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Sulphur-bearing species in the coma of comet 67P/Churyumov–Gerasimenko

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ABSTRACT

Several sulphur-bearing species have already been observed in different families of comets. However, the knowledge on the minor sulphur species is still limited. The comet’s sulphur inventory is closely linked to the pre-solar cloud and holds important clues to the degree of reprocessing of the material in the solar nebula and during comet accretion. Sulphur in pre-solar clouds is highly depleted, which is quite puzzling as the S/O ratio in the diffuse interstellar medium is cosmic. This work focuses on the abundance of the previously known species H2S, OCS, SO, S2, SO2 and CS2 in the coma of comet 67P/Churyumov–Gerasimenko measured by Rosetta Orbiter Spectrometer for Ion and Neutral Analysis/Double Focusing Mass Spectrometer between equinox and perihelion 2015. Furthermore, we present the first detection of S3, S4, CH3SH and C2H6S in a comet, and we determine the elemental abundance of S/O in the bulk ice of (1.47 ± 0.05) × 10−2. We show that SO is present in the coma originating from the nucleus, but not CS in the case of 67P, and for the first time establish that S2 is present in a volatile and a refractory phase. The derived total elemental sulphur abundance of 67P is in agreement with solar photospheric elemental abundances and shows no sulphur depletion as reported for dense interstellar clouds. Also the presence of S2 at heliocentric distances larger than 3 au indicates that sulphur-bearing species have been processed by radiolysis in the pre-solar cloud and that at least some of the ice from this cloud has survived in comets up the present.


1 INTRODUCTION

Comets are thought to represent a link between the interstellar dense cloud from which the solar nebula and then the Sun and planets formed, and today’s Solar system. Cometary material is thought to contain material from the interstellar dense cloud, which has been reprocessed during Solar system formation. The discussion of the degree of reprocessing ranges from more or less unprocessed material to complete dissociation and formation in the solar nebula. By studying the volatile material of comets, we can try to assess how pristine cometary material is and from there obtain boundary conditions for the formation of planetesimals and their history in the Solar system.

The rich sulphur chemistry observed in comets and in pre-solar clouds is especially suited to test several hypotheses on the degree of reprocessing of cometary material prior to its incorporation into comets. Sulphur is the 10th most abundant element in
the universe. Organic sulphur chemistry resembles oxygen chemistry. Many molecules are very similar just exchanging oxygen by sulphur like e.g. formaldehyde (H₂CO) and thioformaldehyde (H₂CS). It is therefore interesting to look for these organo-sulphur species in the cometary coma. However, due to its ability to exist in the form of many allotropes, second only to carbon, sulphur is much more versatile and is found in very different molecules, starting from the polar H₂S to the stable, refractory ring molecule S₈. In dense clouds and star-forming regions, sulphur seems to be highly depleted by about a factor of 1000 relative to its cosmic abundance (Penzias et al. 1971; Tieftrunk et al. 1994) whereas in the diffuse dense clouds and star-forming regions, sulphur seems to be highly depleted by about a factor of 1000 relative to its cosmic abundance (Penzias et al. 1971; Tieftrunk et al. 1994) whereas in the diffuse interstellar medium (ISM) it is present with its cosmic abundance relative to oxygen of ~1/37 (Savage & Sembach 1996; García-Rojas et al. 2006; Howk, Sembach & Savage 2006; Jenkins 2009).

Many papers have addressed this interstellar sulphur puzzle (see Woods et al. 2015 and references therein). Gas-phase sulphur chemistry requires at least one endothermic reaction for the formation of the corresponding hydride (van Dishoek & Blake 1998). It is therefore commonly thought that grain surface chemistry plays an important role in the formation of sulphur-bearing molecules, as it does in the formation of water. Atomic sulphur may have been frozen out on to dust grains, where it is hydroxylated to form H₂S. However, H₂S is not detected in the ice in cold clouds at levels of H₂S/H₂O < 3 per cent (van der Tak et al. 2003), with even more stringent limits down to 0.2 per cent given by Jiménez-Escobar & Muñoz Caro (2011). These limits are clearly lower than the overall S/O ratio of 1/37. The detection of S₂ in comet C/1983 H₁ IRAS–Araki–Alcock (A‘Heam, Schleicher & Feldman 1983) then led to the hypothesis that H₂S is destroyed in water-rich grain mantles by UV photons, X-rays or cosmic rays (i.e. highly energetic ions, also denoted as radiolysis; e.g. Grim & Greenberg 1987; Moore, Hudson & Carlson 2007). A large suite of ice processing experiments have been performed, showing that H₂S can indeed be transformed into other molecules such as OCS and S₂ in the ice. In addition, a more refractory component containing larger S-polymers up to S₈ and complex species such as hexathiepan (S₆CH₂) is produced as well when the ice is heated (e.g. Ferrante et al. 2008; Jiménez-Escobar & Muñoz Caro 2011). The products depend on the initial ice composition, as illustrated in recent experiments (e.g. Garozzo et al. 2010; Chen et al. 2015). Note that OCS can potentially also be formed by low-temperature surface reactions of CO with S without the need for photolysis or radiolysis.

The only detected interstellar ices containing sulphur in cold clouds are OCS (Palumbo, Geballe & Tielens 1997) and SO₂ (Boogert et al. 1997; Zasowski et al. 2009) but their abundances of (0.03–0.16) per cent and (0.2–1) per cent with respect to water ice are not enough to account for all of the sulphur. CS₂ may be expected to be the result of photolysis of H₂S ice, but this molecule has also not yet been detected in interstellar ices. Gas-phase observations have identified various sulphur-bearing molecules in protostellar sources (‘hot cores’) where ices have just sublimated off the grains. Many simple molecules like CS, SO, SO₂, H₂S, H₂CS, OCS, NS and others are routinely detected (e.g. Blake et al. 1994; Hatchell et al. 1998; van der Tak et al. 2003; Herpin et al. 2009; Crockett et al. 2014), but other species expected from H₂S processing like S₂, HS₂ and H₂S₂ are not (see Martín-Doménech et al. 2016 and references therein). Again, the total abundances of sulphur-bearing molecules fall below the expected S/O ratio.

For the gas coma of comet C/1995 O1 Hale–Bopp, a S/O ratio 0.02 has been reported (Bockelée-Morvan et al. 2000). This is 23 per cent below the photospheric value reported of 0.0257 ± 0.0018 (Lodders 2010). Since no information on the uncertainty of the Hale–Bopp measurement is provided, it is assumed to be ±0.01. Then, the minimal S/O value of 0.01 for the gas coma of Hale–Bopp would still be above the degree of the depleted elemental abundance S/O seen in dense clouds and star-forming regions.

A major goal of this paper is therefore the question if comets lack sulphur as well as it seems to be the case for dense pre-solar clouds, or if this lack of sulphur is indeed just an observational bias by remote sensing, not being able to detect the refractory sulphur produced by photolysis and radiolysis on grain surfaces.

In the Solar system, sulphur is abundant on many planets and their moons. Sulphur dioxide (Toon, Pollack & Whitten 1982) and atomic sulphur S, S₂, S₈ up to S₈ (Esposito, Winick & Stewart 1979) give a reddish colour to Venus’ fumes. The volcanoes on the Jupiter moon Io also shed sulphur in the form mostly of SO₂ (Pearl et al. 1979) as of course do the volcanoes on Earth. Jupiter has a very interesting sulphur chemistry in its plasmasphere (Hudleston et al. 1998) mostly from ionized sulphur species supplied by Io. Some of the reddish colour on Jupiter may also be due to S₈. It seems that in Jupiter all heavy elements are enhanced compared to their solar value. For sulphur, this enhancement factor is up to 2.5 (Ateya et al. 2003). This enhancement is discussed as being the result of a cold environment at the location where Jupiter was formed. The most plausible hypothesis is an extremely low temperature (less than 30 K) of the planetesimals which trapped and supplied the volatiles containing the heavy elements to Jupiter (Owen et al. 1999). The scenario by Gautier et al. (2001) is an alternate hypothesis which relies on the trapping of volatiles containing the heavy elements in clathrate hydrates in the cooling feeding zone of Jupiter to explain their high abundance. This hypothesis overestimates the sulphur abundance in Jupiter by a factor of 2. Pasek et al. (2005) claim that sulphur chemistry in the solar nebula cannot be looked at in isolation rather it must be considered together with the abundance of water vapour. This condition very much depends on whether the chemistry takes place inside or outside the water snow line. All these observations make sulphur and its chemistry a very important topic to study in comets as they can give a clue on the mysterious sulphur depletion in star-forming regions as well as on the formation scenarios of the giant planets.

In 1980, the first detection of sulphur species in a cometary coma was reported, namely the radicals S and CS in comet C/1975 West (Smith, Stecher & Casswell 1980). Since then, many more sulphur-bearing species like SO, SO₂, OCS, CS₂, H₂S and S₂ (see Table 1) have been added pointing to a complex sulphur chemistry in comets. Hydrogen sulphide (H₂S) is the major sulphur-bearing species in comets including 67P/Churyumov–Gerasimenko. Prior to Rosetta, only comet Hale–Bopp has been bright enough to detect all of the above species in one comet.

Following the definition of Cottin & Fray (2008), there are three possible sources for molecules and radicals measured in the cometary coma: a nucleus source, parent molecules directly released from the subsurface ice of the nucleus, a secondary source for daughter species, which is due to the photodissociation of parent molecules in the coma or by chemical reactions in the coma, and a distributed source which is due to volatiles and semi-volatiles sublimating from dust grains or the thermal degradation of dust grains in the coma. Remote sensing is especially sensitive to the radicals SO, S and CS but it is not clear whether they are only daughter species from secondary sources or if they are also present as parent molecules. This question can be answered by direct in situ mass spectrometry.

Shortly after the arrival of Rosetta in the close vicinity of 67P/Churyumov–Gerasimenko (hereafter 67P), still at large
heliocentric distances (above 3 au), all of the above sulphur-bearing species were found by ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis; Balsiger et al. 2007) in the coma of the Jupiter-family comet. The measurements in 67P at a distance of 3.15 au from the Sun (Le Roy et al. 2015) are listed in Table 1 with two different values corresponding to the Northern (summer) and Southern (winter) hemispheres. Except SO, the abundances of S-bearing species relative to water were a factor of 3–8 higher above the winter compared to the summer hemisphere. SO/H$_2$S on the other hand is about a factor of 3 lower above the winter with respect to the summer hemisphere. These measurements were done outside of the water snow line and thus abundances relative to water are not expected to be representative of the bulk composition. The two hemispheres at that heliocentric distance showed a very heterogeneous coma with water coming mainly from the northern part and CO$_2$ coming from the south (Hässig et al. 2015), which may explain the large difference between the two hemispheres for the relative sulphur-bearing species abundances. In this paper, we extend the investigation of sulphur-bearing compounds to a much larger time interval which covers heliocentric distances from 3.5 to 1.24 au and which also covers the equinox early 2015 May, when the southern part became the summer hemisphere. Based on this extensive data set covering large heliocentric distances, it is possible to address the question of the bulk ice composition in 67P with respect to sulphur. During the more active part of the mission close to perihelion, additional sulphur-bearing species were detected which are also discussed.

### 2 OBSERVATIONS

In this paper, the distances between Rosetta and 67P are given with respect to the nucleus centre and time stamps are given in UTC.

#### 2.1 Rosetta/ROSINA

Since early 2014 August, the European Space Agency spacecraft Rosetta has been accompanying the Jupiter-family comet 67P. Part of the scientific payload is the ROSINA, which consists of two complementary mass spectrometers and a pressure sensor. Here we will only introduce the Double Focusing Mass Spectrometer (DFMS). The main characteristics of DFMS are a high mass resolution of $m/\Delta m = 3000$ at 1 per cent peak height on mass-to-charge ratio 28 u/e and its dynamic range of 10$^6$ making it possible to measure minor species. Besides this, DFMS is designed in such a way that it covers a mass range from $m/z = 12$–140 u/e, has good energy focusing properties in order that $\Delta E/E$ is up to 1 per cent and a high mass dispersion in the focal plane making it possible to use a position-sensitive detector (Balsiger et al. 2007).

#### 2.2 Measurements

ROSINA was almost continuously sampling the coma since the beginning of mission in 2014 August. Thus, the S-bearing species H$_2$S, SO, OCS, S$_2$, SO$_2$, CS$_2$ and atomic sulphur could be followed over a long period between the spacecraft arrival in 2014 August and perihelion in 2015 August. Since H$_2$S is the major sulphur species in the coma, its evolution has been followed during the entire period between beginning of mission to perihelion. For the remaining species listed before, data between equinox in 2015 May and perihelion in 2015 August have been analysed. Furthermore, our work has focused on several periods for which the local densities were high:

(i) October 2014, when Rosetta was within 10 km distance to the comet centre for about 15 d;
(ii) February 14 during a subsolar flyby going down to 8 km;
(iii) March 28 during a flyby going down to 15 km;
(iv) July 30–31 for SO and CH$_3$SH because 67P was almost at perihelion and Rosetta was closest to the comet within the following six weeks.

Those four periods were scrutinized for the presence of S-bearing molecules other than those listed above since the high local densities permit observations of minor species. Fig. 1 shows Rosetta’s orbital parameters such as the latitude in the frame attached to comet 67P (Scholten et al. 2015) and heliocentric distance between

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Table 1. Abundance of S-bearing species relative to water. This table is based on table 1 in Rodgers & Charnley (2006) and on table 1 in Bockelée-Morvan et al. (2004a). Please note that most of these values come from remote sensing measurements, for which CS is assumed to be the photodissociation product of CS$_2$.
equinox May 10 and perihelion 2015 August 13. The uppermost panel shows the subsatellite latitude as defined by Scholten et al. (2015) and the phase angle. In the middle panel, the nadir-off pointing and local time are shown while the lower panel shows the heliocentric and cometocentric distance. The first dark grey rectangle denotes the period as the phase angle changed from about 60◦ while the second light grey rectangle denotes the period when Rosetta did the transition from the equator to −45◦ back to the equator.

3 DFMS DATA TREATMENT
All data used in this study were acquired with ROSINA/DFMS in high-resolution mode (see Balsiger et al. 2007). In the following section, the operation principle of DFMS and the data reduction will be summarized. Both have been explained in more detail by Le Roy et al. (2015) and references therein.

3.1 DFMS operation principle
DFMS is operated in such a way that positively charged primary ions entering the instrument in neutral mode have energies outside the allowed energy range of ΔE/E = 1 per cent. Thus, they will not be transmitted towards the detector. The ion source is located after the entrance slit. Neutral particles are ionized by electron impact ionization at 45 eV. This process leads to positively charged atomic and molecular ions, which are either the corresponding parent molecule or one of its fragments. Therefore, even in neutral mode, what is ultimately detected is/are the corresponding ion(s). In most cases, the ions are singly charged but occasionally also doubly charged particles are detected at half the mass. Due to its construction, DFMS can sample only a single mass spectrum in high-resolution mode at a time. In order to observe a certain mass-to-charge ratio (CM), a mass-dependent acceleration voltage is applied. Then the ions are guided towards the analyser which consists of a 90◦ electrostatic energy analyser and a 60◦ magnetic sector. In the electrostatic analyser, the ion beam is focused according to the ion energy while in the magnet focusing occurs based on the mass-to-charge value of the ions. The ions are detected by the microchannel plate/Linear Detector Array (MCP/LEDA), which consists of two MCPs in chevron configuration followed by a position-sensitive imaging detector (Berthelier et al. 2002; Nevejans et al. 2002; Balsiger et al. 2007). This detector consists of two rows (A and B) with 512 pixels each. Each impinging ion releases an electron cascade in the MCP depending on the ion’s energy, species, the voltage applied on the MCP and its degree of deterioration. The incoming electron current on the LEDA is measured in analogue mode and converted to a digital signal. Before a spectrum is acquired, the on-board software sets the overall gain to one of 16 pre-defined gain steps (GS) which represent 16 different potentials applied on the MCP. Each spectrum represents 3000 individual 6.6 ms scans which are added together. For CM above 70 u/e, an additional potential is applied at the front plate of the MCP to enhance...
the ion energy and consequently enhance the electron cascade in the MCP.

3.2 Data reduction

The nominal data reduction procedure for DFMS MCP-LEDA data is done in five steps: (i) subtract LEDA offset, (ii) convert Analog-to-Digital-Converter (ADC) counts to ions per spectra, (iii) derive mass scale, (iv) determine signal per spectra for species \(j\) and (v) calculate number density for species \(j\). Due to the working principle of the LEDA, first a charge (in other words an offset) has to be applied on each pixel (Nevejans et al. 2002). This offset on the detector can be represented by a polynomial of third order degree with different parameters for rows A and B. In principle, the shape of the curve is preserved for each row but the level can vary by about 10 per cent. However, a deviation of this shape has been observed for CM which are a few integer u/e away from 18 u/e, 28 u/e and 44 u/e. This deviation indicates that there are disturbances to the offset due to the high signal of the very abundant species. Therefore, for every spectrum, a polynomial is done in areas where no peaks are detected. The ADC counts \(\text{counts}_{\text{ADC}}\) per pixel are converted to ion counts per pixel and spectra \(n_{\text{ioa}}(p)\) using

\[
n_{\text{ioa}}(p) = \frac{\text{counts}_{\text{ADC}}(p) \cdot c_{\text{ADC}} \cdot c_{\text{LEDA}}}{pg(p, GS) \cdot g_{\text{MCPS}}(GS) \cdot e \cdot y},
\]

where \(c_{\text{LEDA}} = 4.2 \times 10^{-12} \text{F}\) is the LEDA capacitance, \(c_{\text{ADC}} = 2.5/(2^{12} - 1)\) V is the ADC conversion factor, \(e\) is the elementary charge and \(y\) is the yield of the MCP (Meier & Eberhardt 1993). For DFMS, the MCP yield is part of the measured sensitivity since one cannot separate ionization, transmission and detection yield for calibration measurements. Besides the constant conversion factors, there are two operation time-dependent factors. First, there is the overall gain of the MCP depending on the applied GS \(g_{\text{MCPS}}(GS)\). The second one is the dimensionless pixel gain correction factor \(pg(p, GS)\), which represents the deterioration over time due to releasing electron avalanches in the MCP for each individual pixel and GS. Measurements to determine these factors are executed regularly over the course of the mission. For GS which are not measured, an empirical law is applied to calculate the missing ones. In order to take into account that the detector deterioration is a time-dependent process, a linear interpolation is used between two pixel gain campaigns. For this study, the contribution of spacecraft background has not been taken into account because for the sulphur-bearing species only \(\text{H}_2\text{S}\) was present marginally before the encounter (range of a few detector counts) and for \(\text{H}_2\text{O}, \text{CO}\) and \(\text{CO}_2\), the cometary signal is a few orders of magnitude higher than the spacecraft background before encountering 67P. In addition, only row A has been taken into account, which should have no impact since only relative abundances are presented. For DFMS, the pixel on the LEDA is associated with a certain mass per charge ratio. The relation is

\[
M(p) = M_0 \cdot e^{(p-p_0)/x}H_0,(D-z),
\]

where \(M(p)\) is the mass per charge for pixel \(p\), \(M_0\) is the set mass per charge ratio CM, \(p_0\) is the centre of the ion beam associated with \(M_0\), \(x = 25 \mu\text{m}\) is the distance between two pixels, \(D = 127000 \mu\text{m}\) is the dispersion factor and \(z\) is the zoom factor which is 6.4 for the data shown in this paper. For a more detailed description, the authors refer to Le Roy et al. (2015).

An automatic analysis software has been used to determine the peak area, relative to number of detected ions, corresponding to \(S, \text{H}_2\text{S}, \text{SO}, \text{SO}_2, \text{OCS}, \text{SO}_2, \text{CS}_2, \text{H}_2\text{O}, \text{CO}\) and \(\text{CO}_2\). It uses a simplex algorithm, which yields consistent results. However, in order to obtain accurate results, the characteristics of DFMS and the available knowledge on the coma constituents of 67P are taken into account. This means the mass scale is defined based on the identified peaks in a spectrum. In the case of overlapping species, we use an analytical description of a single species signal, which can be described by the sum of a narrow high Gaussian and a broad small Gaussian, as introduced by Le Roy et al. (2015). Unfortunately, \(S_2\) could only be determined using the software between the mission start and a few weeks after equinox. After these times, the signal became too low and data had to be analysed manually. For comparison between manual and automatic analysis, the entire data set from 2015 July has been selected, since higher signals close to perihelion were expected. Another special case is SO because there is an interference with CHCl. The automatic analysis software could not fit this properly since the peaks were too close together. Samples from each of the four periods yielded a deviation of the signal due to SO, and the maximum deviation between automatic and manual analysis is 20 per cent. In order to follow SO over the mission, the signals of both SO and CHCl have been used. For the \(\text{CS}, \text{H}_2\text{CS}, \text{CH}_3\text{SH}\) and \(\text{C}_2\text{H}_4\text{S}\), the automatic analysis could not be used as there were too many interferences with other species or the signal-to-noise ratio was too low. These spectra have been analysed semi-automatically using a constrained least-squares fit. The constraints were obtained from the peak centre of the identified species. The number density of species \(j\) \((n_j)\) in the vicinity of DFMS entrance is given by

\[
n_j = \frac{n_{j,\text{ioa}} \cdot \frac{\Sigma_i q_i}{Q_o} \cdot S_j}{\Sigma_i Q_i},
\]

where \(n_{j,\text{ioa}}\) is the number of ions in the spectra due to species \(j\), \(t_{\text{ioa}} = 19.8 \text{s}\) is the total integration time per spectra, \(\frac{\Sigma_i q_i}{Q_o}\) is the fragmentation of \(j\) relative to the total amount of fragments produced in DFMS’s ion source and \(S_j\) is the total sensitivity of the species \(j\). In order to obtain the correct value for \(n_{j,\text{ioa}}\), the measured signal has to be corrected for the contribution from other species. For example, \(S\) is produced through electron ionization of every sulphur-bearing species in the ion source of DFMS. Thus, the signal on m/e 32 u/e for \(S\) has to be corrected for all the contributions at 32 u/e originating from other S-bearing molecules. Due to the sequential nature of the DFMS measuring mode, different species are in general not obtained simultaneously. Therefore, for the purposes of corrections between species and comparison between species, the closest measurements within 40 min have always been used. If there was none, then the data set has not been taken into account. Species fragmentation patterns and sensitivities are instrument-specific. Consequently, calibration measurements need to be done with the instrument copy of DFMS in the lab. However, it is not possible to calibrate every species seen in the coma since some of them are dangerous for human health and/or the instrument like HCN, for example. For these species, the fragmentation pattern from the National Institute of Standards and Technology (NIST) data base (Stein et al. 2016) is used as a first approach. Both NIST and DFMS use the same process for ionization, but the electron energy used is different. For NIST it is 70 eV while the nominal value for DFMS is 45 eV. Laboratory work with DFMS has shown that in general slightly fewer fragments are produced in DFMS. Consequently, using NIST fragmentation patterns will lead to a slight underestimation of the parent molecule. For some molecules like \(\text{H}_2\text{CS}, \text{H}_2\text{S}, \text{SO}\), there are no fragmentation patterns reported in the NIST data base. In such cases, the fragmentation pattern of a molecule with similar structure and constituting molecules has been used. For the sensitivity, an empirical relation between the
CM of the parent molecule and the sensitivity has been established. The input parameters are the CM of the parent ion e.g. for CH$_3$SH it would be 48 u/e and the ionization cross-section at 45 eV that has been taken from the NIST data base (Llovet et al. 2014). Table 2 lists it would be 48 u/e and the ionization cross-section at 45 eV that has been taken from the NIST data base (Llovet et al. 2014). Table 2 lists the detected species and references for their fragmentation patterns and sensitivities used to derive the reported number densities.

### 3.3 Measurement uncertainties

Part of the data reduction is the correction for the deterioration of the MCP and its gain over the course of the mission. In order to determine the deterioration, calibration measurements are done on a regular basis and the uncertainty due to these corrections is assumed to be not larger than 7 per cent. The remaining uncertainties are given by the uncertainty of the overall gain (5 per cent) and the uncertainties of measured sensitivities and fragmentation patterns. For species which were not calibrated with the instrument copy in the lab, the situation is more difficult since here we can only estimate the uncertainties introduced using NIST values and calculated sensitivities. We generally assume in this case a 10 per cent uncertainty for the fragmentation pattern. The uncertainty of the sensitivity can be up to a factor of 2. This represents a constant systematic uncertainty which affects absolute abundances and ratios while the relative change of these is not affected. As a consequence, this systematic uncertainty is not taken into account for the error propagation as it would mask the real changes in signal. However, this bias will be discussed together with the final results. For SO, another 20 per cent has been taken into account since at least 80 per cent of the peak area of the cumulative peak of SO and CHCl determined automatically is due to SO. Based on the uncertainties described above, we obtain the final statistical and methodical uncertainties for densities and relative abundances.

### 4 RESULTS

This section is divided into five subsections.

(i) First, we present the detection of S-bearing species never before observed in comets.

(ii) Then we focus on the question whether S, SO, H$_2$CS and CS are of cometary origin or a product of fragmentation of higher mass parent species in DFMS’s ion source.

(iii) Afterwards we show the quantitative impact of photodissociation and photoionization on the species in the coma.

(iv) For H$_2$S, the changes in abundance relative to H$_2$O are shown in order to see how the major species contribute to the S and O budget over the mission.

(v) For S, SO, OCS, S$_2$, SO$_2$ and CS$_2$, the changes in abundance relative to H$_2$S are presented between equinox in 2015 May and perihelion in 2015 August.

(vi) The evolution of the SO/SO$_2$ ratio is presented between equinox and perihelion.

(vii) Finally, the elemental abundance S/O based on the local densities of the above-mentioned species and H$_2$O, CO, CO$_2$ and O$_2$ between equinox and perihelion in 2015 August is presented.

#### 4.1 Detection of new S-bearing species

4.1.1 Observation of CH$_3$SH and C$_2$H$_5$S

The equivalent of methanol with S substituting O is methanethiol (CH$_3$SH). In Fig. 2, for each of the selected periods, a sample spectrum is shown. From this graph, it can be seen that CH$_3$SH has an interference with C$_4$ and H$_2$NO$_2$. However, the latter one is of minor importance. The peak is too broad to be solely due to C$_4$, and of the C, H, N, O and S-bearing molecules CH$_3$SH fits best.

In 2014 October during the 10 km period, a signal on the m/z 62 u/e temporarily appeared which could be linked to C$_2$H$_5$S. In total, four spectra show this signal in 2015 October. In addition, it could be detected again during 2016 March 28 when local coma densities were comparable. From both periods, two representative spectra are shown in the right-hand panel of Fig. 3. It is seen that the peak is not centred on C$_2$H$_5$S, most likely due to the presence of C$_2$H$_3$S, a fragment of a heavier hydrocarbon. The mass scale has been calibrated thanks to the presence of OC$_{14}$S that is not shown here. The peak around m/z 62.015 u/e is slightly asymmetric indicating the presence of an additional species. A preliminary search suggested CH$_3$NO$_2$, but this will not be discussed further here.

As a consequence of the similarity in mass-to-charge ratio of C$_2$H$_5$S and C$_2$H$_3$S, mass spectra at lower integer m/z ratio have to be checked for corresponding fragments of both molecules for the unambiguous detection of C$_2$H$_5$S. This is further complicated...
S-bearing species at 67P/Churyumov–Gerasimenko

Figure 3. From right to left are shown mass spectra with \( m/z \) 59, 61 and 62 u/e of DFMS MCP-LEDA row B. Two of the measurements were acquired in 2014 October during the 10 km orbits and two around equinox in 2016 March. Identified peaks are indicated with labelled dashed lines.

because C\(_2\)H\(_6\)S has two isomers ethanethiol and dimethyl sulphide. The major difference in fragmentation pattern according to NIST is for the fragment CH\(_3\)S on \( m/z \) 48 u/e which is formed from ethanethiol and dimethyl sulphide by 47 per cent and 96 per cent of the parent, respectively. Unfortunately, CH\(_3\)SH contributes as well to CH\(_3\)S. The signal (not densities!) of CH\(_3\)SH is about an order of magnitude larger than that of C\(_2\)H\(_6\)S. Thus, nothing can be learned about the structure of C\(_2\)H\(_6\)S from the measured CH\(_3\)S. For most of the major fragments of the two isomers, there is interference with another species or its fragments. This leaves signals above \( m/z \) 59 u/e for comparison. The most abundant fragment with \( m/z > 59 \) u/e is on \( m/z \) 61 u/e but this mass there is the overlap with C\(_2\)H as can be seen from the middle panel of Fig. 3. In order to have no interference with the fragments of the type C\(_x\)H\(_y\), one has to check \( m/z \) 59 u/e on which, according to NIST, a signal relative to parent between 3 per cent and 7 per cent is expected for ethanethiol and dimethyl sulphide, respectively. The corresponding mass spectra of 59 u/e are shown in the left-hand panel of Fig. 3. It can be seen that the signal appears rather small. In addition, there might be a contribution from CH\(_2\)NO\(_2\), and by comparing the amplitude of the peaks on \( m/z \) 59 and 62 u/e, none of them fits with the fragmentation pattern of NIST. However, the presence of a signal on \( m/z \) 59, 61 and 62 u/e confirms that C\(_2\)H\(_6\)S is present in the volatile phase of 67P. Although it cannot be distinguished between the two isomers ethanethiol and dimethyl sulphide.

4.1.2 Observation of S\(_3\) and S\(_4\)

Already at about 2 au it became evident that molecules with masses up to 100 u/e, at the end of DMFS nominal mass range, were present. In 2015 March during a close flyby, signals on \( m/z \) 96 u/e were detected in 14 spectra acquired over a period of 12 h. Careful data analysis indicated S\(_3\) to be a likely candidate. When 67P was closer to perihelion and the environment became dusty, it became evident that molecules with higher masses were present as well. The \( m/z \) range was therefore increased up to 140 u/e. The higher the measured mass, the lower the sensitivity. Nevertheless, DFMS detected some molecules in this mass range. Among these were again clear peaks on \( m/z \) 96 u/e and in addition on 128 u/e. Careful data analysis revealed that these peaks are due to S\(_3\) and S\(_4\). It is not clear if these are real parent molecules or if they are the products of even heavier S\(_n\), which fragment into S\(_3\) and S\(_4\) Fig. 4 shows the spectra of the highest signal of S\(_3\) acquired with row B. However, it is very likely that these species represent the products of radiolysis of H\(_2\)S ice as described in e.g. Woods et al. (2015). The condensation temperature of S\(_3\) is \( \sim 280 \) K. For S\(_4\) it is even higher. It is unlikely that they desorb directly from the nucleus, as the surface temperature of the nucleus is too low even at perihelion according to the model of de Sanctis, Capria & Coradini (2005). Their model predicts surface temperatures on the dayside at perihelion to be below 260 K for a dusty crust and to be lower than 200 K for the water-containing layer underneath. Temperatures are therefore most likely not high enough to release S\(_3\) or S\(_4\) directly from the nucleus. Dust grains released into the coma can reach much higher temperatures (Lien 1990), thus making the release of S\(_3\) and S\(_4\) possible. There is circumstantial evidence pointing to dust as source. First of all, S\(_3\) has been detected during the flyby in March where a considerable amount of dust was in the vicinity of Rosetta resulting in a safe mode of the spacecraft. Secondly, the further S\(_3\) detections have all been done during a slew of Rosetta on 2015 August 4 when Rosetta turned its instrument platform more towards the Sun. In the foregoing
measurement period between the end of 2015 July and 2015 August 4, the instrument platform of Rosetta was hardly sunlit and Rosetta was in a dusty environment as it approached perihelion. Thus, it is assumed that some dust grains were collected and preserved. During the slew on 2015 August 4, some of it is thought to be exposed to the Sun, heat up and disintegrate. Thirdly, previous and subsequent slews of the same kind did not result in further detections of S3 and S4 indicating that the reservoir was depleted. Fourthly, the same measurement procedure during the cruise phase of Rosetta did not result in further detections; thus, it is unlikely that S3 and S4 were part of the spacecraft background.

There are only a few measurements of these species always associated with clear signatures of dust. As S3 and S4 are most likely part of the spacecraft background, high. In Fig. 5, we show four representative spectra of S2H and H2S lead to the formation of S2H and H2S, in the ice (Jiménez-Escobar et al. 2012). To check the presence of these molecules in the coma of 67P, October 25 has been selected because during that time the local density for H2S is very high. In Fig. 5, we show four representative spectra of m/z 65 u/e, acquired between 23.10.2014 12:00 and 26.10.2014 02:20 which is equivalent to more than one full rotation of 67P, together with identified species indicated by dashed lines. Fig. 5 shows no distinct peak due to S2H, which is further complicated by the interference between S2H and 33SO2. It is not possible to check for the presence of H2S since it has almost the same mass-to-charge ratio as 34SO2 and cannot be resolved by DFMS.

4.1.3 Search for H2S2 and S2H

Laboratory experiments of UV irradiation of ice mixtures of H2S and H2O lead to the formation of S2H and H2S2 in the ice (Jiménez-Escobar et al. 2012). To check the presence of these molecules in the coma of 67P, October 25 has been selected because during the 10 km orbits the local density for H2S on this day was very high. In Fig. 5, we show four representative spectra of m/z 65 u/e, acquired between 23.10.2014 12:00 and 26.10.2014 02:20 which is equivalent to more than one full rotation of 67P, together with identified species indicated by dashed lines. Fig. 5 shows no distinct peak due to S2H, which is further complicated by the interference between S2H and 33SO2. It is not possible to check for the presence of H2S since it has almost the same mass-to-charge ratio as 34SO2 and cannot be resolved by DFMS.

4.2 Origin of S, SO, H2CS and CS

4.2.1 Atomic sulphur

The ROSINA measurements show a surprisingly large amount of atomic sulphur (S) in the coma of 67P. In order to determine the amount of atomic sulphur, one has to take into account the contributions from the heavier S-bearing molecules. These contributions arise from electron ionization of S-bearing molecules into S+ + A inside the mass spectrometer whereas A can be [X] + e−, [X]+ or [X]+ + 2e−. After the subtraction of all these contributions, the remaining S-signal is due to atomic sulphur in the coma. Fig. 6 shows an overview of these contributions, for the major S-bearing molecules using the data since beginning of the mission until 2015 August. One can see a strong correlation between the measured atomic sulphur signal and H2S, which is the most dominant source of fragmented sulphur. Good knowledge of the molecules’ individual fragmentation patterns is essential to make accurate statements about the different contributions and finally the amount of atomic S. DFMS was calibrated for H2S, but for other compounds the NIST data base was used (see Table 2). On average, the ratio between S due to H2S and total measured S is about 20 percent while all the other contributing molecules together deliver about 5 percent of the total measured S. To explain the total measured S with H2S in the coma, one would need about a factor of 5 more H2S than...
detected. All other sulphur-bearing species, even with larger uncertainties in terms of DFMS’s fragmentation pattern, cannot account for the signal on atomic sulphur. Thus, atomic sulphur can be clearly identified as a species in the coma though its origin, whether it is released from a substance on the surface or within the nucleus, is not clear yet.

### 4.2.2 SO

First, it has to be asserted whether SO is indeed released from the nucleus. This is important as SO also forms through photodissociation in the coma and, more importantly, through electron impact ionization of SO$_2$ inside the ion source of DFMS. According to NIST, 49 per cent of SO$_2$ fragments into SO$^+$ ions by electron impact bombardment, the type of ionization used in DFMS. Therefore, based on the abundance of SO$_2$, a corresponding amount of SO has to be subtracted from the total SO signal. Fig. 7 shows the measured total signal of SO with respect to SO$_2$ between beginning of the mission in 2014 August and perihelion. The black line indicates the amount of SO expected from dissociation of SO$_2$ in DFMS, in case the comet contains no parent SO. Theoretically, no signal for SO can be below (the black line) what is produced by the fragmentation of SO$_2$ inside the instrument. However, given that DFMS measures SO and SO$_2$ not at the same time but with a time shift of approximately 8 min, the SO abundance can occasionally drop below this line, even more so when the spacecraft attitude changes within the observation period. Nevertheless, it becomes apparent that SO$_2$ alone cannot explain the observed signal of SO. OCS (carbonyl sulphide) is the only other species detected so far containing S and O. But according to NIST, its fragmentation does not produce SO ions. According to Huebner & Mukherjee (2015), the photodissociation rate for SO$_2$ to SO is at 1 au $1.59 \times 10^{-8}$ s$^{-1}$. As a consequence, the contribution to SO is negligible as the gas propagation time is merely seconds from the surface of the comet to Rosetta (see Table A1). Sulphur monoxide can therefore clearly be identified as a species in the coma, i.e. to be present in the ices in the form of SO, outgassing from the nucleus itself and/or from an additional source.

**Figure 7.** Total measured SO abundance including contribution from fragmentation of SO$_2$ (black squares). The black line shows the contribution to SO by fragmentation of SO$_2$ inside DFMS’s ion source.

### 4.2.3 H$_2$CS

The signal of thioformaldehyde (H$_2$CS), the equivalent of formaldehyde, has a mass-to-charge ratio of about 46 u/e. Unfortunately, C$^{16}$O$^{18}$O has a similar mass-to-charge ratio. Therefore, the signal of H$_2$CS, if present, is most of the time hidden in the signal due to the isotopologue of CO$_2$. Nevertheless, during the close flyby on 2015 March 28, the density of CO$_2$ was low enough to reveal the corresponding signal of H$_2$CS. In Fig. 8, we show the typical signal of the $m/z$ 46 u/e in grey (squares), the spectra with the least contribution of C$^{16}$O$^{18}$O during the flyby in black (circle) and the fit considering H$_2$CS, NO$_2$ and C$^{16}$O$^{18}$O. Indicated by dashed black lines are the location of identified species as C$^{16}$S or C$_2$H$_4$O. Although there is no distinct peak due to H$_2$CS, there is as well not a distinct peak due to C$^{16}$O$^{18}$O and NO$_2$ as in other cases. This signal shape is best explained by two or more species with similar signal strength close to each other. Of all species with a lower mass-to-charge ratio than NO$_2$, it is H$_2$CS which fits best. However, the signal has to be corrected for the fragment of CH$_3$SH which was present as well. In Fig. 9, a comparison is done between the measured signal (not density) of H$_2$CS and the fragment of CH$_3$SH. The first two and the last measurements of H$_2$CS could be explained solely by the presence of CH$_3$SH taking into account uncertainties (σ). However, this is not the case for the remaining measurements. Even assuming 3σ boundaries, H$_2$CS could only be explained in half of the remaining cases by fragmentation of CH$_3$SH inside DFMS. In addition, no distinct signal due to C$_2$H$_4$S. Consequently, thioformaldehyde can be clearly identified as a species in the coma, i.e. to be present in the ices in the form of H$_2$CS, either outgassing from the nucleus itself or from an additional source.

In addition to H$_2$CS, the spectrum of 2014 October 25 at 17:13 UTC indicates the presence of an additional species because the signal does not decrease between C$^{15}$S and the cumulative peak of C$^{16}$O$^{18}$O, NO$_2$ and H$_2$CS (Fig. 8). Considering volatile species bearing C, N, H, O and S, it is NS which fits best. However, a first check of the 10 km data in 2014 October for other and stronger signals at the location of NS was not successful. This is therefore only a tentative detection.
The radical CS has been detected in numerous comets by remote sensing observations (see Table 3) but for 67P no CS has been reported yet. In terms of DFMS, it has an interference with CO₂ on m/z 44 u/e. Thus, similar to H₂CS, the best chance to detect CS is when CO₂ is comparatively low. In addition, it is crucial to know how much CS is present due to the fragmentation of H₂CS, OCS, CS₂ and CH₃SH. The total measured CS with 2CS produced inside DFMS, is due to OCS followed by CS₂, H₂CS and CH₃SH. The contribution due to C₂H₆S can be neglected first because the parent signal is already small and second according to NIST only about 4 per cent of the parent fragments into CS. The analysis is then restricted to the flyby during 2015 March when H₂CS was detected. In Fig. 10, the total measured signal of CS is shown in grey. In addition, the contributions to CS from other molecules are shown. The largest contribution to CS, produced inside DFMS, is due to OCS followed by CS₂, H₂CS and CH₃SH. The total measured CS with 2σ boundaries lies within the calculated range (2σ) of CS fragments. Thus, CS was not detected in the coma of 67P in 2015 March. Thus, contrary to SO and S, CS is not originating directly from the nucleus of 67P. Outside of this period, no statement can be done since a possible CS signal was in general overlapped by the signal of CO₂.

### 4.3 Abundance ratios

#### 4.3.1 Impact of photodissociation and ionization on abundance ratios

Most of the time between equinox and perihelion Rosetta spent within 200 km of the nucleus while the heliocentric distance was decreasing from 1.66 to 1.24 au. Closer to the Sun, photodissociation and ionization potentially become more important for the coma composition since the rates increase. Photodissociation and ionization rates for most sulphur-bearing species in this study have been computed from the values by Huebner & Mukherjee (2015) at 1 au for active and quiet Sun. Here we used the values for quiet Sun. The photodissociation and ionization rates at different heliocentric distances have been estimated assuming a 1/r² law. In order to take into account the distance to the comet, it has been assumed that 

$$N = N_{0} \cdot \exp^{-\beta t}$$,

where β is the photodissociation/ionization rate at a certain heliocentric distance and t the time it takes for a particle to fly from the nucleus’ surface to the spacecraft. Based on the

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**Table 3.** Assumed half-values (±1σ, me) in the coma of 67P relative to H₂O and H₂S, respectively. The upper panel gives the ratio without taking into account loss and gain of species in the coma due to photodissociation/ionization while in the lower panel the values have been corrected (see Section 4.3.1).

<table>
<thead>
<tr>
<th>Relative to</th>
<th>H₂S</th>
<th>H₂O</th>
<th>SO²</th>
<th>S₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ (per cent)</td>
<td>0.68×10⁻²</td>
<td>0.10×10⁻⁵</td>
<td>0.68×10⁻²</td>
<td>0.10×10⁻⁵</td>
</tr>
<tr>
<td>H₂S (per cent)</td>
<td>60.71</td>
<td>100</td>
<td>60.71</td>
<td>100</td>
</tr>
<tr>
<td>H₂O (per cent)</td>
<td>14.11</td>
<td>14.4</td>
<td>14.11</td>
<td>14.4</td>
</tr>
<tr>
<td>SO² (per cent)</td>
<td>50.07</td>
<td>100</td>
<td>50.07</td>
<td>100</td>
</tr>
<tr>
<td>S₂ (per cent)</td>
<td>50.07</td>
<td>100</td>
<td>50.07</td>
<td>100</td>
</tr>
</tbody>
</table>

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Systematic uncertainty of sensitivity is estimated to be 50 per cent and not included here.

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Uncertainty of 20 per cent due to the automatic treatment is taken into account here.

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4.10.15-26.07.2015 show positive latitudes and corrected for photodissociation/ionization: S₂/H₂O ≈ 0.95 ± 0.46 × 10⁻⁴ = 6.35 × 10⁻⁵, S₂/H₂S ≈ (3.41 ± 0.35) per cent, σ = 4.90 per cent.
S-bearing species at 67P/Churyumov–Gerasimenko

4.3.2 Abundance of $\text{H}_2\text{S}$ relative to water

Fig. 11 shows the relative $\text{H}_2\text{S}$ abundance compared to water. The spread of the values is considerable, ranging from below 0.1 per cent to almost 10 per cent. This is not due to uncertainties of the measurement as the statistical error is rather small, but rather to the relative position of the spacecraft to the comet, illumination conditions, seasonal and diurnal variations, and heliocentric distance.

$\text{H}_2\text{S}$ is more volatile than $\text{H}_2\text{O}$. Whereas the sublimation temperature of $\text{H}_2\text{S}$ is $\sim 80$ K (Collings et al. 2004), a temperature which is reached according to de Sanctis et al. (2005) even at aphelion, the sublimation temperature for water is only reached inside of 3 au. One would therefore expect that the $\text{H}_2\text{S}/\text{H}_2\text{O}$ ratio would drop dramatically with decreasing heliocentric distance outside of the water snow line, which is outside of $\sim 2.8$ au. This is clearly not the case. In the beginning of the mission between 2014 August and November, which is heliocentric distances between 3.6 and 3 au, the ratio increased by a factor of 10. The spacecraft spent most of this time in terminator orbit sampling both hemispheres. There is a strong asymmetry between the two hemispheres where $\text{H}_2\text{S}$ is depleted in the southern winter hemisphere (Fig. 12) early in the mission, thus following water and not $\text{CO}_2$ (Hässig et al. 2015), although $\text{H}_2\text{S}$ is more volatile than $\text{CO}_2$. The Northern hemisphere at these large heliocentric distances is depleted in most volatiles (Le Roy et al. 2015). There are several possibilities why the ratio of water to more volatile species is different from the northern part of the neck. It could be due to layering as more volatile species have been sublimated whereas water has not. However, this is in contradiction to the fact that in the Southern hemisphere during the long winter this apparently did not happen, although temperatures according to de Sanctis et al. (2005) would have been high enough for the more volatile species. Then the Visible and Infrared Thermal Imaging Spectrometer has seen a recondensation of water from the interior (De Sanctis et al. 2015). However, this is a diurnal variation and would not explain our measurements which are seasonal and not diurnal, e.g. Rubin et al. (2014). As the excessive water production comes mainly from the neck area (Fougere et al. 2016) where there is a gravitational potential well, another explanation could be...
transport of water ice grains during the perihelion passage to the dark side of the nucleus as observed earlier in the mission by the camera OSIRIS (Thomas et al. 2015). Like this the local ice composition would be changed in favour of water and in consequence it would appear to be less rich in volatiles.

Between 2015 February and end of June, the H₂S/H₂O ratio stayed remarkably constant. The sublimation temperature of pure H₂S ice in ultrahigh vacuum is 80 K (Collings et al. 2004). However, if H₂S is in a water matrix, a large fraction of the H₂S co-desorbs with H₂O in the 130–170 K temperature range, showing two maxima around 145 and 163 K (Jiménez-Escobar & Muñoz Caro 2011).

According to Jiménez-Escobar & Muñoz Caro (2011) and Viti et al. (2004), no sulphur-bearing species shows a desorption behaviour like CO in an ice matrix, although for example pure S₂ has a condensation temperature of 20 K, therefore even below CO. They classify the sulphur-bearing species according to their sublimation behaviour:

(i) HS, H₂S₂, OCS, H₂S, SO₂, HCS, NS as intermediate, showing two peaks when warmed up;
(ii) H₂CS, SO as water-like;
(iii) S₂, CS₂, S-residue as refractory.

The constant ratio between water and H₂S over many months and the strong very similar heterogeneity of the two species in the coma could very well reflect this desorbing pattern. From the end of June until perihelion in mid-August, the spacecraft encountered significant dust. The H₂S/H₂O ratio increased by at least a factor of 3. From this, we deduce that at least part of the H₂S is associated with dust grains or that deeper layers of the comet experienced temperatures above 82 K, the sublimation temperature of pure H₂S ice into ultrahigh vacuum (Collings et al. 2004). As cometary dust gets hot in the coma (Lien 1990), much hotter than the cometary surface, dust can shed its semi-volatile mantle, thus releasing many of the molecules which are most probably present in the dust mantle. Icy grains in the coma, which would mostly release water vapour, would not increase the H₂S/H₂O ratio. In addition, due to higher production rates and thus higher gas drag, there are also more and bigger dust particles in the coma, which are not only due to the surface layer of the comet, but are released by the jet-like features of the comet from the interior. The increase of H₂S/H₂O during perihelion is most probably not a purely seasonal effect as the spacecraft spent most of this time over the Northern winter hemisphere.

It is hard to say which value represents best the bulk H₂S/H₂O ratio for the comet. The most plausible value for the bulk is the value after equinox up to the start of the phase where there was significant dust. During this time, the less dust covered Southern hemisphere was sunlit and the comet was well inside the water ice line with sublimation of water and H₂S. The mean value corrected for photodissociation and ionization of H₂S/H₂O between 10.05 2015 and 30.05 2015 is (1.10 ± 0.05) per cent with σ = 0.68 per cent. The same period is used for all species to determine the bulk abundance.

4.3.3 Abundance of S, SO, OCS, S₂, SO₂ and CS₂ relative to H₂S between equinox and perihelion

Fig. 13 shows from top to bottom the abundance of S, SO, OCS, S₂, SO₂ and CS₂ relative to H₂S for the period between equinox and perihelion while the bottom panel shows the evolution of H₂S/H₂O. During this period, two significant changes in spacecraft attitude occurred. First, at the end of May 2015 Rosetta did a transition (highlighted in grey in Fig. 13) in phase angle from around 60° to 90° while going to the South Pole. Secondly, Rosetta went at the end of July after ~6 weeks above the Northern hemisphere to 45° south (highlighted in light grey in Fig. 13) then back to the equator together with a transition from 200 to 350 km distance to 67P (for more details, see Fig. 1).

This separates the presented data into four parts which are discussed in the following.

During the first period between equinox and end of 2015 May, S, SO, OCS, S₂, SO₂ and CS₂ follow H₂S which itself follows water. Thus, these species follow water very closely at that time. As previously mentioned, we use this period when being above southern latitudes to estimate bulk abundances of the volatile species in 67P. With mean ratio to water of 0.011, H₂S is the most abundant S-bearing species in the coma of 67P. The second most abundant species is S with 45.8 per cent with respect to H₂S while SO₂, SO and OCS are in the 10 per cent range relative to H₂S. S₂ and CS₂ have a mean value relative to H₂S of less than 1 per cent and are thus trace species. The measured mean values and the ones corrected for photodissociation are given in Table 3.

Between June 2 and July 26, Rosetta was constantly above Northern hemisphere; nevertheless, the density of S₂ increased by a factor of ~13 higher than the bulk value. The mean value for S₂/H₂S between July 1 and July 26 yields (3.41 ± 0.35, σ = 4.90) per cent. Then the subsolar point was between ~26° and ~40°; thus, in the Northern hemisphere there was winter. The significant increase between May (bulk) and July for S₂/H₂S implies that an additional source than sublimation from the nucleus is present for S₂ since the Northern hemisphere got less active. The fact that during the same period more dust was released implies a relation between the enhanced S₂ density and dust activity. In general, all species show more scattering between June 2 and 26. Nevertheless, they follow at large H₂S.

When Rosetta returned to the Southern hemisphere going down to ~45° latitude for SO₂/H₂S and SO/H₂S, a distinct decrease is present. For the remaining S-bearing species, only the S/H₂S ratio might show the same qualitative behaviour. However, the size of scattering is too large to make a meaningful statement. For both periods highlighted in grey, Rosetta was measuring above the Southern hemisphere; nevertheless, the abundances relative to H₂S do not show the same behaviour. This might be explained by the location of the subsolar latitude. Around 2015 June 1, it was around ~9° while beginning of 2015 August it was around ~43°. Thus, in the
Figure 13. The first six panels going from top to bottom show the abundance of S, SO, OCS, S$_2$, SO$_2$ and CS$_2$ relative to H$_2$S, while the last one shows the corresponding H$_2$S/H$_2$O ratio. The shown data cover the period between equinox on 2015 May 10 and perihelion 2015 August 13. The first grey strip shows the transition of the phase angle from 60° to 90° while the second one in lighter grey shows the period during which Rosetta was going from 0° to −45° and back to the equator while doing the transition from 200 to 300 km.

In essence, it is seen that none of the discussed species follow entirely H$_2$O nor H$_2$S. However, comparing the entire bulk period, the first two weeks of June and the period between July 26 and August 8, it can be seen that at least S follows more or less H$_2$S. This suggests in general a common origin in the ice matrix. In addition, OCS and SO$_2$ show the same general behaviour relative to
H₂S. Both stay constant until mid-June, and then at the end of July they show a similar decrease. S₂ and CS₂ both show an increase comparing beginning of July with May. However, beginning of August while Rosetta was going to larger cometocentric distances only S₂ decreases but not CS₂. The decrease for S₂ is thought to be at least partly due to photodissociation/ionization, although the degree of decrease is a factor of 3 higher than what would be expected from photodissociation/ionization. It is not understood yet why CS₂ did not decrease but a plausible explanation can be an additional source.

Comparing the resulting bulk values corrected for photodissociation and ionization (lower panel Table 3) with the values reported by Le Roy et al. (2015), it becomes clear that the bulk abundances for OCS and CS₂ are somewhere between the Northern and Southern hemisphere values while for SO, SO₂ and S₂ the bulk is higher.

4.3.4 Relative abundances of the organo-sulphur species to H₂S

In the following paragraph, we present the abundances of all sulphur-bearing species relative to H₂S for which we do not have continuous data over the mission. For CH₃SH the ratio relative to H₂S is shown in Fig. 14 for the four selected periods. As one can see from Fig. 14 mean ratio of CH₃SH to H₂S is within errors the same during the end of 2014 October and during the two flybys in 2015 February and March, respectively. However, at the end of 2015 July it increased significantly to (1.44 ± 0.42) per cent. Applying the correction due to photodissociation of CH₃SH for the last period, the mean yields (3.5 ± 1.0) per cent relative to H₂S. The measured mean values with 1σ for the above discussed periods are given in Table 4.

Based on the measurements during the flyby on March 28 for H₂CS, a mean value of (2.28 ± 1.38) × 10⁻³ for the abundance relative to H₂S could be determined. This value does not need to be corrected for photodissociation/ionization since measurements were obtained within 50 km distance to 67P at heliocentric distance of about 2.3 au. However, there is still the systematic uncertainty up to a factor of 2 which is not taken into account (see Section 3.3). Single values and the mean with 1σ are given in Table 5.

In the data of the 10 km orbits around 67P in 2014 October, a signal due to C₂H₆S could be identified in four spectra. Its presence could be confirmed by measurements from 2016 March when Rosetta was within 14–17 km distance to the centre of the nucleus. Thus, we had comparable local densities as in 2014 October. Assuming that the measured signal is either due to ethanethiol or dimethyl sulphide, the relative abundance to H₂S and H₂O could be derived for the four measurements (see Table 6). The resulting mean value with respect to H₂S assuming ethanethiol and dimethyl sulphide to be the parent is (3.38 ± 0.72) × 10⁻⁴ and (2.76 ± 1.47) × 10⁻⁴, respectively.

4.3.5 Upper limits for H₂S₂ and S₂H

Based on the four spectra shown in Section 4.1.3, it is possible to derive an upper for S₂H/H₂S and H₂S₂/H₂S during 2014 October. The estimated maximum peak area due to S₂H is 25 ions. Then one has to distinguish two cases, first S₂H is a fragment due to the ionization process in DFMS, second S₂H is present in the coma. For both S₂H and H₂S₂, neither fragmentation pattern nor ionization cross-section is reported in the literature. Thus, local densities were calculated using the fragmentation pattern of C₂H₂ since it has a similar molecular structure while for the ionization cross-section the one of S₂H has been used. Assuming that S₂H is present in the coma, this yields an upper limit for S₂H/H₂S of 1.0 × 10⁻⁴. In case S₂H is solely due to fragmentation of H₂S₂, the limit for H₂S₂/H₂S is 5.7 × 10⁻⁴. The uncertainties in these limits are estimated to be a factor of 10.

4.4 SO/SO₂

Fig. 15 shows the time series of SO/SO₂ between equinox and perihelion. The significant changes in spacecraft attitude and orbit are indicated by the dark and light grey areas (for more details, see Fig. 1). The values reported in the following paragraph have been corrected for the effects of photodissociation and ionization. Between equinox and end of May, the mean value for SO/SO₂ is 0.39 ± 0.01 (σ = 0.11). During this time, Rosetta was sampling evenly summer and winter hemisphere while staying between Sun and comet (phase angle < 90°). Between beginning of June and end of July, less data are available and the scatter of SO/SO₂ is about a factor of 6 higher than during the previous period. The mean is 0.59 ± 0.04 (σ = 0.66) and represents more the SO/SO₂ ratio for the northern latitudes during winter since around 81 per cent of the data were sampled above the northern latitudes. Between the end of July and perihelion, SO/SO₂ reached its maximum with a mean of about 2.3 au. However, there is still the systematic uncertainty up to a factor of 2 which is not taken into account (see Section 3.3). Single values and the mean with 1σ are given in Table 5.

Table 5. Relative abundances of H₂CS during the flyby in 2015 February with respect to H₂S and H₂O, respectively. At the bottom, the mean value (± 1σ) is given. Systemic uncertainty of up to a factor of 2 (see Section 3.3) is not taken into account.

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>H₂CS/H₂S</th>
<th>H₂CS/H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.03.2015 12:14</td>
<td>(5.27 ± 1.45) × 10⁻⁴</td>
<td>(2.67 ± 0.75) × 10⁻⁵</td>
</tr>
<tr>
<td>28.03.2015 12:20</td>
<td>(2.46 ± 0.59) × 10⁻³</td>
<td>(1.30 ± 0.32) × 10⁻⁵</td>
</tr>
<tr>
<td>28.03.2015 13:07</td>
<td>(1.78 ± 0.43) × 10⁻³</td>
<td>(1.14 ± 0.28) × 10⁻⁵</td>
</tr>
<tr>
<td>28.03.2015 13:13</td>
<td>(4.73 ± 1.11) × 10⁻³</td>
<td>(3.21 ± 0.78) × 10⁻⁵</td>
</tr>
<tr>
<td>28.03.2015 14:00</td>
<td>(1.92 ± 0.47) × 10⁻³</td>
<td>(1.25 ± 0.31) × 10⁻⁵</td>
</tr>
<tr>
<td>Mean ± σ</td>
<td>(2.28 ± 1.38) × 10⁻³</td>
<td>(1.43 ± 0.97) × 10⁻⁵</td>
</tr>
</tbody>
</table>

Table 4. Mean values (± σ) of CH₃SH relative to H₂S and H₂O, respectively. Systemic uncertainty of up to a factor of 2 (see Section 3.3) and the effect of photodissociation/ionization are not taken into account here.

<table>
<thead>
<tr>
<th>Period</th>
<th>CH₃SH/H₂S (per cent)</th>
<th>CH₃SH/H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014 October</td>
<td>0.35 ± 0.12</td>
<td>(2.85 ± 1.11) × 10⁻⁵</td>
</tr>
<tr>
<td>Flyby 14.02.2015</td>
<td>0.47 ± 0.22</td>
<td>(4.98 ± 3.80) × 10⁻⁵</td>
</tr>
<tr>
<td>Flyby 28.03.2015</td>
<td>0.40 ± 0.08</td>
<td>(2.64 ± 0.64) × 10⁻⁵</td>
</tr>
<tr>
<td>2015 July 30–31</td>
<td>1.44 ± 0.42</td>
<td>(2.19 ± 0.72) × 10⁻⁴</td>
</tr>
</tbody>
</table>
Table 6. Relative abundances of C$_2$H$_6$S in 2014 October relative to H$_2$S and H$_2$O, respectively with the mean value (± 1σ). Since DFMS cannot distinguish between ethanethiol and dimethyl sulphide, two cases were assumed. First, the signal is only due to ethanethiol and second only due to dimethyl sulphide. Systemic uncertainty of up to a factor of 2 (see Section 3.3) and the effect of photodissociation/ionization are not taken into account here.

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>C$_2$H$_6$S/H$_2$S (Ethanethiol)</th>
<th>C$_2$H$_6$S/H$_2$S (Dimethyl sulphide)</th>
<th>C$_2$H$_6$S/H$_2$O (Ethanethiol)</th>
<th>C$_2$H$_6$S/H$_2$O (Dimethyl sulphide)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.10.2014 11:46</td>
<td>(3.63 ± 1.11) × 10$^{-4}$</td>
<td>(2.97 ± 1.05) × 10$^{-4}$</td>
<td>(1.61 ± 0.42) × 10$^{-6}$</td>
<td>(1.32 ± 0.47) × 10$^{-6}$</td>
</tr>
<tr>
<td>19.10.2014 17:05</td>
<td>(3.47 ± 1.05) × 10$^{-4}$</td>
<td>(2.84 ± 0.98) × 10$^{-4}$</td>
<td>(3.41 ± 0.89) × 10$^{-4}$</td>
<td>(2.79 ± 0.98) × 10$^{-6}$</td>
</tr>
<tr>
<td>20.10.2014 08:06</td>
<td>(6.70 ± 2.33) × 10$^{-5}$</td>
<td>(5.48 ± 0.22) × 10$^{-5}$</td>
<td>(4.98 ± 1.23) × 10$^{-7}$</td>
<td>(4.07 ± 1.67) × 10$^{-7}$</td>
</tr>
<tr>
<td>23.10.2014 11:15</td>
<td>(5.73 ± 1.71) × 10$^{-4}$</td>
<td>(4.69 ± 1.61) × 10$^{-4}$</td>
<td>(2.31 ± 0.60) × 10$^{-6}$</td>
<td>(1.89 ± 0.66) × 10$^{-6}$</td>
</tr>
<tr>
<td>Mean ± 1σ</td>
<td>(3.38 ± 1.80) × 10$^{-4}$</td>
<td>(2.76 ± 1.47) × 10$^{-4}$</td>
<td>(1.96 ± 1.06) × 10$^{-6}$</td>
<td>(1.60 ± 0.87) × 10$^{-6}$</td>
</tr>
</tbody>
</table>

Table 7. Overview on the S$_2$H/H$_2$S and H$_2$S$_2$/H$_2$S ratios measured in the low-mass protostar IRAS 16293–2422, derived from laboratory studies of ice analogues, and upper limit in 67P during 2014 October.

<table>
<thead>
<tr>
<th></th>
<th>S$_2$/H$_2$S</th>
<th>S$_2$/H$_2$S</th>
<th>H$_2$S$_2$/H$_2$S</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAS 16293–2422$^a$</td>
<td>&lt;5.5 × 10$^{-1}$</td>
<td>&lt;2.0 × 10$^{-2}$</td>
<td>&lt;1.5 × 10$^{-2}$</td>
</tr>
<tr>
<td>Laboratory study$^b$</td>
<td>-</td>
<td>15</td>
<td>&lt;25.0</td>
</tr>
<tr>
<td>67P upper limit</td>
<td>2.61 × 10$^{-5}$</td>
<td>&lt;1.0 × 10$^{-4}$</td>
<td>&lt;5.7 × 10$^{-4}$</td>
</tr>
</tbody>
</table>

$^a$Martín-Doménech et al. (2016).
$^b$Martín-Doménech et al. (2016) derived the ratios from a laboratory study performed by Jiménez-Escobar et al. (2012).

Figure 15. SO/SO$_2$ ratio between equinox and perihelion. Significant spacecraft attitude changes are indicated by dark grey rectangle for going from phase angle 60° to 90° and with light grey rectangle when Rosetta went to 45° south and back to the equator while being in terminator orbit.

Figure 16. Sulphur-bearing species budget: for H$_2$S, S, SO, SO$_2$, OCS, S$_2$, and CS$_2$, the assumed bulk values have been used; for CH$_3$SH the supposed bulk measured at the end of 2016 July is used, while for the remaining species the mean has been used. All values have been corrected for the effect of photodissociation (see Section 4.3.1).

4.5 Elemental abundance ratio S/O

A quantity of importance of sulphur chemistry in comets, is the S/O bulk abundance, in order to find out if comets contain their full complement of sulphur or if comets also lack sulphur as do the pre-solar dense clouds. In Fig. 16, the relative contributions to the overall sulphur content in the volatile material of the comet are shown. H$_2$S is the most abundant species and contributes ~57 per cent to the total sulphur content. The atomic sulphur is surprisingly high with about 27 per cent, whereas S$_2$ adds only 0.1 per cent of the sulphur. The oxygenated S-bearing species contribute less than 14 per cent and the organo-sulphur species about 2 per cent. If we neglect the minor sulphur-bearing species (e.g. organo-sulphur) and the minor oxygenated species (e.g. alcohols) in the coma, we can calculate the S/O ratio in the volatile material according to

$$S/O = \frac{n_{H_2S} + n_S + n_{OCS} + 2 \cdot n_{S_2} + n_{SO} + 2 \cdot n_{CS_2} + n_{SO_2}}{n_{H_2O} \cdot (1.0 + 2 \cdot 0.038) + n_{CO} + 2 \cdot n_{CO_2}},$$

where $n_x$ is the number density of species $x$. In order to take into account molecular oxygen, the mean value of 3.8 per cent relative to water has been used (Bieler et al. 2015). These data have not been corrected for photodissociation which introduces a bias estimated up to 10 per cent towards perihelion. The overall uncertainty of the obtained S/O value of the measured volatiles is 120 per cent due to the unknown sensitivities of several species.

The resulting S/O ratio between equinox and perihelion is shown in Fig. 17 together with the chondritic and the photospheric value (Lodders 2010), the value for dust at Halley (Jessberger, Christoforidis & Kissel 1988), the mean value between equinox and perihelion of (1.47 ± 0.03, $\sigma = 1.16$) × 10$^{-2}$, the mean between equinox and end of May representing the ice in 67P of (1.47 ± 0.05, $\sigma = 0.74$) × 10$^{-2}$, and the derived total S/O ratio (see Section 5.6).

Unlike H$_2$S/H$_2$O, S/O shows considerable variation between equinox and perihelion, which can be explained by the variation in the ratios of the minor sulphur-bearing species to H$_2$O. However,
similar to some of the presented species before, one can divide the time range into three periods. During the first period, S/O is rather constant when Rosetta was sampling both hemispheres equally with phase angles <90°. During the second period, Rosetta was in terminator orbit, sampling solely the Northern hemisphere and S/O increased by almost a factor of 2. In the third period, when Rosetta was going back to southern latitudes and doing the transition from 200 to 300 km, distance to the comet S/O increases slightly compared to bulk. However, the increase is not significant.

5 DISCUSSION

In the following, we discuss (i) how the inventory of sulphur-bearing species compares to measurements in other comets, (ii) what can be learned from the newly detected species, (iii) the implications on radiolysis of H$_2$S with respect to comets, (iv) why the detection of S$_2$ is a key measurement for the Solar system formation, (v) how 67P compares to the recent interstellar chemistry model by Woods et al. (2015), and (vi) finally we discuss the elemental abundance S/O of the volatile phase in 67P and estimate the total elemental abundance for 67P.

5.1 Comparison of 67P to other comets

H$_2$S has been detected in all comets listed in Table 1 and ranges at 1 au from 0.2 per cent in 73P/Schwassmann–Wachmann3/B to 1.5 per cent in C/1995 O1 Hale–Bopp relative to water. Besides H$_2$S, OCS, SO$_2$, CS$_2$, SO and S$_2$ have been detected in several comets. SO$_2$ has been seen only in one, namely Hale–Bopp and H$_2$CS in the comets Hale–Bopp and C/2014 Q2 Lovejoy. In the following, a comparison to those comets is done without considering their dynamical origin since there is no distinct proof linking compositional heterogeneity and dynamical origin.

5.2 What can be learned from newly detected parent species and the presence of atomic sulphur in the coma of 67P

It is evident from our measurements that atomic sulphur cannot be accounted for by just electron impact ionization of the sulphur-bearing species inside DFMS or by their photodissociation in the coma. Part of the measured atomic sulphur may be either sputtered or thermally released from the (semi-) refractory part of the sulphur reservoir, the sulphur polymer S$_n$. According to Woods et al. (2015), significant amounts of atomic sulphur are produced by radiolysis but it is unclear if and how atomic S can survive in the ice. Therefore, the origin of the measured atomic sulphur is unclear, and laboratory experiments are required to see if atomic sulphur can remain in the ice over a long time.

However, organo-sulphur molecules (C, H, S) have been detected in other objects outside of the Solar system. The most simple
organo-sulphur molecule H$_2$CS has been detected in the low-mass protostar IRAS 16293–2422 (Schöier et al. 2002). This detection is of importance for cometary science since this source is thought to be a ‘template’ source for astrochemistry in a low-mass protostar as the Sun was once (Blake et al. 1994). In addition to H$_2$CS, the detection of CH$_3$SH, the second simplest organo-sulphur molecule, has been reported by Majumdar et al. (2016) for the same source.

CH$_3$SH has also been detected in massive star-forming regions such as SgrB2 close to the galactic centre (Linke, Freking & Thaddeus 1979; Müller et al. 2016), in the chemically rich massive hot core G327.3–6 (Gibb et al. 2000) and in Orion KL (Kolesniková et al. 2014). In all these sources, the detected molecules are thought to have just sublimated off the icy grains. For IRAS 16293–2422, Majumdar et al. (2016) report a modelled abundance of $4 \times 10^{-9}$ compared to H$_2$ for the hot core region. The abundance relative to H$_2$S can be estimated by taking the abundance of H$_2$S (compared to H$_2$) of $9 \times 10^{-8}$ reported by Schöier et al. (2002). This leads to CH$_3$SH/H$_2$S = $4.4 \times 10^{-2}$ for IRAS 16293–2422, which is a factor of 3 higher than that of 67P at $(1.44 \pm 0.42) \times 10^{-2}$. However, due to the unknown exact sensitivity for CH$_3$SH with DFMS, the measured CH$_3$SH/H$_2$S can be biased by up to a factor of 2, and the interstellar value has a similar overall uncertainty. Consequently, the two measurements can still be consistent.

The presence of C$_2$H$_2$S indicates that even more complex organo-sulphur molecules exist. Ethanethiol, one of the two isomers of C$_2$H$_2$S, has been detected so far in the hot core of Orion KL by Kolesniková et al. (2014). In addition, they detected CH$_3$SH and estimated the CH$_3$SH/C$_2$H$_2$S ratio to be about 5 based on the measured column densities. This ratio is similar to that of 11$^\text{18}$O/11$^\text{16}$O found for 67P. However, the relative sensitivities of the same molecule type are thought to be in the range of 30 per cent. Since these two molecules are similar in structure and differ only slightly in their number of atoms, the above ratio between CH$_3$SH and C$_2$H$_2$S in 67P has an accuracy which makes a comparison with the interstellar result meaningful.

The two ratios are surprisingly close, even though Orion KL is a high-mass star-forming region rather than a solar-mass protostar. This may again point to a formation mechanism with grain surface chemistry in the parent cloud followed by incorporation into comets. Overall, ice abundances and grain surface chemistry show many similarities for low- and high-mass protostars (e.g. Herbst & van Dishoeck 2009; Öberg et al. 2011).

5.3 Radiolysis of H$_2$S

The fact that S$_2$ was already seen at distances larger than 3 au suggests that it is improbable that S$_2$ is formed by chemistry in the cometary coma. Densities at that time were very low (Bieler et al. 2015), making collisions among the volatile particles very rare. According to A’Hearn et al. (1983), S$_2$ could be produced in long-period comets by photolysis from CS$_2$ and other sulphur-bearing species, but not in short-period comets like 67P. Since 67P loses more than 1 m of its surface on the Southern hemisphere per orbit (Keller et al. 2015) to which depth cosmic rays can hardly penetrate, we would have to observe a decrease of S$_2$ with time, which we do not. The suggestion that H$_2$S formed in the dust mantles and was then converted into S$_2$ and other species is also in line with the proposal that O$_2$ in the comet may have formed by radiolysis (Bieler et al. 2015). Both species, H$_2$S and O$_2$, seem to be very well trapped by the matrix in which they were formed and are released only when water actually sublimates, which is at temperatures between 140 and 180 K (Jiménez-Escobar & Muñoz Caro 2011; Mousis et al. 2016). Bieler et al. (2015) have argued that O$_2$ has to be primordial as the O$_2$ abundance shows a very good correlation with water, but no dependence on latitude, and also did not change during the orbit of the comet from 3.5 to 1.3 au. Mousis et al. (2016) show that radiolysis was not efficient enough and/or did not last long enough in the solar nebula to produce sufficient O$_2$ even assuming extreme levels of cosmic rays. The same seems to be true for S$_2$. For oxygen also, some HO$_2$ and H$_2$O$_2$ were detected at low levels but no O$_3$ (Bieler et al. 2015). In the case of sulphur, we have very low upper limits for S$_2$H and H$_2$S, which are always present in laboratory experiments at quite high levels when irradiating H$_2$S in an H$_2$O matrix (see Table 7). Contrary to oxygen, we detect S$_2$ and even S$_4$ and we also detected a dependence of the S$_2$ abundance on dust which we attribute to semi-refractory S$_2$. The very low abundances of the by-products of radiolysis of H$_2$O and H$_2$S are a puzzle which is not solved and probably needs more laboratory work. Whereas O$_2$ could also be due to gas-phase chemistry, at least in warm clouds (Taquet et al. 2016), this pathway does not seem to work for S$_2$ and the puzzle of the missing by-products remains.

5.4 Implication of volatile S$_2$ on cometary ice

The detection of S$_2$ being a very volatile species has a very important implication. The photo lifetime of S$_2$ at 1 au is 250 s by UV photons with a wavelength of 280 nm (De Almeida & Singh 1986). This means that once S$_2$ is released from the ice, it is destroyed almost immediately. For our measurements at less than 400 km from the comet, it means that more than 50 per cent is lost when we measure at 300 km. However, more importantly, as S$_2$ was most probably formed in the pre-solar cloud in dust ice mantles, this means that some of these dust ice mantles have survived the formation of the solar nebula and the formation of comets.

In addition to the short photo lifetime of S$_2$, no shielding effect is expected to be present as abundant molecules such as CO, H$_2$O and CO$_2$ do not have any significant absorption bands in this wavelength regime (Tchang-Brillet et al. 1992; Mordant, Ashfold & Dixon 1994; Song et al. 2014) and because of its low abundance, S$_2$ is also not expected to be able to efficiently shield itself from UV photodissociation (unlike, e.g. water; Bethell & Bergin 2009). Therefore, the disc is presumably optically thin for UV photons capable of dissociating S$_2$. Then, the lifetime of S$_2$ at 30 au in the disc would be substantially shorter than the formation time of comets.

This means that 67P contains at least some unaltered volatile ice from the pre-solar cloud. This most certainly also precludes clathrates in comets which contain S$_2$, such as 67P as described by Mousis et al. (2016). In this paper, the authors claim that amorphous ice could have transformed into crystalline ice around 120–150 K, thus expelling all molecules into the gas phase except O$_2$ and then later trap them again in clathrates. This contradicts the presence of volatile S$_2$ which would have been destroyed very quickly after its release.

5.5 Comparison with interstellar models

The relative abundances of the sulphur-bearing species in the coma of comet 67P (Fig. 16) show generally good agreement with the ice mantle model by Woods et al. (2015, their fig. 3) for collapsing cloud models in which cosmic rays are somewhat enhanced and hydrogenation of the accreting species is less than 50 per cent. This model is a follow-up of Esplugues et al. (2014), who investigated the time-dependent sulphur chemistry evolution using a coupled
gas-grain model approach starting with the cloud collapse and condensation of species on to grain surfaces followed by sublimation and subsequent chemical reactions during the formation of the central protostar. The main addition of the Woods et al. (2015) models is the inclusion of the results of the ice photolysis and radiolysis experiments to form refractory sulphur-bearing species.

In interstellar clouds, the ratios of SO and SO$_2$ with respect to H$_2$S have attracted significant attention as a potential chemical ‘clock’ for hot cores. The idea, suggested by Charnley (1997), is that H$_2$S ice sublimes into the gas and is then gradually converted into SO and SO$_2$ by high-temperature gas-phase chemical reactions over a period of about 10$^7$ yr (see also Buckle & Fuller 2003 for low-mass cores). Various studies have pointed out difficulties with this scenario, however (e.g. Viti et al. 2004; Wakelam, Hersant & Herpin 2011). Our conclusion that both SO and SO$_2$ are parent molecules in cometary ices further strengthens the notion that these ratios are of limited value as a clock.

The average relative bulk abundances for 67P of H$_2$S/SO$_2$/SO = 100/13/7 (Table 3) suggest a fairly limited chemical evolution of H$_2$S to other species. This is furthermore supported by the even lower abundance of carbonyl sulphide and other C-S-bearing species which are generally formed at even later stages in these models (Buckle & Fuller 2003; Jørgensen, Schöier & van Dishoeck 2004).

### 5.6 Elemental abundance of sulphur

The photospheric value of S/O (Lodders 2010) is about a factor of 1.9 higher than our bulk value during May, but still within the 2σ boundary. In addition, our value just represents the volatile and probably only part of the semi-volatile sulphur. The bulk ice value S/O in 67P of (1.47 ± 0.05) × 10$^{-2}$ is ~1.4 lower than the gas-phase value reported for comet Hale–Bopp (Bockelée-Morvan et al. 2000). However, as there is limited information on the uncertainty of this value, the only conclusion that can be drawn is that both 67P and Hale–Bopp are within 2σ boundary photospheric.

There is not yet a S/O value available from the dust mass spectrometer Cometary Secondary Ion Mass Spectrometer (COSIMA) on Rosetta. However, at comet Halley S/O in the dust has been measured by the PUMA instrument and yields (8.1 ± 2.8) per cent (Jessberger et al. 1988). According to Geiss (1988), 23 per cent of oxygen is in the refractories with a dust/ice ratio for Halley of 2, whereas for 67P this ratio is 4 ± 2 (Rotundi et al. 2015). We therefore assume that in 67P 47 per cent of the oxygen is in dust. Assuming the same S/O ratio in dust for both comets, we then arrive at a bulk abundance for S/O of 3.6 per cent. This is slightly higher, but certainly within 1σ of the value by Lodders (2010). Some of this may be due to the fact that the semi-refractories are measured in both cases, once as the product of thermal fragmentation in the volatiles, once as part of the dust grains. This means that comet 67P has its full complement of sulphur and therefore we deduce, assuming that the Solar system represents the nominal case, that the apparent sulphur deficit in pre-solar clouds/star-forming regions is due to an observational bias, because the products of radiolysis (the refractory sulphur species in the ice) and ice phase sulphur cannot be detected by remote sensing.

### 6 CONCLUSIONS

ROSINA/DFMS detected four sulphur-bearing species (S$_2$, S$_3$, CH$_3$SH, C$_2$H$_6$S) never seen in comets before in the coma of 67P, and this list is likely not exhaustive! There might be more sulphur-bearing species hidden in the data. The fact that most sulphur-bearing species could be observed over much of the orbit of 67P shows desorption patterns and helps distinguish between species desorbing from ice or dust.

CS, which has been detected in other comets, is most likely not a parent in the coma of 67P but a fragment of OCS and CS$_2$. The detection of S$_2$, S$_3$ and S$_4$ makes radiolysis of H$_2$S a very likely process which could well connect the cometary ice to the ISM. If these species were produced in the cloud prior to the formation of the protosun, this would mean that at least part of the ice never sublimated before being incorporated in 67P. This is supported by the fact that there is very volatile S$_2$ present already at 3 au, which has a very short photo lifetime, thus making its survival in the gas phase of the solar nebula very unlikely.

The field of exoplanet exploration is evolving rapidly thanks to more sophisticated techniques. With this evolution, the question of how to detect life on other planets and star systems gains importance. Comparing a list of bio-signatures recently published by Seager, Bains & Petkowski (2016) reveals that many of the detected sulphur species in comet 67P are defined as such. In addition to the sulphur species 67P also contains O$_2$ (Bieler et al. 2015), HCN, CH$_4$ (Le Roy et al. 2015) and glycine (Altwegg et al. 2016) in its coma. However, it is not possible to have life in the cold, primitive environment of a comet. Consequently, one has to be very careful when defining and searching for bio-signatures. Furthermore, the strong links between the comet and the ISM suggest that the involved processes and species are not unique to our Solar system but rather common throughout the Universe.

### ACKNOWLEDGEMENTS

ROSINA would not give such outstanding results without the work of the many engineers, technicians and scientists involved in the mission, in the Rosetta spacecraft and in the ROSINA instrument team over the last 20 years, whose contributions are gratefully acknowledged. Rosetta is a European Space Agency (ESA) mission with contributions from its member states and NASA. We acknowledge herewith the work of the whole ESA Rosetta team.

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### REFERENCES


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**ACKNOWLEDGEMENTS**

ROSINA would not give such outstanding results without the work of the many engineers, technicians and scientists involved in the mission, in the Rosetta spacecraft and in the ROSINA instrument team over the last 20 years, whose contributions are gratefully acknowledged. Rosetta is a European Space Agency (ESA) mission with contributions from its member states and NASA. We acknowledge herewith the work of the whole ESA Rosetta team.

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### REFERENCES


Appendix A

Table A1. Fraction of initial number density which is expected to be present in the coma at a distance of 200 and 300 km at equinox, end of May and perihelion, respectively.

<table>
<thead>
<tr>
<th>Species</th>
<th>Non-dissociated fraction per cent</th>
<th>Relative to water per cent</th>
<th>Relative to hydrogen sulphide per cent</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Equinox 1.66 au</td>
<td>End May 1.55 au</td>
<td>Perihelion 1.24 au</td>
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<tr>
<td>H₂O</td>
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<td>100</td>
<td>100</td>
</tr>
<tr>
<td>H₂S</td>
<td>97</td>
<td>95</td>
<td>92</td>
</tr>
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<td>100</td>
<td>100</td>
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<tr>
<td>SO</td>
<td>94</td>
<td>93</td>
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<td>99</td>
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<td>SO₂</td>
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<tr>
<td>CS₂</td>
<td>72</td>
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<tr>
<td>CH₃SH</td>
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<td>72</td>
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<td>S₂</td>
<td>66</td>
<td>62</td>
<td>48</td>
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<td>54</td>
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<td>33</td>
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</table>

aDe Almeida & Singh (1986).
Table A2. Abundance of S-bearing species relative to water. This table is based on table 1 in Rodgers & Charnley (2006) and on table 1 in Bockelée-Morvan et al. (2004a). Please note that most of these values come from remote sensing measurements, for which CS is assumed to be the photodissociation product of CS₂.

<table>
<thead>
<tr>
<th>Comet</th>
<th>(r_{\text{H}}) (au)</th>
<th>(H_2S)</th>
<th>OCS</th>
<th>SO</th>
<th>SO₂</th>
<th>CS</th>
<th>CS₂</th>
<th>(H_2CS)</th>
<th>(S_2)</th>
<th>NS</th>
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<td>C/1995 O1 (Hale–Bopp)</td>
<td>~1</td>
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<td>–</td>
<td>0.004₀⁻₀.₀₁⁷</td>
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<td></td>
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<td></td>
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<td>0.00₁⁸²</td>
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<td>0.00₀₀₈³</td>
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<tr>
<td>153P/2002 C1 (Koyama–Zhang)</td>
<td>~1</td>
<td>0.00₈²¹⁹</td>
<td>&lt;0.₀₀₂₁₆⁻₀.₀₀₅₁⁹</td>
<td>–</td>
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<td>73P/SW3/B</td>
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<td>~1</td>
<td>0.0₀₁₆⁻₀.₀₀₃²⁰</td>
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1Kim & A’Hearn (1991); 2Biver et al. (1999); 3Wouterloot et al. (1998); 4Biver et al. (2000); 5Bockelée-Morvan et al. (2001); 6Weaver et al. (1999); 7Snyder et al. (2001); 8Bockelée-Morvan et al. (2004b); 9Eberhardt et al. (1994); 10Biver et al. (2002); 11Crovisier et al. (1991); 12Woodney et al. (1997); 13Dello Russo et al. (1998); 14Bockelée-Morvan et al. (2000); 15Irvine et al. (2000); 16Bockelée-Morvan et al. (2004a); 17Weaver et al. (2002); 18Feldman et al. (1999); 19Biver et al. (2006); 20Biver et al. (2008); 21Biver et al. (2007); 22Woodney (2000); 23Weaver et al. (1996); 24Meier & A’Hearn (1997); 25Weaver (2000); 26Dello Russo et al. (2016).

Comments: 14Abundances relative to water are computed assuming \([\text{HCN}] / [\text{H}_2\text{O}] = 2.5 \times 10^{-3}\). 20Please note that the values have been determined graphically.

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