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A B S T R A C T

On 10th July 2010 the Rosetta spacecraft passed within 3160 km of asteroid 21 Lutetia during which seven instruments attempted to detect an exosphere. A comparison of the sensitivity is made between the different instruments based on a simple spherical out-gassing point source model, which was used to infer that the Lutetia exosphere production rate was determined by MIRO to be < 4.3 × 10²³ molecules s⁻¹ for water and by ROSINA RTOF to be < 1.7 × 10²⁵ molecules s⁻¹ for carbon monoxide. Consideration of the flyby geometry and combined instrument operations places further constraints on the exosphere structure and gas production rate. Experience gained during the flyby will prove invaluable for operations planning during Rosetta’s approach and orbit of comet 67P/Churyumov–Gerasimenko in 2014.

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1. Introduction

Asteroids and comets have traditionally been considered as two separate and distinct classes of minor bodies: the asteroids, mostly residing within the main belt (2.0–3.2 AU), being volatile-depleted and showing no insolation-related activity, and the comets, volatile-rich bodies showing the effects of their transient proximity to the Sun often resulting in the generation of stunning sublimation-driven comae and tails. However, the traditional view of a clear distinction between comets and asteroids has become blurred, starting with the discovery of a coma around asteroid 7968 Elst-Pizarro (Hsieh et al., 2004). Subsequent observations have shown that this body exhibits comet-like behaviour, with periodic out-gassing during perihelion leading to the dual classification 113P/Elst-Pizarro (Hsieh et al., 2010). Further searches have found other asteroids showing out-gassing, leading to their classification as Main Belt Comets (Hsieh and Jewitt, 2006), with their activity attributed to collisions exposing buried volatiles. Evidence for the spectacular results of impacts in the main belt was obtained for a body discovered in 2010 (P/2010 A2). Although originally classified as a comet, on account of it having a tail, it looks increasingly likely that it is, in fact, an asteroid, the tail being the consequence of the recent impact (Jewitt et al., 2010; Snodgrass et al., 2010).

Near-infrared observations indicate that many asteroids (including Lutetia) exhibit adsorption features in the 3 μm region indicative of hydrated mineral (Rivkin et al., 1995, 2000). Further evidence that asteroids are not volatile-poor bodies has been provided by near-infrared observations of 24 Themis (Campins et al., 2010; Rivkin and Emery, 2010) and 65 Cybele (Landsman et al., 2010). The 3.1 μm feature is consistent with water ice being widespread over the surface of the asteroid. Other features in the spectra were best explained by the presence of organics rather than hydrated minerals. In this case, out-gassed species would be expected to have a similar composition to cometary comae. In addition, theoretical modelling (Schorghofer, 2008) has shown
that water ice can exist buried within the top few metres of an asteroid over the lifetime of the Solar System. Ice could then be exposed either by impact events or by micrometeorite impact gardening, similar to those on the Moon.

With so much emerging ambiguity about the exact nature of the minor bodies of the Solar System and their relationships, the Rosetta flyby of Lutetia in July 2010 seemed to offer an excellent opportunity to search for evidence of an asteroidal exosphere (especially since Lutetia is a relatively large asteroid). Prior to the encounter, modelling of Lutetia as a volatile-poor, “airless” body, like Mercury or the Moon, indicated that any exosphere would consist mostly of thermally released solar wind species, giving particle densities at the flyby distance (approximately 3000 km) of about $10^3$ m$^{-3}$ for hydrogen, $10^4$ m$^{-3}$ for helium and a molecular density of $10^7$ m$^{-3}$ for H$_2$O (Schläpfi et al., 2008). Other processes, such as solar wind ion sputtering and photon stimulated desorption, were thought likely to impart, respectively, refractory elements and sodium at levels of $\sim 10^3$ m$^{-3}$ in each case. So these represented a baseline view of what might be detectable. But this was against the backdrop of a rather traditional view of asteroids and there was in any case another intriguing uncertainty involving the spectral type of the body, which had been rather ambiguously assigned as either M- or C-type. An M-type (metallic) asteroid would be expected to show little out-gassing. However a C-type (carbonaceous) could have much larger out-gassing from water in hydrated minerals and buried ice. Furthermore the oblique spin axis determined by observations prior to the Rosetta encounter (Carr et al., 2010) meant that parts of the asteroid could experience larger solar heating at the sunward facing pole than normally expected.

The Rosetta spacecraft is designed to measure the physical and chemical compositions of comet 67P/Churyumov–Gerasimenko and its coma as it travels towards perihelion. Two of the main science themes are determining physical properties and chemical composition of the coma (e.g. Wirth et al., 2009). As a result, many of the instruments are designed to operate within and measure the relatively high pressure of the coma. However, from the outset, another science goal of the Rosetta mission was to carry out observations during the flyby of two separate asteroids (Glassmeier et al., 2007, 2009a). Within this theme was an opportunity to study the asteroid environment during the flyby. Although any exosphere was expected to be of very low density there are several reasons why this might be enhanced:

(i) water could be preserved for Solar System time-scales if Lutetia was a C-type asteroid as ice buried beneath the surface;

(ii) for the number of months preceding the encounter the North polar axis of Lutetia was pointing towards the Sun, providing enhanced insolation of the pole;

(iii) a recent impact event might have the capacity to cause out-gassing over a time-scale of thousands of years;

(iv) on the basis of recent observations/modelling there should no longer be any a priori reason to expect an asteroidal exosphere to conform to the notion of some kind of homogeneous, spherical shell of material;

(v) Astroidal out-gassing phenomena may include directional jets.

In addition to the scientific return, the flyby manoeuvre was an opportunity to rehearse co-ordinated instrument activities similar to those that are expected to be carried out at the comet. The various instrument requests and incompatibilities were co-ordinated into the pre-planned timeline. During the flyby the one-way light time of 20 min was similar to that expected at comet encounter, and so all sequences were operated autonomously.

2. Rosetta exosphere campaign

The Rosetta spacecraft has 7 instruments capable of detecting an exosphere: three mass spectrometers, ROSINA (on the Orbiter), Ptolemy and COSAC (both on the Philae Lander); a suite of plasma instruments, RPC (on the Orbiter) and ROMAP (on Philae); and two instruments on the Orbiter, namely Alice, an ultraviolet imaging spectrometer, and MIRO, a microwave instrument. In principle, it would have been highly desirable to have had all of the requisite instruments operating continuously during the flyby. Indeed, during the flyby, as opposed to on-comet investigations, there would have been adequate power resources to allow this. But, nevertheless there were issues. Firstly, the overriding criterion for success during this part of the mission was that the spacecraft flyby at a distance of 3160 km, allowing accurate tracking of the asteroid during Close Approach for imaging reasons (Barucci and Fulchignoni, 2009). Secondly, most instruments desired to be pointing towards the asteroid. Furthermore, it was already known that operation of certain instruments caused interferences for others, so a schedule had to be devised that took account of this. Of particular concern was the effect of interference from the Lander instruments on the RPC instruments because of a current loop between the Lander umbilical and the spacecraft. This can be compensated by simultaneous measurements by ROMAP on the Lander as long as currents used by Lander instruments are well characterised and are constant. However both Ptolemy and COSAC mass spectrometers have high frequency power fluctuations during measurements. Since RPC measurements were considered to be more critical during the flyby it was decided to ensure that Lander current use was constant at least for 12 min on either side of Close Approach (CA).

ROSINA measurements during the Steins flyby (Jäckel et al., 2009) and subsequent analysis of spacecraft out-gassing (Schläpfi et al., 2010) indicate that the limit of detection for ROSINA was the spacecraft out-gassing and not the instrument sensitivity. Tests performed earlier during the Cruise Phase had shown that ROSINA could detect an increase in pressure when instruments were switched on and with changes of spacecraft orientation with respect to the Sun. These out-gassing events had a duration of about 1 h. An ideal encounter scenario for the mass spectrometer instruments was to have all other instruments switched off and no changes in spacecraft orientation for about 2 h on either side of CA, clearly incompatible with remote sensing instrument requests to be operating and pointing towards Lutetia. Instrument effects were minimised by having all instruments switched on for at least 4 h before CA so that their effects were at a minimum and constant. Instrument operations during the Lutetia flyby are shown in Fig. 1.

Spacecraft out-gassing was minimised by suitable planning and operation of the spacecraft during the flyby (i.e. CA $\pm 4$ h). The autonomous use of reaction thrusters, a known source of contamination (Graf et al., 2008), was disabled over a month before Lutetia encounter, spacecraft orientation being achieved by the reaction wheels. The final use of the reaction thrusters was a manual offloading of the reaction wheels at about CA $\pm 36$ h. A schematic diagram of the spacecraft is shown in Fig. 2, with most instruments mounted on the $+Z$ panel. For the flyby the spacecraft was orientated so that the $+Z$-axis always pointed towards the asteroid and the $Y$-axis was perpendicular to the solar illumination with tracking of the asteroid achieved by rotation through the $Y$-axis as shown in Fig. 3. In this way the $+Y$-panels of the spacecraft were not illuminated throughout the flyby. Up to
the sub-solar point the $-Z$-panel receives almost constant illumination with the $+X$-panel receiving a small and gradually decreasing insolation. After the sub-solar point the $-X$-panel (on which the Lander is attached) began to become illuminated, reaching a maximum at CA, whereupon the $+Z$-panel started to become illuminated. Thus out-gassing was expected to increase and reach a maximum around CA.

The spacecraft orientation resulted in the Lander being exposed to direct solar illumination for an extended period of time before CA. Since the Lander was designed to operate at 3.0 AU within the dusty environment of a comet it is insulated to such an extent that modelling showed that even at the distance of 2.7 AU it could exceed its maximum operating temperature. During the long-distance observations of Lutetia, prior to CA $-4$ h, the spacecraft was periodically pointed away from Lutetia such that the Lander was in shadow (as in normal flight operations), to prevent overheating. The periods when the Lander was illuminated also helped to remove condensed surface volatiles accumulated during the Cruise Phase when the Lander was permanently in shadow. During the encounter the Lander power was kept to a minimum and the Lander was switched off at CA $+1$ h.

The instruments on Rosetta are broadly split into two classes: the remote sensing instruments (Alice and MIRO) and the in-situ instruments (RPC, ROSINA, Ptolemy and COSAC). In general the remote sensing instruments are tuned to detect specific molecules and measure the column density of the target molecules to derive a global out-gassing rate for the asteroid, whereas the in-situ instruments measure the density (often converted to pressure) of the exosphere at the spacecraft location and are more sensitive to local variations in the exosphere structure. The mass spectrometers can also measure the composition giving the possibility of distinguishing between different sources such as sublimation, micrometeorite sputtering and spacecraft effects.

The high flyby speed of 15 km s$^{-1}$ of Rosetta during the Lutetia flyby has a major advantage in that any detection would be for a very short time near CA with the high speed creating a pressure ram effect on the forward face of the spacecraft and enhancing the sensitivity for the mass spectrometer and pressure sensing instruments ROSINA, Ptolemy and COSAC (Wurz et al., 2007). The average molecular speed is given as $v=(8 k_B T/\pi m)^{0.5}$ (Delchar, 1993), where $T$ is the temperature, $m$ is the mass of the molecule and $k_B$ is the Boltzmann constant ($1.38 \times 10^{-23}$ J K$^{-1}$). At a temperature of 240 K water has an average speed of approximately 530 m s$^{-1}$, so giving an effective pressure increase during the asteroid approach of $(v_s \cos \alpha + 0.53)/0.53$, where $v_s$ is the spacecraft velocity and $\alpha$ is the spacecraft $Z$-axis phase angle. The effective pressure increase for small values of $\alpha$ would be about
30; this is even further enhanced for heavier, although probably less abundant, molecules.

Details of the types of instrument and their capabilities for detecting and analysing the exosphere are briefly described in the sub-sections below. A summary of each instrument’s capabilities of detection limit is shown in Table 1.

2.1. Mass spectrometers and pressure sensor

There are a total of four mass spectrometers: two on the orbiter as part of the ROSINA instrument (a Double-Focussing Mass Spectrometer (DFMS), and the Rosetta Time-Of-Flight mass spectrometer (RTOF;) Balsiger et al., 2009) and two on the Philae lander; COSAC (Goesmann et al., 2009) and Ptolemy (Morse et al., 2009). The ROSINA instrument includes a pressure sensor (the Comet Pressure Sensor (COPS)). All these instruments measure the gas pressure in-situ with the mass spectrometers measuring gas composition. Both of the orbiter mass spectrometers point along the +Z axis and gain from the ram effect. The two Lander instruments are designed to measure comet solid samples by GC–MS; however in the absence of helium carrier gas they operate in “sniff mode”, monitoring the external environment via helium vent pipes. An overview of the mass spectrometer capabilities is shown in Table 1.

ROSINA operations during Lutetia flyby consisted in operating all three instruments but with some modification (described in full in Altwegg et al., 2012). The high speed encounter with Lutetia did not allow adequate time for the DFMS to scan a full mass spectrum, so it was operated at a single peak, mass 18, with a collection time of 10 s. Meanwhile RTOF was reserved for operation closer to the asteroid since high voltage flash-over problems earlier in the mission were resolved only just prior to the flyby. Unfortunately due to the changes in operational procedures and software use, DFMS and COPS were unintentionally switched off during the CA. However DFMS measurements made before and after the spacecraft flip indicate that the water pressure from the spacecraft was gradually increasing throughout the close encounter; this was used to calibrate RTOF. Just before CA, RTOF detected an increase in water signal equivalent to 1.8 (± 0.5) × 10⁵ cm⁻³ exactly as expected for an exosphere, which was not observed during the Lutetia rehearsal. However out-gassing from the spacecraft could not be ruled out and so this does not constitute a positive detection (Altwegg et al., 2012).

The Lander mass spectrometers operations during the Lutetia encounter (Andrews et al., 2012; Goesmann et al., 2012) consisted of 5 discrete blocks of measurements each lasting a couple of minutes at approximately hourly intervals. The measurements before and after CA were used to monitor the background contamination, whilst the third measurement at CA − 17 min measured background plus any exosphere above the sub-solar point. The location of the COSAC vent pipe precluded direct measurement of any exosphere from Lutetia: during the approach it was facing away from the asteroid and after the flyby the spacecraft speed was much faster than that of the gas flow from Lutetia. However the opportunity of the flyby was used to operate at CA − 3 h and CA + 1 h with the aim of monitoring the internal Lander environment and simultaneous measurements provided a cross calibration between the other mass spectrometers. Both mass spectrometers measured increasing pressure with increasing instrument temperature during the encounter, but Ptolemy indicated an additional 10% increase at the third measurement, equivalent to the pressure increasing by 1.7 × 10⁻¹⁰ mbar. However the spectra at CA − 17 min showed no significant difference between the background measurements, so Ptolemy was unable distinguish whether the increase was caused by an increase in spacecraft out-gassing or an exosphere consisting of mainly water.

2.2. RPC and ROMAP magnetometers

The Rosetta Plasma Consortium (RPC) consists of a suite of 5 instruments designed to measure the local plasma environment (Carr et al., 2009). An exosphere could be detected by an increase in ion concentration with a detection limit of ~1 ion cm⁻³ as it is ionised by the solar wind and also by its effect on the magnetic field of Lutetia, similar to the effects that led to the detection of an atmosphere from Enceladus (Dougherty et al., 2006). The Lander has a separate magnetometer instrument, ROMAP (Auster et al., 2009) for measurements close to and on the surface of the comet. During the Cruise Phase, measurements in parallel with RPC compensate for spacecraft disturbances, especially from the Lander during active phases.

The main objective of RPC was to measure the magnetic field of Lutetia and determine whether it contained a magnetic core. To this end the main instrument deployed during flyby was RPC-MAG (Glassmeier et al., 2009b) with ROMAP, operational for ± 3 days (equivalent to ± 40,000 km) on either side of CA

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**Table 1**

Summary of instrument capabilities.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Type</th>
<th>Measurement</th>
<th>Detection limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROSINA COPS</td>
<td>In-situ</td>
<td>Pressure</td>
<td>Sampling period 10 s</td>
</tr>
<tr>
<td>ROSINA DFMS</td>
<td>In-situ</td>
<td>Pressure and composition m/z 12–150 Da⁺</td>
<td>Sampling period 30 min Orbiter +Z pointing ram enhancement</td>
</tr>
<tr>
<td>ROSINA RTOF</td>
<td>In-situ</td>
<td>Pressure and composition m/z 1–300 Da⁺</td>
<td>Sampling period 200 s Orbiter +Z pointing ram enhancement</td>
</tr>
<tr>
<td>Ptolemy</td>
<td>In-situ</td>
<td>Pressure and composition m/z 11–142 Da⁺</td>
<td>Sampling period 135 s Lander, vent pipe +Z pointing, ram enhancement</td>
</tr>
<tr>
<td>COSAC</td>
<td>In-situ</td>
<td>Pressure and composition</td>
<td>Sampling period 126 s Lander, vent pipe −Z pointing</td>
</tr>
<tr>
<td>RPC-MAG ROMAP</td>
<td>In-situ</td>
<td>Plasma environment</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>Alice</td>
<td>Remote</td>
<td>Hx</td>
<td>Global density</td>
</tr>
<tr>
<td>MIRO</td>
<td>Remote</td>
<td>Water</td>
<td>Ammonia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carbon monoxide and Methanol</td>
<td>Column density</td>
</tr>
</tbody>
</table>

*a 1 Da is equivalent to 1 amu.*
Ly and O (with the O I multiplet at 1304 Å), these being produced by the dissociation of water. Volatile species meter/spectrometer is fixed-tuned to measure simultaneously four spectral resolution spectrometer (44 kHz) is interfaced with the for the measurement of near surface temperatures. A very high heterodyne radiometers with centre-band operating frequencies 2.4. MIRO/C2 is 7.5' at 562 GHz. Minimum detectable column densities to produce estimates assume a rotational temperature of 300 K.

of water of 5/C2 3 sigma noise level, giving an upper limit for the column density each of 30 s duration around CA. No signals were detected above a side of CA. The search for water consisted of combining 7 spectra were only within the passband of the receiver for concerning the properties of Lutetia that affect out-gassing of water and 1.3/C2 water and 1.3/C0

3. Discussion
3.1. Comparison of instrument sensitivity

The results from the various instruments (as given in the special issue) are expressed in units specific to each type of measurement/instrument. As such a direct comparison between the data is not straightforward. In this section a simple model of an asteroid exosphere is used in order to allow comparisons between the instruments and calculate their detection limit. The main component is assumed to be water released by sublimation at a temperature of 240 K and expanding outwards homogeneously (i.e. pressure decreasing outwards according to a 1/r^2 relationship). Other production mechanisms, such as ion sputtering by the solar wind and micrometeorite vaporization, were investigated by Schlappi et al. (2008), but the maximum density of 10^3 particles m^{-3} at the flyby distance would be below detection limits.

For a production rate Q in molecule s^{-1}, the number density N at a distance r from the asteroid centre is given by

\[ N = Q/(4\pi r^2 v) \text{[molecules m}^{-3}] \]  

(1)

The pressure P is given from the ideal gas law, where \( P = Nk_BT \);

\[ P = Qk_BT/(4\pi r^2 v) \text{[Pa]} \]  

(2)

In the case of the ROSINA instruments and Ptolemy the pressure measured by the instrument, \( P_{\text{inst}} \), is enhanced by the ram effect, as discussed in Section 2:

\[ P_{\text{inst}} = P(v\cos\alpha + v)/v \text{[Pa]} \]  

(3)

Molecules from Lutetia are ionised by photo-ionisation and interaction with the solar wind with an ionisation scale length at 2.7 AU of 7.3 × 10^5 km (Hansen et al., 2009). The fraction of molecules ionised is 1 - exp(−r/\lambda). Hence, the number of ions at distance r is given by

\[ N_{\text{ion}}(r) = (1 - \exp(-r/\lambda))Q/(4\pi r^2 v) \text{[ions m}^{-3}] \]  

(4)

MIRO measures the column density, \( N_{\text{col}} \), at a distance r, as given by

\[ N_{\text{col}} = Q/(4\pi v) \int_{r_0}^{r} \frac{1}{r^2} dr \text{[molecules m}^{-2}] \]  

(5)

where \( r_0 \) is the radius of the asteroid. Since the spacecraft flyby distance \( r \gg \) the exosphere scale height, the detection limit is close to

\[ N_{\text{col}} = Q/(4\pi v) \text{[molecules m}^{-2}] \]  

(6)

A comparison of the exosphere production rate required for detection by each instrument against distance from the asteroid is shown in Fig. 4. Values were calculated using the simple model described above and using the instrument detection limits in Table 1. An effective detection limit of 10^{-12} mbar was used for the ROSINA RTOF and DFMS mass spectrometers because their sensitivity was reduced by spacecraft out-gassing.

Of interest for the comet encounter is the detection limit of carbon monoxide. In general, the sensitivity of the mass spectrometers (RTOF, DFMS, COSAC and Ptolemy) is increased by a factor of 12 since they are (a) more sensitive to CO, because it is a smaller component of the spacecraft background and (b) have an enhanced signal from the ram effect, which is increased by ~25% with respect to water because of the higher molecular mass of CO compared to H₂O. In contrast, the sensitivity of MIRO for CO is lower by factor 150. These results are summarised in Table 2. None of the instruments detected any indication of CO, giving a global production rate of < 1.7 × 10^{23} molecules s^{-1}.

3.2. Combining instrument results

For most cases the presence of any exosphere was below detection limits, taking the results from MIRO, the most sensitive instrument, and assuming the simple out-gassing model described above, then the water production rate is < 4.3 × 10^{23} molecules s^{-1}. However for the two mass spectrometers that were in operation near CA (RTOF and Ptolemy) there was an apparent increase in water pressure. Whilst recognising that this
is probably due to spacecraft out-gassing, it is instructive for future comet operations to look at combining the individual results and investigating what constraints this implies for an exosphere.

A direct comparison of the mass spectrometer results is shown in Fig. 5. Ptolemy only made a single measurement near CA at the sub-solar point; however, the more sensitive ROSINA instrument did not detect a simultaneous pressure increase, thus suggesting that the Ptolemy measurement was more likely to be due to pressure changes within the Lander environment. The pressure rise measured by ROSINA (inset Fig. 5) shortly before Close Approach was consistent with an exosphere and the measurement was made when it had a sensitivity similar to those of Alice and RPC-MAG (Fig. 4), with a detection limit of $1 \times 10^{26}$ molecules s$^{-1}$ ($\sim 3$ kg s$^{-1}$) equivalent to those of low activity comets. One possibility is that the out-gassing is not homogenous but concentrated in jets similar to comets, e.g. EPOXI observed jets of water not associated with dust jets (A’Hearn, 2010). A similar effect could be occurring on asteroids, albeit at a lower intensity. The orientation of Lutetia results in the sunlit pole being strongly heated compared to the unlit side, so some directional plume would be expected. Alternatively recent cratering may have exposed buried ice, which could result in a localised water emission.

A more rigorous model for directional out-gassing by sublimation (Altweeg et al., 2012) estimated a production rate of $(3.2 \pm 1.6) \times 10^{25}$ molecules s$^{-1}$ ($\sim 1 \pm 0.5$ kg s$^{-1}$). Still above the detection limit of MIRO, but as indicated in Fig. 6, localised active regions could have been missed by MIRO, which has a narrow footprint of about 7 km diameter and was able to detect water only when Rosetta was $\sim 1600$ km from CA. Any increase in sensitivity from directional out-gassing would also increase sensitivity for RPC-MAG and Alice. The detection limit of RPC-MAG assumed that the magnetic field strength of Lutetia was 1 nT at 3160 km; a lower magnetic field would reduce the sensitivity. Furthermore, observations of both RPC-MAG and Alice depend on the extent of dissociation of water into H and O ions by the solar wind, which is variable, so the possibility remains that

**Table 2**

Lutetia exosphere measurements. MIRO is the most sensitive instrument in detecting water. For CO the mass spectrometer sensitivity is increased by 12 because of lower background and increased ram effect. The most sensitive instrument RTOF did not detect any CO (Fig. 5).

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement details</th>
<th>Measurement</th>
<th>Distance to asteroid centre (km)</th>
<th>Global production rate (molecules s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROSINA-COPS</td>
<td>Total</td>
<td>$&lt;4 \times 10^{-14}$ mbar</td>
<td>54,000</td>
<td>$&lt;2 \times 10^{27}$</td>
</tr>
<tr>
<td>ROSINA-DFMS</td>
<td>$H_2O$</td>
<td>$&lt;4 \times 10^{-14}$ mbar</td>
<td>54,000</td>
<td>$&lt;1.7 \times 10^{27}$</td>
</tr>
<tr>
<td>ROSINA-RTOF</td>
<td>$H_2O$</td>
<td>$&lt;3 \times 10^{-15}$ mbar</td>
<td>3800</td>
<td>$&lt;2 \times 10^{28}$</td>
</tr>
<tr>
<td>Ptolemy</td>
<td>$H_2O$</td>
<td>$&lt;4 \times 10^{-12}$ mbar</td>
<td>15,500</td>
<td>$&lt;1.7 \times 10^{28}$</td>
</tr>
<tr>
<td>RPC-MAG/ROMAP</td>
<td>Total</td>
<td>$&lt;1$ nT</td>
<td>3162</td>
<td>$&lt;3.2 \times 10^{25}$</td>
</tr>
<tr>
<td>Alice</td>
<td>$H_2O$</td>
<td>$&lt;1 \times 10^{26}$ mol s$^{-1}$</td>
<td>$&gt;10,000,000$</td>
<td>$&lt;1.0 \times 10^{25}$</td>
</tr>
<tr>
<td>MIRO</td>
<td>$H_2O$</td>
<td>$8.1 \times 10^{17}$ mol m$^{-2}$</td>
<td>$&lt;5000$</td>
<td>$&lt;4.3 \times 10^{23}$</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>$1.3 \times 10^{17}$ mol m$^{-2}$</td>
<td>$&lt;5000$</td>
<td>$&lt;6.9 \times 10^{23}$</td>
</tr>
</tbody>
</table>
None of the instruments detected an unambiguous signal of an exosphere. Assuming a spherical source, the production rate of water \( < 4.3 \times 10^{23} \text{molecules s}^{-1} \) and carbon monoxide \( < 1.7 \times 10^{25} \text{molecules s}^{-1} \). The cause of the tantalising increase in water detected by ROSINA RTOF remains ambiguous, and could be either from an exosphere or simply due to spacecraft out-gassing. However the lack of a water signal detection by the more sensitive MIRO indicates that if this was due to an exosphere then the water out-gassing is directional with a half-width angle \( < 90^\circ \) and a production rate of water of \( 1.5 \times 10^{25} \text{molecules s}^{-1} \) or less. RPC-MAG measurement revealed an asteroid influence on the magnetic field of less than 1 nT at 3160 km.

During the initial comet encounter at 3.5 AU, the expected production rate is of the order \( 6 \times 10^{26} \text{molecules s}^{-1} \) (De Sanctis et al., 2010). All the instruments will have sufficient sensitivity to analyse the coma, since Rosetta will initially be orbiting much closer at a distance of 100 km, reducing over a period of a few months to 20 km. However experience gained from the Lutetia encounter shows that distinguishing spacecraft effects will be more difficult at the comet as Rosetta will be immersed within the coma, so there will be no way to measure background levels and no sensitivity increase due to the ram effect. Measurements made shortly after hibernation will help characterisation of the spacecraft out-gassing and dedicated coma analysis sequences will help reduce the background. Complementary measurements between instruments during the initial orbits will enhance measurements made once the Philae Lander is on the comet surface, where joint measurements will provide data on two locations simultaneously.

The Rosetta spacecraft has now entered its hibernation phase until comet approach in January 2014. During this time more information concerning small Solar System bodies will continue to be gathered with the imminent arrival of the Dawn spacecraft at Vesta followed by its arrival at Ceres a year later.

Acknowledgements


References


