3rd AIAA Atmospheric Space Environments Conference
27 - 30 June 2011, Honolulu, Hawaii

AIAA 2011-3822

Characterization of the gaseous spacecraft environment of Rosetta by ROSINA

B. Schläppi[1], K. Altwegg[2], H. Balsiger[3], U. Calmonte[4], M. Hässig[5], L. Hofer[6], A. Jäckel[7] and P. Wurz[8]
Universität Bern, Bern, 3012, Switzerland

J. J. Berthelier[9]
LATMOS, Saint-Maur, F-94100, France

J. De Keyser[10]
BIRA-IASB, Brussels, B-1180, Belgium

B. Fiethe[11]
TU Braunschweig, Braunschweig, D-38106, Germany

S. A. Fuselier[12]
Lockheed Martin Advanced Technology Center, Palo Alto, California, 94304, USA

U. Mall[13]
Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, D-37191, Germany

H. Rème[14]
University of Toulouse, Toulouse, F-31028, France

and

M. Rubin[15]
University of Michigan, Ann Arbor, Michigan, 48109, USA

For critical optical surfaces and sensitive instrumentation, contamination due to spacecraft outgassing is a nuisance. To avoid or minimize the resulting, limiting factors in the future, a comprehensive understanding of the outgassing mechanisms is necessary. Here we summarize findings from outgassing studies using the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) on the Rosetta spacecraft. Data are available for a flight time of more than six years, a large range of heliocentric distances, and a variety of different test scenarios.

[1] Research Assistant, Physikalisches Institut, Sidlerstr. 5, AIAA Student Member.
[2] Professor, Physikalisches Institut, Sidlerstr. 5.
[3] Professor, Physikalisches Institut, Sidlerstr. 5.
[4] Research Assistant, Physikalisches Institut, Sidlerstr. 5.
[5] Research Assistant, Physikalisches Institut, Sidlerstr. 5.
[6] Research Assistant, Physikalisches Institut, Sidlerstr. 5.
[7] Research Scientist, Physikalisches Institut, Sidlerstr. 5.
[8] Professor, Physikalisches Institut, Sidlerstr. 5.
[9] Professor, Avenue de Neptune 4.
[10] Space Physics Division Head, Space Physics Division, Ringlaan 3.
[11] Research Scientist, IDA, Hans-Sommer Str. 66.
[12] Senior Scientist, Dept. ADCS, 3251 Hanover St.
[13] Senior Scientist, Max-Planckstr. 2.
[14] Professor, UPS, 9 av. du Colonel Roche.
[15] Research Scientist, Department of Atmospheric, Oceanic and Space Science, 2455 Hayward St.

Nomenclature

E_a	=	characteristic activation energy
n_{Dec}	=	particle number density around spacecraft due to decomposition
n_{Des}	=	particle number density around spacecraft due to desorption
n_{Dif}	=	particle number density around spacecraft due to diffusion
R	=	gas constant
T	=	absolute temperature
t	=	time since launch
t_d	=	1/e decay time of desorption

I. Introduction

One of the many difficulties in the construction and fabrication of scientific spacecraft is to ensure an acceptable level of cleanliness and a minimal amount of outgassing, which might deteriorate the performance of subsystems and scientific payload. Even though special attention is paid to contamination control, different spacecraft report that optical surfaces, such as mirrors, windows or solar cells, have accumulated a layer of contaminants. This reduces the optical transmission and therefore can degrade the instrument performance and efficiency[1-3].

Non-isotropic outgassing of spacecraft can cause recoil forces and torques, which can significantly complicate the maneuvering of a probe. Such an observation was reported for the MAP (Microwave Anisotropy Probe) spacecraft during maneuvers[4]. A perturbation of the attitude due to outgassing was also noticed for the European Space Agengy's (ESA) Rosetta spacecraft, during a deep space maneuver in January 2011[5].

Particle instruments such as pressure sensors or mass spectrometers also experience problems in connection with the gas cloud that surrounds a spacecraft: The limit of detection is hampered by signals of the spacecraft contamination background. However, in contrast to optical instruments, the instrument performance is not affected. The MSX spacecraft, which was launched in 1996 into an orbit 900 km from Earth and designed carefully in terms of contamination, was one of the few opportunities to study the neutral gas environment of a spacecraft with dedicated instrumentation. The MSX total pressure sensor and the neutral gas mass spectrometer detected surprisingly high pressures even after seven years in space[6]. In particular, the partial H_2O pressure was clearly above the expected level, which is probably, as the authors suggested, due to water trapped in multilayer insulation (MLI) slowly outgassing over many years. The influence of outgassing and its implications on scientific measurements, in particular the investigation of tenuous atmospheres by mass spectrometry, has been shown to be substantial[7]: The detection limit of sensitive particle sensors is no longer given by the instrument sensitivity but by outgassing from the spacecraft.

The above-mentioned reasons, including the influence of outgassing on optical instruments, spacecraft operation and in situ mass spectrometry, require a comprehensive understanding of the mechanisms of outgassing and the role of particle backscattering in creating the gaseous spacecraft environment. Only when the causes and the applicable physical laws are identified, cleanliness restrictions can be reduced or at best be eliminated. The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) instrument package onboard the ESA comet-chasing Rosetta spacecraft provides a unique opportunity to study spacecraft outgassing and contamination issues.

II. Rosetta and ROSINA

Launched in 2004, the European Space Agency's (ESA) spacecraft Rosetta is on its way to comet 67P/Churyumov-Gerasimenko. In 2014 Rosetta will reach its target and a detailed characterization of the comet will be carried out. A lander unit (Philae) will be deployed to perform a controlled landing on a comet for the first time. The main part of Rosetta, the Rosetta orbiter, will remain in proximity to the comet while it will travel slowly closer to the Sun.

The Rosetta spacecraft, depicted in Fig. 1, consists of a cube-type structure with sides of 2.0 m x 2.1 m x 2.8 m and two large solar panel arrays (each 32 m^2) on both sides of the cuboid mainbus. Because of several sensitive instruments, such as a UV spectrometer, optical camera systems, and the mass spectrometers the spacecraft was designed with the intention to be a very clean spacecraft. Outgassing requirements were stringent for both spacecraft and payload. For passive thermal control of the payload, most of the probe was covered in multi layer insulation (MLI) foils. The MLI were sealed completely with the exception of the opposite panel of the instrument platform (+z panel in Fig. 1), where the spacecraft is vented without affecting sensitive instruments. Rosetta is three axes stabilized and has several thrusters, which are shielded from direct view of the instruments. Nominally attitude control is achieved by reaction wheels, which are offloaded approximately weekly using the thrusters. The lander

Philae is attached to the -x panel of the orbiter, which is in general kept out of sunlight. Philae is designed to operate under thermal conditions expected at the comet surface; too high temperatures are therefore potentially harmful. Other cool surfaces, e.g. for cooling an infrared spectrometer, are located on the same panel of the orbiter.

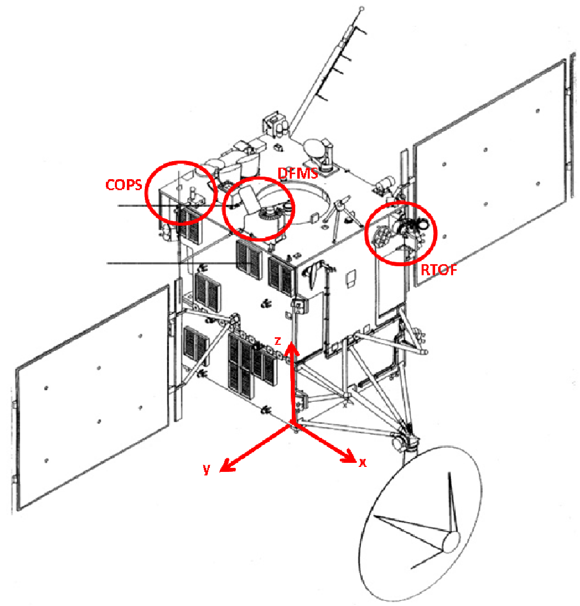

Figure 1. Rosetta with the coordinate system and the three ROSINA instruments: COPS, DFMS and RTOF.

The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) is part of the comprehensive instrumentation of the orbiter that will be used to characterize the comet. ROSINA consists of one pressure gauge (COmet Pressure Sensor, COPS) and two mass spectrometers: A Reflectron-type Time Of Flight instrument, RTOF, and a Double Focusing Mass Spectrometer, DFMS. For a detailed description of this instrument package the reader is referred to Ref. 8. The two mass spectrometers have unprecedented properties in terms of sensitivity and mass resolution: RTOF has a mass resolution of m/Δm > 1000 (at 50% peak height), covers a mass range from 1 to ~300 amu/e, and detects particle densities of 10^4 cm^{-3} within 10-1000 s for a complete mass spectrum. Note that this sensor has not yet been fully optimized. DFMS covers a mass range from 12 to 150 amu/e and has a mass resolution of m/Δm~3000 (at 1% peak height). It detects particle densities of 1 cm^{-3} within 20 s for one mass line and requires approximately 20 min for a complete mass spectrum. The two mass spectrometers have not only complementary properties in terms of performance; they also provide redundancy for the long-running mission. COPS measures the total pressure down to particle densities of 10^4 cm^{-3} in 10 s.

III. Outgassing processes

We have made use of the capabilities of the ROSINA instrument on several occasions during the past seven years since launch to study outgassing effects. The observations can be divided in two different types of phenomena, the permanent spacecraft background and transient outgassing.

A. Permanent spacecraft background

The first phenomenon is an omnipresent particle background observed by all three ROSINA instruments. Early on in a mission, this background mainly depends on the elapsed time since launch. Later, the particle background becomes almost independent on time. This can easily be demonstrated experimentally by monitoring the particle density around the spacecraft as a function of time since launch. Fig. 2 shows the data obtained from COPS and DFMS during the Rosetta cruise phase. COPS was switched on 20 days after launch and showed a pressure of $2{\cdot}10^{-9}$ mbar or a particle number density of approximately $5.5{\cdot}10^{13}$ m^{-3}. Within three months after launch, this pressure decreased to less than $3{\cdot}10^{-10}$ mbar (~$6{\cdot}10^{12}$ m^{-3}), after which it continued to diminish with a clearly different time constant. From about 500 days after launch until March 2011, almost 2500 days in interplanetary space, the particle number density has decreased by not more than a factor 5, from less than $2.5{\cdot}10^{12}$ m^{-3} to $5{\cdot}10^{11}$ m^{-3}. After about 1100 days of flight, the COPS pressure readings are near the detection limit, thus the error bars become large. The particle number density deduced from mass spectra of DFMS, which is significantly more sensitive, confirms the only slight decreased pressure and is consistent with the COPS measurements within error bars. As is evident from Fig. 2, no dependence of the background particle number density around the spacecraft on the heliocentric distance is observed. This will be discussed in more detail later.

According to Ref. 9, the time evolution of the particle density around an outgassing object can be described by three different mechanisms: Desorption, diffusion, and decomposition. All three processes can be described by the relation for the released particle flux being proportional to $e^{-E_a/RT}$, where T is the absolute temperature, E_a the characteristic activation energy of the process, and R is the gas constant. Furthermore the three processes follow different time-dependencies. The process with the lowest activation energy (E_a=4-40 kJ/mol)[9] and an exponential

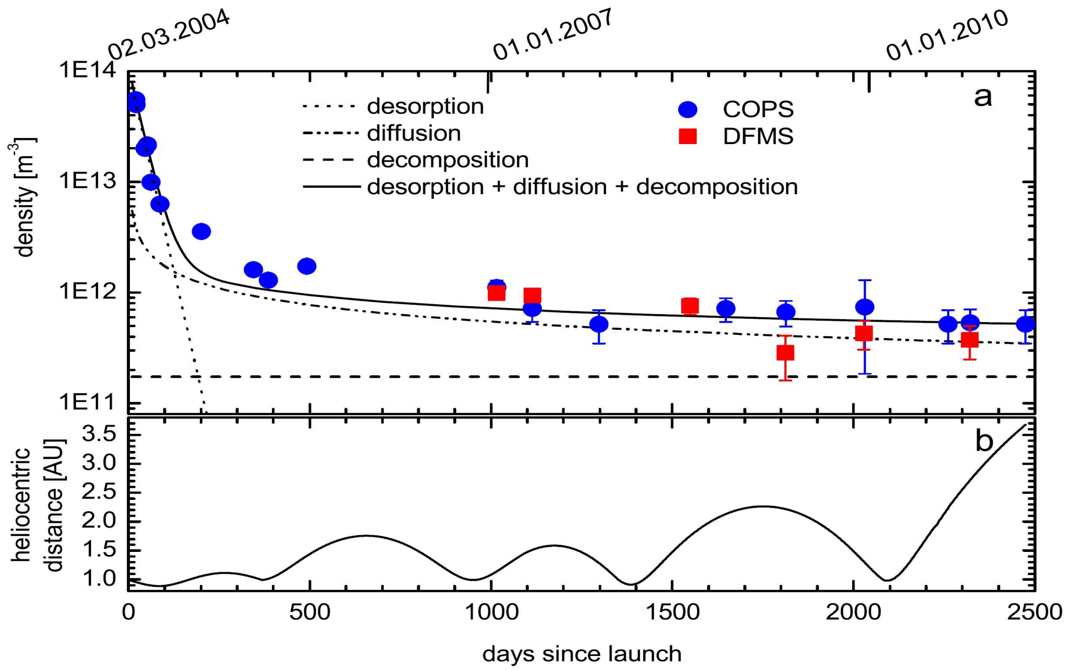

Figure 2. Temporal evolution of the particle density around Rosetta measured by ROSINA COPS and DFMS. ***(a)*** *Data from COPS (blue symbols) and DFMS (red symbols) as a function of time since launch. The dotted line shows the contribution of desorption* $n_{Des} \sim e^{-t/t_d}$ *with* t_d*=30 days. The dashed-dotted line corresponds to the outgassing due to diffusion* $n_{Dif} \sim t^{-0.5}$*, and the dashed line represents decomposition (*n_{Dec}*= const.). The solid black line is the sum of the three contributions.* ***(b)*** *Heliocentric distance of Rosetta.*

time dependence, namely desorption, is responsible for the fast decay of the COPS pressure readings during the first 200 days after launch. The second mechanism, diffusion, requires that material is transported from the inside of the spacecraft and from within all materials to the outside. This process has a higher activation energy (E_a=20-60 kJ/mol)[9] and a moderate time dependence of $t^{-0.5}$ (where t is the time since launch). Decomposition, being the third process, has a high activation energy (E_a=80-320 kJ/mol)[9] and is essentially time independent. Decomposition of material can be caused by high energetic radiation (electrons, ions) or solar UV photons.

With a combination of these basic outgassing mechanisms, the ROSINA particle density measurements around Rosetta can be well understood, as shown by the fit in Fig. 2, for the entire journey so far. Although a considerable heliocentric distance was covered by Rosetta, a correlation of the background density with distance is not observed. This can be explained as follows: Early on, when desorption was important, Rosetta was located in a very limited range of 0.85-1.15 AU relative to the Sun. This implies that the surface temperature of the spacecraft did not change very much. However, when the heliocentric distance has increased substantially, the diffusion process was the dominant process. Diffusion is driven by the interior temperature of the spacecraft, which did not change by more than 20 K while the heliocentric distance was doubled.

B. Transient outgassing phenomenon

Beside the permanent background around Rosetta described above, short-term variations of the pressure can be considerable. Time scales of transient phenomena observed by ROSINA, range from a few seconds to several hours. For examples and detailed discussion of all types of transient outgassing phenomena, the reader is referred to Ref. 7. Here we briefly summarize the three identified causes:

One of the main reasons for observed fluctuations of the outgassing rates are maneuvers and changes in attitude. During such events, the Solar aspect angle changes and parts of the spacecraft, which have been in shadow before, are exposed to sunlight. The additional irradiance can cause desorption of material so that the detected particle densities may increase by several orders of magnitude.

The second reason for fluctuations is based on a similar principle: The change of local temperatures. ROSINA instruments have detected short-term changes in pressure by up to a factor 4 due to turn on and operation, and therefore power dissipation, of other instruments and subsystems. Surprisingly, signals from maneuvers and from other payload operations were detected when the outgassing sources were by no means in the fields of views of the

ROSINA sensors. This includes illumination of the –z panel and operation of instruments onboard the Lander Philae (compare Fig. 1), both clearly detected by DFMS, which is mounted on the +z panel with its wide field of view (20° x 20°) directed along the +z and the narrow field of view (5° x 5°) aligned along +x axis.

As a third cause of particle background variability around Rosetta, we have identified thruster firings. Although all thrusters are shielded from direct view of COPS, the plumes can easily be detected by this sensor[7,11]. The ROSINA mass spectrometers are not operated for safety reasons during thruster firings (high pressures and therefore risk of electrical discharges).

IV. Chemical composition of contaminants

Beside the confirmation of the MSX observations concerning the high water partial pressure and the surprisingly long outgassing time-scales[6], the combination of high sensitivity and mass resolution of ROSINA allows for the identification of minor contaminants in the vicinity of the Rosetta spacecraft. Figure 3 demonstrates the capabilities of the ROSINA DFMS: The low resolution mass spectrum depicts signals on almost any integer mass line in the mass range from 12-100 amu/e. The dominant mass peaks are from the water group (O, OH and H_2O from 16-18 amu/e), at 28 amu/e (CO and N_2) and the CO_2 mass line at 44 amu/e. Obviously, there exists a variety of organic compounds with particle densities < 10^4 cm^{-3}. These can be investigated in detail using the high resolution mode of DFMS. Note that the number densities deduced from ROSINA measurements compare well with estimates for the SOHO spacecraft for both water[1] and organics[2]. Detected species and fragments can be classified in different substance groups[7]:

- Water, which has been adsorbed and contained inside the spacecraft (e.g. in MLI or honeycomb structure) and now slowly diffuses to the spacecraft periphery from where it is released.
- Hydrocarbons and polycyclic-aromatic hydrocarbon molecules: Possible sources of such molecules are polycarbonates and solvents.
- Nitrogen bearing compounds: Among this substance group monomethylhydrazine from the Rosetta propellant has been identified. However, additional sources are required to explain the observed mass distribution. Possibilities are polyurethane, epoxies, polyamines or polyimides.
- Halogen and sulphur bearing matter: Fluorine has been detected by both ROSINA mass spectrometers and may partially come from an instrument internal source. However, chlorine and sulphur were not observed prior to launch and therefore originate from the gas cloud around Rosetta. Potential sources are solvents.
- Lubricants: Using data from the ACIS instrument onboard the Chanda-X-ray mission, Ref. 10 reported X-ray absorption edges consistent with the decomposed lubricant Braycote with the ACIS instrument onboard the Chandra-X-ray mission. Comparison of RTOF and DFMS mass spectra from March 2010 confirmed that Braycote forms aliphatic compounds under radiation and that these products are more volatile than expected.

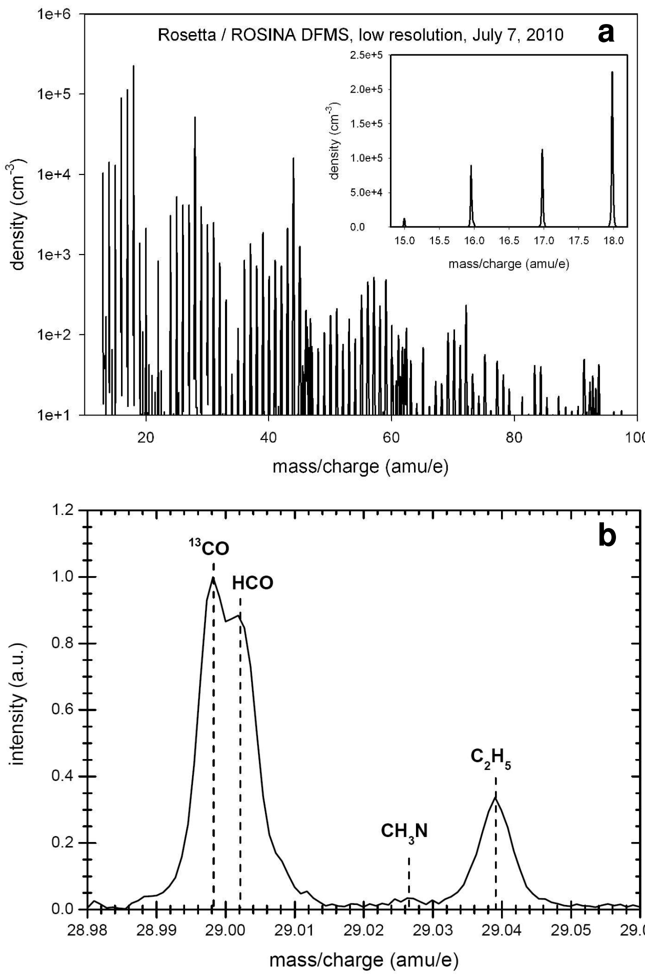

Figure 3. ROSINA DFMS mass spectra in low and high resolution mode. (a) *Low resolution spectrum of the Rosetta background taken in July 2010 at a heliocentric distance of 2.7 AU. The inset shows a part of the spectrum in linear scale for illustration.* **(b)** *High resolution spectrum, obtained in Feb. 2009, demonstrating the ability to separate the 29 amu/e signal into its constituents.*

On several opportunities the DFMS ion source was baked out (T=573 K) for several hours previous to the measurements. This did not result in a substantial change in the composition of the background. We are therefore confident that the signals are external to the instrument and originate from a gas cloud surrounding the spacecraft. The composition of this cloud corresponds to the signature of materials used in the spacecraft construction. However, the gas cloud is highly nonuniform in terms of composition and particle density around the spacecraft: Cold surfaces contain mainly adsorbed water, while illuminated surfaces show larger relative contributions from decomposed matter. These differences are clearly observed when DFMS and RTOF spectra are compared. In line with this reasoning are the compositional changes observed during an outburst during a maneuver in February 2009. The results suggested that transient outgassing phenomena are dominated mainly by H_2O, although possible contributions of CO_2 and CH_4 could not be excluded[7]. This indicates that at this time, more than 1800 days after launch, desorption can still contribute a significant part to the background if illumination conditions are unfavourable.

V. Modelling the physics of spacecraft outgassing

A basic understanding of the different outgassing phenomena and the associated return flux of material is of broad interest. Their disruptive effects include degradation of optical instruments, the built-up of non-volatile crusts by the combination of accumulation of material and UV irradiation[12], background signals for mass spectrometers, and accumulation and subsequent unexpected release of volatiles leading to operational problems. However, a comprehensive description is difficult because of the broad range of unknown parameters. In principle there are only three different options for backscattering material:

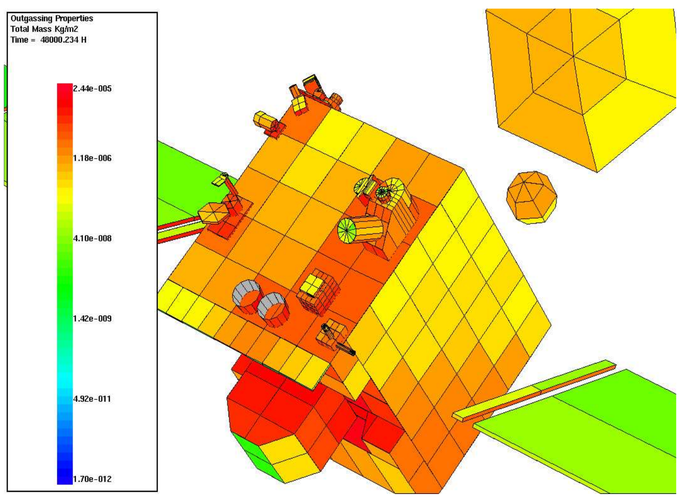

Figure 4. Geometrical model of Rosetta and the ROSINA instruments for the OUTGASSING (Astrium)[12] simulation.

1. Direct flow and multiple scattering of particles off different parts of a spacecraft.
2. Self-scattering: Collisions between released molecules leading to a small fraction reaching the spacecraft.
3. Ambient scattering: Collisions between released and ambient molecules (e.g. from an atmosphere which the spacecraft passes through).

Under the assumption that ambient scattering is negligible for deep space missions, the outgassing behaviour of Rosetta was modelled using the commercially available software OUTGASSING (Astrium)13. Considering direct, multiple, and self-scattering, this model takes into account the material properties with the corresponding outgassing rates and temperatures to estimate the return flux on different nodes of the spacecraft. A graphical representation of such a simulation is shown in Fig. 4. Unfortunately, with presumably adequate outgassing rates and an appropriate distribution of outgassing sources, the obtained ROSINA pressure profile as a function of time since launch could by far not be reproduced. We therefore identify different critical unknowns concerning such simulations:

- The distribution of outgassing sources and their dimensions.
- Outgassing rates.
- Although in general monitored by many sensors, the temperature is not clearly known at every location of a spacecraft.
- The necessary degree of detail of the geometry model might influence the results considerably. Small cavities or shadowy holes and related accumulations of material might contribute to the measured background of a sensor as much as large panels outside the direct field of view.

The largest uncertainties concern the outgassing rates of different materials. Currently materials are considered appropriate if the total mass loss (TML) rate is less than 1% if heated to 125°C over 24 h and the collected volatile condensable material (CVCM) does not exceed 0.1% of the initial sample mass14. This criterion focuses solely on the thermal desorption and diffusion, and does not take into account possible contributions from decomposition. Spacecraft are exposed to a harsh environment, consisting of UV, X-ray and high energetic particle radiation. It is known that certain spacecraft materials, such as polyimide films, experience structural changes if exposed to ion or electron beams and UV photons15. Furthermore, the long-term diffusion rate from the inside of a spacecraft can not be estimated with sufficient accuracy.

Some of the above mentioned uncertainties could be eliminated by a dedicated test campaign in Sept. 2010. Rosetta has reported anomalies during the pressurization of some thruster valves with helium: It was suspected that one of the He feed lines has a leak. During these tests of these lines, COPS was operating. It was possible to determine the precise time and time constant of the pressure decay only by looking at the COPS signal. Since the released amount of helium is well known, this observation offers an excellent test case to simulate the expansion of the gas around the spacecraft. In particular the possible outgassing sources and the dimensions are limited to a manageable number and the outgassing rate is well known. In addition, the temperature is constrained by the spacecraft temperature, whereas during e.g. thruster firings, the gas temperature can deviate significantly from the ambient temperature due to the combustion of fuel and oxidizer. However, using a Direct Simulation Monte Carlo (DSMC) code, initially developed for the simulation of cometary atmospheres, the He release results could not yet be reproduced with an acceptable level of accuracy using a detailed geometrical model of Rosetta. The observed COPS pressure reading was several orders of magnitude higher than the value derived in the simulation. There are two possible explanations for this discrepancy: Either an unexpected leak in the spacecraft structure and MLI close to COPS directs the gas to the sensor in a more efficient way than assumed, or the spacecraft is surrounded by a significantly denser atmosphere that enhances the collision frequency and thus increases the return flux. On one hand, an additional leak of unknown origin could certainly explain this particular observation. However, the detection of gas released outside the field of view of the ROSINA DFMS (compare Section III. B) would still remain unexplained. On the other hand, a mechanism to maintain a substantial atmosphere over long time scales is unknown.

VI. Conclusion

Although outgassing and contamination control has long been a key factor in spacecraft design, many spacecraft experience restrictions due to outgassing phenomena. Taking advantage of the properties of the ROSINA instrument package, it is possible to link the composition of the contaminants to all types of materials used for the spacecraft construction. Therefore, the disturbing influences are consequences of four different mechanisms: Desorption, diffusion, decomposition and deposition from thruster plumes. Furthermore the measurements presented in this work are comparable to estimates from other spacecraft (e.g. SOHO1,2), suggesting that spacecraft outgassing is a common problem. For Rosetta, outgassing remains significant over very long periods (almost seven years since launch) and over a wide range of heliocentric distances (1-3.5 AU).

The implications of the observations described on scientific measurements and instrument performance (e.g. optical cameras and mass spectrometers) are considerable. The detailed characterization of outgassing phenomena by ROSINA will not only be used during Rosetta's comet phase, but could also provide valuable clues as how to reduce outgassing interferences for future spacecraft. A useful way to do this is to reproduce observations with theoretical models. However, current simulations fail to explain the experimental data due to the complexity of the background issue.

Acknowledgments

We thank the following institutions and agencies that supported this work. Work at the University of Bern was funded by the State of Bern, the Swiss National Science Foundation, and the European Space Agency PRODEX Program. Work at BIRA-IASB was supported by the Belgian Science Policy Office via PRODEX/ROSINA PEA90020. Research at Lockheed Martin Advanced Technology Center and work at the University of Michigan were supported under JPL subcontract 1266313 under NASA prime contract NMO710889. The work on ROSINA in France was supported by CNES through grants CNES/ROSETTA/98-70 to 04-70. We also thank the Flight Operations group at ESOC, which provided us with the opportunities to study the outgassing behavior of Rosetta during special tests. A special thank goes to all the engineers who made this wonderful instrument.

References

[1]Defise J.-M., Clette F., Moses D., Hochedez J.-F. E., "In-orbit diagnostics of EIT EUV CCD radiation-induced aging," *Proc. SPIE*, 3114, 1997, pp. 598-607.

[2]McMullin D. R., Judge D. L.,. Hilchenbach M., et al., “In-flight comparison of solar EUV irradiance measurements provided by the CELIAS/SEM on SOHO,“ *Radiometric Calibration of SOHO,* edited by A. Pauluhn, M. C. E Huber and R. von Steiger, ISSI Sci. Rep. SR-02, ISSI Bern, Switzerland, 2002, pp. 135-144.

[3]Bhaskaran S., Mastrodemos N., Riedel J. E., Synnott S. P., “Optical Navigation for the STARDUST Wild 2 Encounter,” *Proceedings of the 18th International Symposium on Space Flight Dynamics*, ESA SP-548, ESA, 2004.

[4]Starin S. R. , O’Donnell J. R. Jr., Ward D. K., Wollack E. J, Bay P. M., Fink D. R., “An anomalous force on the MAP spacecraft,” *AIAA Guidance and Control conference*, AIAA-2002-4581, AIAA Symposium Monteray, CA, 2002.

[5]Hässig M., Altwegg K., Balsiger H., et al., “Investigation of spacecraft outgassing by sensitive mass spectrometry,“ *Spectroscopy Europe*, Vol 23, No. 2, 2011, pp. 20-23.

[6]Uy O. M., Green B. D., Wood B. E., et al., “The gaseous and particle environment observed above the MSX spacecraft after seven years on orbit,” *Proceedings of the 9th International Symposium on Materials in a Space Environment*, ESA SP-540, ESA, 2003.

[7]Schläppi B., Altwegg K., Balsiger H., et al., “Influence of spacecraft outgassing on in situ mass spectrometry,“ *J. Geophys. Res.* Vol. 115, 2010, A12313, doi:10.1029/2010JA015734 .

[8]Balsiger H., Altwegg K., Bochsler P., et al., “ROSINA- Rosetta Orbiter Spectrometer for Ion and Neutral Analysis,” *Space Sci. Rev.,* Vol. 128, 2007, pp. 745-801, doi:10.1007/s11214-006-8335-3.

[9]Tribble A. C., *Fundamentals of contamination control*, SPIE Press, Bellingham, Washington, 2000.

[10]Marshall H. L., Tennant A., Grant C. E., Hitchcock A. P., O’Dell S., Plucinsky P. P., “Composition of the Chandra ACIS contaminant,” *Proc. SPIE*, 5165, 2004, pp. 497-508.

[11]Graf S., Altwegg K., Balsiger H., Bochsler P., Fiethe B., Montagnon E., “Thruster plumes: Sources for high pressure and contamination at the payload location,” *J. of Spacecraft and Rockets*, Vol. 45, No. 1, 2008, pp. 57-64.

[12] Riedo A., Wahlström P., Scheer J. A., Wurz P., Tulej M., “Effect of long duration UV irradiation on diamond-like carbon surfaces in the presence of a hydrocarbon gaseous atmosphere,” *Jou. Appl. Phys*. Vol. 108, No. 11, 2010, 114915, doi: 10.1063/1.3517832.

[13]Fusero F., “OUTGASSING software, User’s manual,” EADS Astrium, 2009.

[14]Campbell W. A., Scialdone J. J., “Outgassing Data for selecting spacecraft materials,” NASA Reference Pubilcation 1124 (NASA-RP_1124-Rev-3), 1993.

[15]Tahara H., Kawabata T., Zhang L., Yasui T., Yoshikawa T., “Exposure of spacecraft polymers to energetic ions, electrons and ultraviolet light,” *Nuclear Instruments and Methods in Physics Research B*, Vol. 121, 1997, pp. 446-449