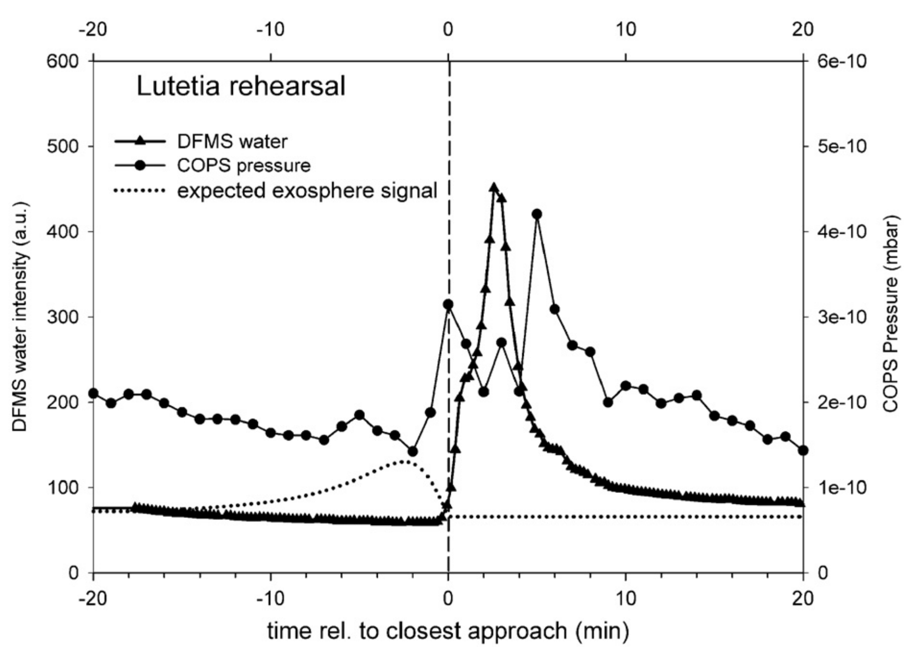

Fig. 4. Lutetia rehearsal from −20 to +20 min around "closest approach" t_0. The dotted line represents the shape of a theoretical exosphere signal expected for the Lutetia flyby.

around the z-axis (arrow a). The 4 h of the spacecraft flip preceding the closest approach were insufficient to reach the background pressure for COPS as well as for DFMS. At and after the time t_0 of the "closest approach" (arrow b) there was again a large peak as a result of the spacecraft slew around the y-axis. Fig. 4 shows a narrow time range around the CA of Fig. 3. The peaks were seen within 2 min by both instruments; however, the shapes of the peaks are not identical. Again this is most probably connected to the location(s) of outgassing and the different field of views of the two sensors. It is clearly seen that before t_0 DFMS exhibited no signal increase at all, while COPS showed a small peak 5 min prior to t_0. Also plotted in a theoretical curve for an exosphere signal to be measured by DFMS had the asteroid been present. As the closest approach was planned to be 3160 km from the asteroid the shape of this curve is given by the density n at large distance of the asteroid ($n \sim 1/r^2$, with r being the distance between asteroid and spacecraft) and by the angle α between the bore sight of the sensor and the ram direction, which changed due to the slew of the spacecraft near CA:

$$n = n_0/r^2 \cos\alpha$$

Here the angle α is between the spacecraft velocity vector and spacecraft z-axis. Because COPS has a FOV of about 4π, an asteroid exosphere signal recorded by COPS would be symmetrical around t_0. Because DFMS did not find any peaks prior to t_0 and COPS detected only a small peak at a different location than a hypothetical exosphere it could be assumed that during the real flyby any peak around 2 min before closest approach in DFMS could be attributed to an asteroid exosphere.

3. Lutetia flyby

From the measurements during the rehearsal it was clear that it would be difficult, but not impossible to detect an exosphere at Lutetia. Due to the rather large flyby velocity of 15 km/s it could be expected that the measured exosphere density would be enhanced by a factor 50 due to the ram pressure (Wurz et al., 2007) and therefore exosphere densities around 10^3 cm^{-3} should yield a signal larger than the spacecraft background.

All three sensors were put into measurement modes approximately 10 h before the Lutetia flyby. DFMS was mainly measuring mass 18 with an integration time of 10 s, whereas RTOF measured over the full mass range with an integration time of 200 s. Just at the start of the spacecraft flip RTOF was switched off by the ROSINA data processing unit (DPU) due to a problem in the data transfer. Two hours later the DPU experienced a reset, which caused an inverted status of the three sensors. RTOF was switched on while DFMS and COPS were switched off. All anomalies were due to a memory management problem. The time to closest approach did not allow for commanding the sensors again into their nominal modes. DFMS and COPS remained off, while RTOF measured flawlessly throughout the flyby. The data for the full measurement period can be seen in Fig. 5. Because RTOF was not operated before the Lutetia flyby for more than 2 months, the ion source first had to warm up and outgass, which explains the continuous decrease of the water signal until the spacecraft flip (Fig. 5, arrow a). With the start of the flip the total density measured by COPS increased by two orders of magnitude as seen during the rehearsal (see Fig. 3); the water density of DFMS also showed some increase but only by about 10%. This is due to the different fields of view. RTOF was switched off at that time. After the reset of the DPU, RTOF was switched on again and its ion source had to warm up again releasing a decreasing amount of water as before (arrow b). The two other sensors, COPS and DFMS, were switched off. The dashed line in Fig. 5, left panel, indicates our estimation of the time-dependent water background, which was established using the available DFMS water measurements. Together with the COPS measurements of the total density, where water is a major contributor, it allowed for preliminary in-flight calibration of the RTOF data. Since the RTOF operation has been changed significantly from the pre-launch time this in-flight calibration became necessary.

There is again a clear density peak just after closest approach (CA) as seen before during the Lutetia rehearsal and the Steins

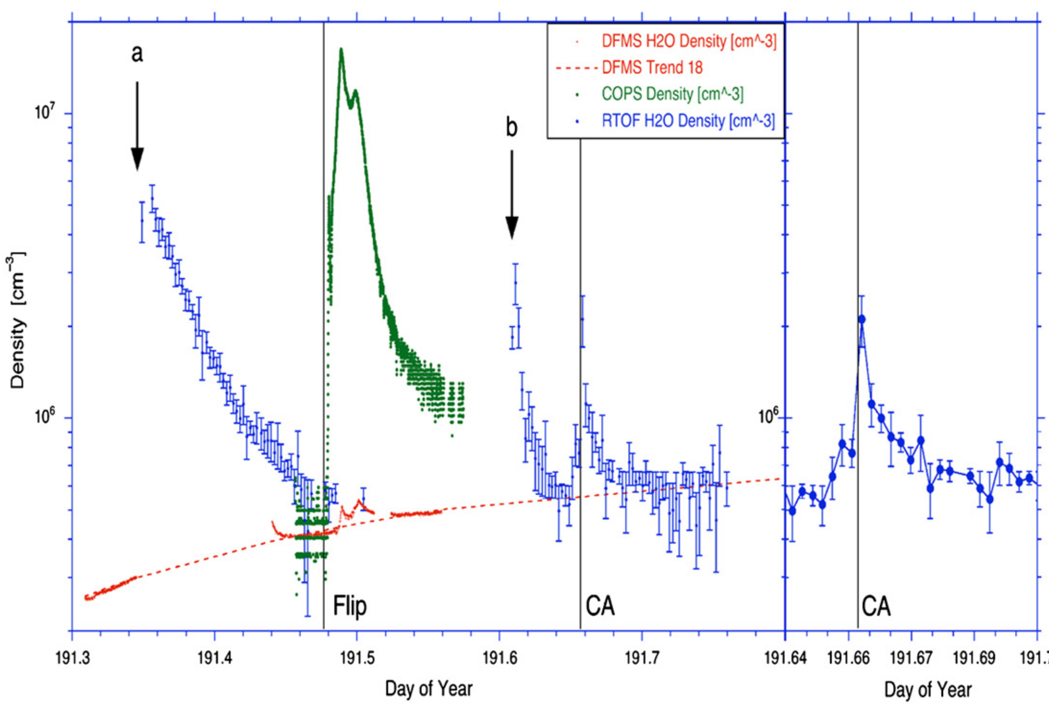

Fig. 5. ROSINA data recorded during the Lutetia flyby from all three ROSINA sensors; whole data set in left panel, detail during CA in the right panel. (a) Switch-on of RTOF and subsequent ion source outgassing; flip: spacecraft flip around the z-axis, (b) Switch-on of RTOF after DPU reset; CA: closest approach.

flyby, which results from the solar illumination of spacecraft areas that have been in shadow before. The signal from Lutetia's exosphere is expected shortly before CA, as shown in Fig. 4. Indeed, a water signal ($m/z=18$ amu) of the expected shape is observed during the Lutetia flyby, as can been seen in Fig. 5, right panel, with a measured water density of $n_0=(1.8\pm0.5)\times10^5$ cm^{-3}.

Fig. 6 shows the uncalibrated data for several mass lines of interest near closest approach. As discussed above most of the signals recorded in the mass spectra can be attributed to spacecraft outgassing. For example $m/z=1$ and 2 (H and H_2) are fragments from hydrocarbons and water (see Figure 1 and discussion in Schläppi et al., 2010). H_2 shows a small peak at closest approach corresponding to the water peak observed at that time. Other mass lines of interest in the search of an exospheric signal of Lutetia are $m/z=16$ (CH_4, but with contributions from O from fragmented H_2O), $m/z=28$ (CO and N_2), and $m/z=44$ (CO_2). Contributions of hydrocarbons to these mass lines are same. Another mass line of interest is $m/z=4$, solar wind helium implanted into Lutetia's regolith, and subsequently being released thermally. All these mass lines do not show any indication of a signal at the expected position of the exospheric signal. These signals are basically constant with time indication of a stable gaseous background originating from the spacecraft, as discussed earlier (Schläppi et al., 2010) with the only exception of CO_2, which shows a little peak at CA, coinciding with the water peak. This may be interpreted by having not only frozen water on spacecraft panels, particularly the lander unit, being in shadow for a long time, but also a small amount of frozen CO_2.

In summary, the only signal that shows a possible signature of Lutetia's exosphere is the water line ($m/z=18$). However, given the many ways of the release of such small amounts of water we have to consider this signal as an upper limit, since a source on the spacecraft cannot be ruled out. RTOF measurements performed during a similar maneuver after the Lutetia flyby support this conclusion.

In the following we will interpret the measured water density of $n_0=(1.8\times0.5)\times10^5$ cm^{-3} assuming it has its origin in the exosphere of Lutetia. After correcting for the ram pressure enhancement we deduce a H_2O density of $(3.5\pm1.0)\times10^3$ cm^{-3} at closest approach, i.e. at a distance of 3160 km from Lutetia. From the asteroid exosphere model (Schläppi et al., 2008; Wurz and Lammer, 2003) we deduce an exospheric water density at Lutetia's surface of $(1.7\pm0.5)\times10^7$ cm^{-3} (see Fig. 7). From this calculation we derive the column density of the water is $(8.4\pm2.5)\times10^{13}$ cm^{-2} and the tangential column density at the distance of the CA of $(1.4\pm0.4)\times10^{12}$ cm^{-2}. Assuming the release of water is by sublimation from an ice fraction on the surface of Lutetia, we deduce a water ice abundance on Lutetia's surface of $(1.0\pm0.5)\times10^{-7}$. For this calculation we used a simplified temperature map ($T(\varphi,\theta)=T_{night}+(T_{sub\text{-}sol}-T_{night})(\cos\varphi\cos\theta)^{1/4}$ with φ the longitude and θ the latitude) of the sun-lit surface, and the water sublimation rates as compiled recently by Grigorieva et al. (2007). Considering loss from the exosphere by Jeans escape and by photo-ionization, we deduce a total water outgassing rate from Lutetia of $(3.2\pm1.6)\cdot10^{25}$ molecules/s. This outgasing rate corresponds to a mass loss of 1.0 ± 0.5 kg/s. Again, all these values have to be considered as upper limits.

The water exosphere could also have its origin in hydrated minerals and hydrosilicates being present on the surface and become decomposed by ultra-violet radiation and solar wind ion irradiation. However, VIRTIS infra-red spectral measurements of the surface performed during the Lutetia flyby showed no signal of such minerals (Tosi et al., 2012). A water ice fraction of $(1.0\pm0.5)\times10^{-7}$ on the surface of Lutetia represents the end

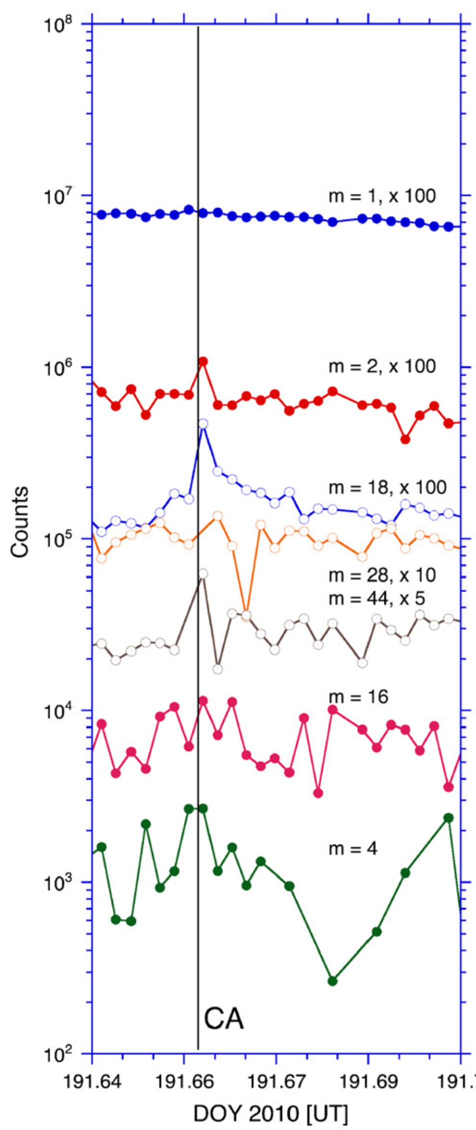

Fig. 6. Temporal evolution of selected mass lines near the CA from ROSINA/RTOF.

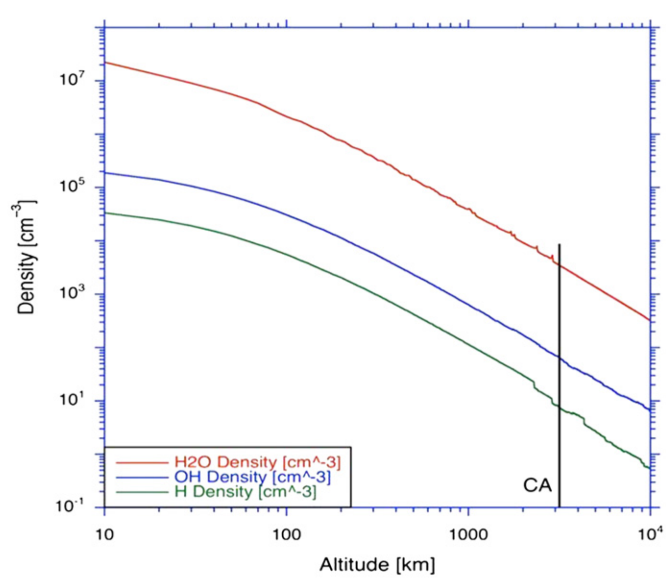

Fig. 7. Calculated exospheric profiles for water released thermally from the surface via sublimation. Also the fragments O and OH resulting from photo-fragmentation by solar UV light are shown. Calculation is for the sub-solar point.

point of the water depletion from the inside unperturbed reservoir of water ice to the surface. Depending on thermal profile of the regolith and thickness of the regolith the inside water fraction will be substantially larger than on the surface. Such water fractions are compatible with a carbonaceous chondrite body, which can have water to a level of 20% (Mason, 1962). Schorghofer (2008) has shown that water ice can indeed survive several billion years in 2–3 AU from the Sun as long as the thermal inertia is very low. Data from Herschel (O'Rourke et al., 2012) show that Lutetia has an extremely low inertia of only 5 $\mathrm{J m^{-2} s^{-0.5} K^{-1}}$.

4. Conclusions

ROSINA measurements performed during the cruise phase and during maneuvers performed before the flyby demonstrated that spacecraft outgassing is a severe limitation to measurements of exospheric gases at the level of 10^{-11} mbar (i.e. densities at the level of 10^5 $\mathrm{cm^{-3}}$), as discussed in detail by Schläppi et al. (2010). The measurements during the flyby showed many of the spacecraft outgassing signals associated with changes in the attitude of the spacecraft. In addition, a small water signature at the right time and of the correct shape is observed shortly before the CA. Despite having the proper features of the expected exosphere signal we cannot rule out a spacecraft origin of this signal and thus have to regard the derived water density of $n_{exo}(3160\ \mathrm{km})=(3.5\pm1.0)\times 10^3\ \mathrm{cm^{-3}}$ of Lutetia's exosphere at the location of the spacecraft at CA as an upper limit.

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