Sulphur and carbon isotopes towards Galactic centre clouds

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ABSTRACT

Context. Measuring isotopic ratios is a sensitive technique used to obtain information on stellar nucleosynthesis and chemical evolution. Aims. We present measurements of the carbon and sulphur abundances in the interstellar medium of the central region of our Galaxy. The selected targets are the +50 km s\(^{-1}\) Cloud and several line-of-sight clouds towards Sgr B2(N). Methods. Towards the +50 km s\(^{-1}\) Cloud, we observed the J = 2–1 rotational transitions of \(^{32}\)S\(^{12}\)C\(^2\)S, \(^{32}\)C\(^{12}\)S\(^{12}\)S, \(^{13}\)C\(^{12}\)S\(^{12}\)S, \(^{12}\)C\(^{13}\)S\(^{12}\)S, and \(^{13}\)C\(^{13}\)S\(^{12}\)S, with the IRAM-30 m telescope, as well as the J = 6–5 transitions of \(^{32}\)C\(^{14}\)S and \(^{13}\)C\(^{14}\)S with the APEX 12 m telescope, all in emission. The J = 2–1 rotational transitions of \(^{12}\)C\(^{32}\)S, \(^{12}\)C\(^{34}\)S, \(^{13}\)C\(^{32}\)S, and \(^{13}\)C\(^{34}\)S were observed with ALMA in the envelope of Sgr B2(N), with those of \(^{13}\)C\(^{12}\)S and \(^{13}\)C\(^{14}\)S also observed in the line-of-sight clouds towards Sgr B2(N), all in absorption. Results. In the +50 km s\(^{-1}\) Cloud we derive a \(^{13}\)C/\(^{12}\)C isotopic ratio of 22.1\(^{+3.3}_{-2.4}\), that leads, with the measured \(^{13}\)C\(^{32}\)S/\(^{12}\)C\(^{34}\)S line intensity ratio, to a \(^{33}\)S/\(^{32}\)S ratio of 16.3\(^{+0.7}_{-1.0}\). We also derive the \(^{33}\)S/\(^{32}\)S isotopic ratio more directly from the two isotopologues \(^{13}\)C\(^{32}\)S and \(^{13}\)C\(^{12}\)S, which leads to an independent \(^{33}\)S/\(^{32}\)S estimation of 16.3\(^{+2.1}_{-1.7}\) and 17.9\(^{+5.0}_{-5.0}\) for the +50 km s\(^{-1}\) Cloud and Sgr B2(N), respectively. We also obtain a \(^{34}\)S/\(^{32}\)S ratio of 4.3\(^{+0.2}_{-0.2}\) in the +50 km s\(^{-1}\) Cloud. Conclusions. Previous studies observed a decreasing trend in the \(^{32}\)S/\(^{34}\)S isotopic ratios when approaching the Galactic centre. Our result indicates a termination of this tendency at least at a galactocentric distance of 130\(^{+16}_{-16}\) pc. This is at variance with findings based on \(^{12}\)C/\(^{13}\)C, \(^{14}\)N/\(^{15}\)N, and \(^{18}\)O/\(^{17}\)O isotope ratios, where the above-mentioned trend is observed to continue right to the central molecular zone. This can indicate a drop in the production of massive stars at the Galactic centre, in the same line as recent metallicity gradient (\(^{16}\)O/\(^{18}\)O) studies, and opens the path towards a comparison with Galactic and stellar evolution models.

Key words. Galaxy: centre – submillimetre: ISM – Galaxy: formation – Galaxy: evolution – stars: atmospheres – submillimetre: general

1. Introduction

Studying stellar nucleosynthesis and chemical enrichment of rare isotopes of a given element at optical wavelengths is difficult because the observed atomic isotope lines are usually affected by blending (e.g. Hawkins & Jura 1987; Levshakov et al. 2006; Ritchey et al. 2011). However, at radio and (sub)millimetre wavelengths, transitions from rare isotopic substitutions of a given molecular species, called isotopologues, are well separated in frequency from their main species, typically by a few percent of their rest frequency.

While the relative abundances of C, N, and O isotopes provide information on carbon–nitrogen–oxygen (CNO) and helium burning, sulphur isotopes allow us to probe late evolutionary stages of massive stars and supernovae (SNe) of Type Ib/c and II (oxygen-burning, neon-burning, and s-process nucleosynthesis) (Wilson & Rood 1994; Chin et al. 1996; Mauersberger et al. 1996), filling a basic gap in our understanding of stellar nucleosynthesis and the chemical evolution of the Universe (e.g. Wang et al. 2013).

In the interstellar medium (ISM), atomic sulphur is thought to freeze out on dust grain mantles and to be later released from the grains due to shocks, leading to the formation of several molecular species in the gas phase, such as OCS, SO\(_2\), H\(_2\)S, and H\(_2\)CS (Millar & Herbst 1990), which serve as both shock and high-mass star formation tracers in starburst galaxies (Bayet et al. 2008).

Among the sulphur-bearing compounds, CS (carbon monosulfide) is the most accessible molecular species: its lines are ubiquitous in the dense ISM and tend to be strong at sites of massive star formation in the spiral arms of our Galaxy, in the Galactic centre (GC) region and in external galaxies (e.g. Linke & Goldsmith 1980; Mauersberger et al. 1989; Bayet et al. 2009; Kelly et al. 2015).
Sulphur has four stable isotopes: $^{32}$S, $^{33}$S, $^{34}$S, and $^{36}$S. Their solar system fractions are 95.018:0.750:4.215:0.017 (Lodders 2003), respectively. In the ISM, Chin et al. (1996) found a relation between $^{32}$S/$^{34}$S isotope ratios and their galactocentric distance ($D_{GC}$) of $^{32}$S/$^{34}$S = $(3.3 \pm 0.5)(D_{GC}/kpc) + (4.1 \pm 3.1)$ by using a linear least-squares fit to the unweighted data, with a correlation coefficient of 0.84, while no correlation was obtained between $^{34}$S/$^{32}$S ratios and $D_{GC}$. However, most of the sources observed in that study are located within the galactocentric distance range $5.5 \leq D_{GC} \leq 7.0$ kpc, with the minimum distance at 2.9 kpc from the Galactic centre. Therefore, it is important to also cover the inner region of the Milky Way to find out whether the trend proposed by Chin et al. (1996) is also valid for the inner Galaxy as has been reported for the $^{15}$C/$^{12}$C (see e.g. Yan et al. 2019), $^{14}$N/$^{14}$O (Adande & Ziurys 2012) and $^{18}$O/$^{17}$O (Wouterloot et al. 2008; Zhang et al. 2015) isotopic ratios.

The GC region harbours one of the most intense and luminous sites of massive star formation in the Galaxy, Sgr B2 (Molinari et al. 2014; Ginsburg et al. 2018). It provides an extreme environment in terms of pressure, turbulent Mach number, and gas temperature (Ginsburg et al. 2016) over a much more extended region than encountered in star-forming regions throughout the Galactic disc (Morris & Serabyn 1996; Ginsburg et al. 2016; Schöier et al. 2019; Dale et al. 2019). These conditions are comparable to those in starburst galaxies (Belloche et al. 2013; Schöier et al. 2019). We therefore expect unique results in this GC study from sulphur ratios, which are a tool for tracing stellar processing (see Sect. 6). For a compilation of sulphur ratios determined in our Milky Way, we refer to Tables 2 and 7 in Maurer et al. (2004) and Müller et al. (2006), respectively.

As is true for our Galaxy, detections of $^{34}$S in extragalactic objects remain scarce. Some observations, also accounting for $^{12}$C/$^{13}$C ratios (using the double-isotope ratio method, Sect. 4.1.1) led to values of $\sim$16–25 and 13.5 ± 2.5 for the $^{32}$S/$^{34}$S ratio in the nuclear starbursts of NGC 253 and NGC 4945, respectively (Wang et al. 2004; Henkel et al. 2014), although the ratio in the nuclear starburst of NGC 253 and NGC 4945, respectively.

In the present study we focus on the $J = 2\rightarrow 1$ transitions of $^{12}$C/$^{13}$C (hereafter CS), $^{12}$C/$^{34}$S (hereafter C$^{34}$S), $^{13}$C/$^{34}$S (hereafter $^{13}$CS), $^{13}$C/$^{33}$S (hereafter C$^{33}$S), and $^{15}$N/$^{15}$O, the transition of CS and C$^{34}$S, and the $J = 6$–5 transitions of C$^{34}$S and $^{13}$CS, all observed together towards the Sgr A Complex (see, e.g., Sandqvist et al. 2015). We have also studied absorption features caused by the envelope of Sgr B2(N) in the $J = 2\rightarrow 1$ rotational transition of CS, C$^{34}$S, $^{13}$CS and $^{15}$N, as well as CS and C$^{34}$S absorption features caused by i.o.s. clouds towards Sgr B2(N). These absorption and emission profiles allow us to obtain $^{12}$C/$^{13}$C and the missing $^{32}$S/$^{34}$S ratios close to the Galactic nucleus. Expanding the database for sulphur isotope ratios in the GC region is important in order to constrain models of steller interiors as well as models of the chemical evolution of the Galaxy (e.g. Kobayashi et al. 2011).

The paper is organized as follows. In Sect. 2, we describe the observations. In Sect. 3, we describe in detail our targets. In Sect. 4, we present measured opacities and isotopologue ratios from CS species, the modelling of our Sgr B2(N) data, and a comprehensive study of CS fractionation. In Sect. 5, we compare our results with previous studies. In Sect. 6, we discuss the results in the context of trends with galactocentric distance and give some explanations for our findings, before summarizing and concluding in Sect. 7.

### 2. Observations

#### 2.1. +50 km s$^{-1}$ Cloud

The +50 km s$^{-1}$ Cloud observations were conducted with the IRAM 30 m and the APEX 12 m telescopes over a period of 1.5 yr, from 2015 May to 2016 September, under varying weather conditions. The observed position was EQJ2000: 17°45′50.20′′, −28°59′41.11′′ for both telescopes, and the representative spectral resolution was 0.6 km s$^{-1}$. With the IRAM 30 m telescope, three frequency set-ups were observed with the E090 and E150 receivers in combination with the Fast Fourier Transform Spectrometer (FFTS, at 195 kHz resolution mode). For the observations presented in this paper, we covered the 93.2–100.98 GHz frequency range (CS, $^{34}$S, and $^{13}$CS $J = 2\rightarrow 1$) in one set-up with the E090 receiver. In a separate E090 set-up, our tuning covered the frequency range 85.5–93.3 GHz ($^{13}$CS and $^{13}$CS $J = 2\rightarrow 1$), while simultaneously the E150 receiver covered the frequency range from 143.5 to 151.3 GHz (for CS and C$^{34}$S $J = 3\rightarrow 2$). The observations were conducted in total power position switching mode. No spectral contamination was found in our off-source reference position (17°46′10.4′′, −29°07′08′′). The main beam efficiencies for our IRAM 30 m measurements were computed using the Ruze formalism (Ruze 1966). Adopted values were 0.8 and 0.7 at 98 and 147 GHz, respectively. We discarded data taken under poor weather conditions (precipitable water vapor content (pwv) > 7 mm) by discarding data taken with system temperatures > 500 K. The representative half-power beam widths (HPBW) values are about 25″ at 98 GHz and 17″ at 147 GHz for the IRAM 30 m observations.

The Atacama Pathfinder Experiment 12 m telescope (APEX) 12 m (Güsten et al. 2006) was used for observations of the $J = 6$–5 lines of the CS, $^{13}$CS, and $^{13}$C$^{34}$S isotopologues at roughly 280 GHz. The measurements were conducted simultaneously using the FLASH345 (Klein et al. 2014) receiver connected to the extended FFTS (XFFTS) backend. These observations were also executed in total power position switching mode and the same off-source reference position, which was found to be clean. The HPBW was about 22″ at the observed frequency and the adopted main beam efficiency was 0.7.

All line intensities are reported in main beam brightness temperature units ($T_{MB}$). While the spectral resolution was instrument dependent (between 0.4 and 0.6 km s$^{-1}$ for the IRAM and 0.08 km s$^{-1}$ for the APEX data), all spectra were smoothed to a resolution of 3 km s$^{-1}$ for analysis.

The data were reduced with the GILDAS package and required minimal flagging, followed by a baseline subtraction of order two.

#### 2.2. Line-of-sight clouds towards Sgr B2(N)

For Sgr B2(N), we used the Exploring Molecular Complexity with ALMA (EMoCA) survey (Belloche et al. 2016) that was performed with the Atacama Large Millimetre/submillimetre
3. Sources

The +50 km s\(^{-1}\) Cloud (also known as M−0.02−0.07, although +50 km s\(^{-1}\) Cloud could include additional molecular knots on its positive-longitude side; Ferrière 2012), observed here with IRAM and APEX, is a giant molecular cloud (GMC) of hook or on its positive-longitude side; Ferrière 2012), observed here with the 3. Sources

Some associated parameters is given in Table 1.

5. The survey covers the frequency range from 84.1 to 144.4 GHz, which includes carbon monosulfide J = 2–1 lines, with a spectral resolution of 488 kHz (1.7 to 1.3 km s\(^{-1}\)) at a median angular resolution of 1.6, or ~0.06 pc. The average noise level is ~3 mJy beam\(^{-1}\) per channel. Details of the calibration and deconvolution of the data are reported in Belloche et al. (2016, Sect. 2.2). For this work, we corrected the data for primary beam attenuation. Several isotopologues of CS are detected in the EMoCA survey. To determine the \(^{32}\)S/\(^{34}\)S and \(^{13}\)C/\(^{12}\)C isotopic ratios, we use four isotopologues: CS, C\(^{34}\)S, \(^{13}\)CS, and \(^{13}\)C\(^{34}\)S.

A list of the observed transitions of CS isotopologues and some associated parameters is given in Table 1.

3. Results

In the following we first discuss the measured profiles towards the +50 km s\(^{-1}\) Cloud, and provide the equations used to determine peak opacities and the carbon isotope ratio (Sect. 4.1). Then we determine the \(^{32}\)S/\(^{34}\)S isotope ratio in two different ways (Sects. 4.1.1 and 4.1.2) from the J = 2–1 lines of the different detected CS isotopologues. The J = 3–2 opacities and the \(^{34}\)S/\(^{32}\)S ratio are the topics of Sects. 4.1.3 and 4.1.4. Sgr B2(N) data are analysed in Sect. 4.2, while the relation between the \(^{32}\)S/\(^{34}\)S

Fig. 1. ALMA continuum map of Sgr B2(N) at 85 GHz. The black contour lines show the flux density levels at 3\(\sigma\), 6\(\sigma\), 12\(\sigma\), and 24\(\sigma\) and the dotted lines indicate −3\(\sigma\), where \(\sigma\) is the rms noise level of 5.4 mJy beam\(^{-1}\). The white crosses denote the positions of the two main hot cores, Sgr B2(N1) and Sgr B2(N2). The black cross, located between the white ones, indicates the phase centre. The green crosses show peaks of continuum emission selected for our absorption study. They label the ultra-compact H\(\alpha\) region K4, two peaks in the shell of the H\(\alpha\) region K6 and one peak in the shell of the H\(\alpha\) region K5 (Gaume et al. 1995). The green ellipse in the lower left corner shows the size of the Galactic centre, Sgr A*.

This massive star-forming region harbours five hot cores, namely Sgr B2(N1−N5), with kinetic temperatures ranging from ~130 to 150 K for N3−N5, between 150 and 200 K for N2, and between 160 and 200 K for N1, assuming LTE conditions in all these cases (Belloche et al. 2016, 2019; Bonfand et al. 2017). In addition, there are 20 −1.3 mm continuum sources associated with dense clouds in Sgr B2(N) that exhibit a rich chemistry (Sánchez-Monge et al. 2017; Schwörer et al. 2019). Recently, Ginsburg et al. (2018) detected 271 compact continuum sources at ~3 mm in the extended Sgr B2 cloud, thought to be high-mass protostellar cores, representing the largest cluster of high-mass young stellar objects reported to date in the Galaxy.
Table 1. Some observational and physical parameters for the five measured CS isotopologue transitions in the +50 km s\(^{-1}\) Cloud and the four transitions from the L.o.s. clouds towards Sgr B2(N), which are also located in the Galactic centre region.

| Target  | Telescope | Isotopologue | Transition | \(v_0\)\(^{(a)}\) (GHz) | \(E_{\text{up}}/k\)\(^{(b)}\) (K) | \(A_{\text{ul}}\)\(^{(c)}\) \((s^{-1})\) | HPBW\(^{(d)}\) (") |
|---------|-----------|--------------|------------|----------------|----------------|----------------|----------------|
| +50 Cloud | IRAM 30 m | \(^{15}\)C\(^{34}\)S | 2–1 | 90.9260260 | 6.55 | 1.19 \times 10^{-5} | 27.0 |
| +50 Cloud | IRAM 30 m | \(^{13}\)CS | 2–1 | 92.4943080 | 6.66 | 1.41 \times 10^{-5} | 26.6 |
| +50 Cloud | IRAM 30 m | C\(^{34}\)S | 2–1 | 96.4124945 | 6.25 | 1.60 \times 10^{-5} | 25.5 |
| +50 Cloud | IRAM 30 m | C\(^{33}\)S | 2–1 | 97.1720639 | 7.00 | 1.63 \times 10^{-5} | 25.3 |
| +50 Cloud | IRAM 30 m | CS | 2–1 | 97.9809533 | 7.05 | 1.67 \times 10^{-5} | 25.1 |
| +50 Cloud | IRAM 30 m | C\(^{34}\)S | 3–2 | 144.6171007 | 11.80 | 5.74 \times 10^{-5} | 17.0 |
| +50 Cloud | IRAM 30 m | CS | 3–2 | 146.9690287 | 14.10 | 6.05 \times 10^{-5} | 16.6 |
| +50 Cloud | APEX 12 m | \(^{13}\)CS | 6–5 | 277.4554050 | 46.60 | 4.40 \times 10^{-4} | 22.1 |
| +50 Cloud | APEX 12 m | C\(^{34}\)S | 6–5 | 289.2090684 | 38.19 | 4.81 \times 10^{-4} | 21.2 |
| Sgr B2(N) | ALMA | \(^{13}\)C\(^{34}\)S | 2–1 | 90.9260260 | 6.55 | 1.19 \times 10^{-5} | 1.8 \times 1.6 |
| Sgr B2(N) | ALMA | \(^{13}\)CS | 2–1 | 92.4943080 | 6.66 | 1.41 \times 10^{-5} | 2.9 \times 1.5 |
| Sgr B2(N) | ALMA | C\(^{34}\)S | 2–1 | 96.4129549 | 6.25 | 1.60 \times 10^{-5} | 1.9 \times 1.4 |
| Sgr B2(N) | ALMA | CS | 2–1 | 97.9809533 | 7.05 | 1.67 \times 10^{-5} | 1.8 \times 1.3 |

Notes. (\(^{(a)}\))Rest frequency. (\(^{(b)}\))Upper energy level. (\(^{(c)}\))Einstein coefficient for spontaneous emission from upper \(u\) to lower \(l\) level. (\(^{(d)}\))Half-power beam width. For the IRAM sources it was calculated following Eq. (1) in http://www.iram.es/IRAMES/telescopeSummary/telescopeSummary.html.

Table 2. Line parameters for the nine measured CS isotopologue transitions in the +50 km s\(^{-1}\) Cloud.

| Isotopologue | Transition \((\times 10^3)\) | \(T_{\text{mb}}\)\(^{(a)}\) (K km s\(^{-1}\)) | Peak velocity (km s\(^{-1}\)) | FWHM (km s\(^{-1}\)) | \(T^{\text{peak}}\) \((\text{K})\) | \(\tau^{(a)}\) |
|--------------|-----------------|----------------|----------------|----------------|-------------|---------|
| \(^{13}\)C\(^{34}\)S \(^{(b)}\) | 2–1 | 1.25 \pm 0.12 | 48.44 \pm 0.92 | 20.99 \pm 2.24 | 0.06 \pm 0.005 | – |
| \(^{13}\)CS | 2–1 | 23.28 \pm 0.28 | 46.94 \pm 0.12 | 22.28 \pm 0.29 | 0.98 \pm 0.01 | 0.08 \times 0.05 |
| C\(^{34}\)S | 2–1 | 32.61 \pm 0.41 | 46.45 \pm 0.13 | 23.07 \pm 0.32 | 1.33 \pm 0.02 | – |
| C\(^{33}\)S | 2–1 | 7.73 \pm 0.31 | 47.05 \pm 0.45 | 27.61 \pm 1.14 | 0.26 \pm 0.01 | – |
| CS\(^{(+)}\) | 2–1 | 250.00 \pm 6.66 | 48.10 \pm 0.11 | 27.56 \pm 0.51 | 8.52 \pm 0.16 | 1.9 \times 1.1 |
| CS\(^{(-)}\) | 2–1 | –37.62 \pm 0.13 | 48.09 \pm 0.19 | 10.85 \pm 0.82 | –3.26 \pm 0.32 | – |
| C\(^{34}\)S | 3–2 | 21.19 \pm 0.19 | 45.95 \pm 0.09 | 22.39 \pm 0.22 | 0.89 \pm 0.01 | 0.05 \times 0.15 |
| CS\(^{(+)}\) | 3–2 | 250.00 \pm 14.22 | 47.87 \pm 0.10 | 25.59 \pm 0.61 | 9.18 \pm 0.73 | 1.0 \times 2.8 |
| CS\(^{(-)}\) | 3–2 | –78.71 \pm 14.69 | 48.45 \pm 0.12 | 13.97 \pm 0.77 | –5.29 \pm 0.71 | – |
| \(^{13}\)CS | 6–5 | 2.39 \pm 0.12 | 43.94 \pm 0.43 | 18.61 \pm 1.04 | 0.120 \pm 0.005 | – |
| C\(^{34}\)S | 6–5 | 3.32 \pm 0.10 | 44.42 \pm 0.26 | 18.51 \pm 0.62 | 0.169 \pm 0.005 | – |

Notes. (\(^{(a)}\))Peak opacity. (\(^{(b)}\))A CH\(_2\)OCH\(_3\) (see Sect. 4.1 and Fig. 2) contribution was subtracted before performing a single Gaussian fit to this line. (\(^{(+)}\))Positive component (in blue in Fig. 2). (\(^{(-)}\))Negative component (in green in Fig. 2).

isotope ratios from CS and the actual interstellar \(^{32}\)S/\(^{34}\)S values is the topic of Sect. 4.3. Generally, the analysis assumes that lines with the same rotational quantum numbers, related to different CS isotopologues, are co-spatial. We present a summary of our results in Table 3.

4.1. Peak opacities and column density ratios in the +50 km s\(^{-1}\) Cloud

The CS emission lines observed towards the +50 km s\(^{-1}\) Cloud are presented in Fig. 2. All lines show peaks in agreement with the local standard of rest (LSR) velocity of the system, ~50 km s\(^{-1}\) (Sandqvist et al. 2008; Requena-Torres et al. 2008). In addition to the CS \(J=2\rightarrow1\) isotopologue lines, there are probably weak features of cyanoformaldehyde (NCCHO) and ethanol (C\(_2\)H\(_3\)OH) at 96.4269958 GHz and 96.4273380 GHz, respectively, on the blue-shifted side (~0 km s\(^{-1}\)) of C\(^{35}\)S; dimethyl ether (CH\(_3\)OCH\(_3\)) at 90.9375080 GHz or ~10 km s\(^{-1}\) on the blueshifted side dominates the \(^{13}\)C\(^{35}\)S spectrum. Those molecules have been observed already in Sgr B2 (Zuckerman et al. 1975; Nummelin et al. 1998; Martín-Pintado et al. 2001; Remijan et al. 2008; Belloche et al. 2013).

Moreover, the CS \(J=2\rightarrow1\) and \(J=3\rightarrow2\) line profiles show double-peaked profiles, which are readily explained by self-absorption, centered at the systemic velocity of the cloud in the \(J=2\rightarrow1\) transition and with a self-absorption marginally redshifted (by ~0.4 km s\(^{-1}\)) in the \(J=3\rightarrow2\) transition. The CS parameters allowed to vary freely and obtained from single- or double-component Gaussian fitting are summarized in Table 2. They were obtained using a series of Python codes, mainly within the Lmfit package\(^4\).

\(^4\) https://lmfit.github.io/lmfit-py/intro.html
As can be seen in Fig. 2, for the CS \( J = 2–1 \) and \( J = 3–2 \) lines, we have fitted a double Gaussian considering a positive (in blue) and a negative (in green) Gaussian component each. Their parameters are summarized in Table 2, where the uncertainties were taken directly from the lmfit package (for details see Appendix D).

Given that CS \( J = 2–1 \) and \( J = 3–2 \) show double-peaked profiles, while the rare isotopologues exhibit a single peak in between, the CS lines are likely optically thick. This was also suggested by Tsuibo et al. (1999) who find that CS \( J = 1–0 \) is moderately optically thick in this object, with an opacity of around 2.8. Then, we can further assume as a first approximation that \( CS_{34} J = 2–1 \) is optically thin in the expected case that \( 32S/33S \approx 3 \) (see Sect. 4.1.2 for a confirmation of this assumption; see also Frerking et al. 1980 and Corby et al. 2018). In this case \( CS_{34} J = 2–1 \) is definitely optically thin.

In the following, we consider an excitation temperature range of 9.4–300 K for our column density computations in order to obtain conservative estimates. Our column density values were calculated using Eq. (80) in Mangum & Shirley (2015) assuming a filling factor of unity. We then deduce from the integrated line intensities of \( CS_{34} J = 2–1 \) and \( CS_{34} J = 2–1 \), converted to column densities, a \( 12C/13C \) ratio of \( 22.1^{+3.3}_{-2.4} \). This value is used in Eqs. (1) and (2) (denoted \( R_C \)), and it agrees with previous observations in the GC within the uncertainties (~17–25; e.g. Frerking et al. 1980; Corby et al. 2018), and with the values derived from many transitions of complex organic molecules (COMs) in the hot core Sgr B2(N2) (Belloche et al. 2016; Müller et al. 2016), indicating that our approach is correct and confirming that \( CS_{34} \) is indeed optically thin.

Assuming equal excitation temperatures (see Appendix B) and beam filling factors for \( CS_{13} \) and \( CS_{12} \), the \( CS_{13} J = 2–1 \) peak opacity \( \tau(13CS) \) can then be determined from

\[
\frac{T_{MB}(12CS)}{T_{MB}(13CS)} = \frac{1 - e^{-\tau(13CS)\rho_C}}{1 - e^{-\tau(13CS)}}, \quad R_C = \frac{12C}{13C}. \tag{1}
\]

However, as there is a self-absorption feature at the centre of the \( CS_{13} J = 2–1 \) and \( CS_{12} J = 2–1 \) profiles, we measure the line temperatures of both \( CS_{13} \) and \( CS_{12} \) at a redshifted velocity, \( v_r = 63 \text{ km s}^{-1} \), where the line shape is not affected by self-absorption. We can then retrieve the opacity at the systemic velocity, assumed to be the \( CS_{13} J = 2–1 \) peak velocity, \( v_{sys} = 49.64 \text{ km s}^{-1} \), by considering a Gaussian distribution. First, we compute the opacities at \( v_r \) in the following way:

\[
\frac{T_{MB}(12CS)}{T_{MB}(13CS)} = \frac{1 - e^{-\tau(13CS)\rho_C}}{1 - e^{-\tau(13CS)}}, \quad R_C = \frac{12C}{13C} \tag{2}
\]

\[
0.24 \pm 0.11 = \frac{1 - e^{-22.1^{+3.3}_{-2.4}\tau(13CS)\rho_C}}{1 - e^{-\tau(13CS)}}, \quad \tau(13CS)_{v_{sys}} = \frac{\tau(13CS)_{v_{sys}}}{e^{-(v_r - v_{sys})^2/2\sigma^2}}. \tag{3}
\]

Here, \( T_{MB}(12CS) \) and \( T_{MB}(13CS) \) are the main-beam brightness temperatures of CS and \( 13CS J = 2–1 \) at \( v_r \). This results in \( \tau(13CS)_{v_{sys}} = 0.02 \pm 0.01 \), considering the same uncertainties for the peak temperatures as those obtained by performing a single Gaussian fit in those lines. We can now retrieve the opacity at the systemic velocity as

\[
\tau(13CS)_{v_{sys}} = \frac{\tau(13CS)_{v_{sys}}}{e^{-(v_r - v_{sys})^2/2\sigma^2}}. \tag{4}
\]

where \( \sigma \) is the full width at half maximum (FWHM) of \( 13CS_{v_{sys}} \) divided by \( \sqrt{8\ln(2)} \) (FWHM/ \( \sqrt{8\ln(2)} = 9.46 \pm 0.12 \text{ km s}^{-1} \)) and
\[ v_{\text{sys}} = 46.942 \pm 0.118 \text{ km s}^{-1}. \] We obtain \( \tau(^{13}\text{CS}_{\nu m}) = 0.08^{+0.05}_{-0.04} \). Multiplying this by \( R_{C} \), we obtain \( \tau(^{13}\text{CS}_{\nu m})/R_{C} = \tau(\text{CS}_{\nu m}) = 1.9^{+1.1}_{-0.8} \), consistent with previous observations \( \tau(\text{CS}_{\nu m}) \approx 2.8; \text{Tsaboi et al. 1999} \). The uncertainty on \( v_{\text{sys}} \) corresponds to a 0.15% variation in the \( \tau(\text{CS}_{\nu m}) \) value in the worst case. Therefore, it is ignored in the following.

### 4.1.1. A \(^{32}\text{S}/^{34}\text{S} \) ratio obtained through the double isotope method

As we have seen, CS must be moderately optically thick. Then, the \(^{32}\text{S}/^{34}\text{S} \) isotope ratios cannot be determined from the observed \( N(^{13}\text{CS})/N(^{34}\text{CS}) \) ratio. Instead, we can use the column densities of \(^{13}\text{CS} \) and \(^{34}\text{CS} \) by realistically assuming that those lines are optically thin (see Sect. 4.1). Therefore, we have derived the values for \(^{32}\text{S}/^{34}\text{S} \) making use of the carbon isotopic ratio mentioned above, in the following way:

\[
\frac{^{32}\text{S}}{^{34}\text{S}} = \frac{12\text{C}}{13\text{C}} \frac{N(^{13}\text{CS})}{N(^{13}\text{CS})}. \tag{5}
\]

From Eq. (5), we obtain a \(^{32}\text{S}/^{34}\text{S} \) \( J = 2–1 \) ratio of 16.3\(^{+3.0}_{-2.3} \). By using the \(^{13}\text{CS} \) and \(^{34}\text{CS} \) \( J = 6–5 \) transitions, we obtain a \(^{32}\text{S}/^{34}\text{S} \) \( J = 6–5 \) ratio of 15.8\(^{+3.5}_{-2.9} \). This agreement within the uncertainties can be taken as another argument in favour of the low opacity of \(^{34}\text{S} \) and the subsequent validity of our assumptions and calculations. If some of the \(^{34}\text{S} \) lines in the rotational ladder were not optically thin, we would expect different \( N(^{13}\text{CS})/N(^{34}\text{S}) \) ratios in the \( J = 2–1 \) and \( 6–5 \) transitions due to photon trapping leading to higher excitation temperatures in the more abundant isotopologue, which is not observed.

### 4.1.2. \(^{32}\text{S}/^{34}\text{S} \) ratio from direct observations

As we have measured the \(^{13}\text{CS} \) \( J = 2–1 \) transition, we can also obtain the \(^{32}\text{S}/^{34}\text{S} \) ratio directly from

\[
\frac{^{32}\text{S}}{^{34}\text{S}} = \frac{N(^{13}\text{CS})}{N(^{13}\text{CS})}. \tag{6}
\]

Using this we obtain a \(^{32}\text{S}/^{34}\text{S} \) \( J = 2–1 \) ratio of 16.3\(^{+3.1}_{-2.4} \), consistent with the ratio obtained through the double-isotope method in Eq. (5) and again indicating that our initial assumptions concerning line saturation were correct. In the following, we use the latter value for our analysis because it was determined in the most direct way. In order to estimate the opacity of CS from \(^{34}\text{S} \) (see Sect. 4.1.3), we use this \(^{32}\text{S}/^{34}\text{S} \) \( J = 2–1 \) ratio of 16.3\(^{+2.4}_{-1.7} \) as the sulphur isotopic ratio \(^{32}\text{S}/^{34}\text{S} \) and call it \( R_{S} \).

To compare our results with those of Chin et al. (1996), we also derived a sulphur ratio from the integrated intensities: \(^{32}\text{S}/^{34}\text{S} \sim \nu(1\text{CS})/\nu(^{13}\text{CS}) \). This results in a \(^{32}\text{S}/^{34}\text{S} \) value of 18.6\(^{+2.2}_{-1.8} \). The differences between the column density and integrated intensity ratios are due to the rotational partition functions, rotational constants, and Einstein A-coefficients for spontaneous emission of radiation that slightly differ for the different isotopologues.

### 4.1.3. CS and \(^{34}\text{S} \) \( J = 3–2 \) opacities

Now we are able to determine the opacities of CS and \(^{34}\text{S} \) \( J = 3–2 \) by proceeding in the same way as in Eqs. (2) and (4), but considering this time the sulphur ratio. Here, in Eq. (2), we also assume equal excitation temperatures (see Appendix B) and beam filling factors, this time for \(^{34}\text{S} \) and \(^{34}\text{S} \). This agreement within the uncertainties can be taken as another argument in favour of the low opacity of \(^{34}\text{S} \) and the subsequent validity of our assumptions and calculations. If some of the \(^{34}\text{S} \) lines in the rotational ladder were not optically thin, we would expect different \( N(^{13}\text{CS})/N(^{34}\text{S}) \) ratios in the \( J = 2–1 \) and \( 6–5 \) transitions due to photon trapping leading to higher excitation temperatures in the more abundant isotopologue, which is not observed.

### 4.2. Modelling the Sgr B2(N) data

Here, we rely on the modelling of the absorption profiles of the isotopologues of CS carried out by Thiébl (2019) using the EMoCA survey, following the same method as Thiébl et al. (2019). They used the software Weeds (Maret et al. 2011) to model the absorption profiles. Their work assumes that all transitions of a molecule have the same excitation temperature and that the beam filling factor is unity, which is a reasonable assumption given that most absorption features are extended on scales of 15'' or beyond in the ALMA maps (see Thiébl et al. 2019, their Sect. 5.4), while the beam size is 1''6 (see Sect. 2.2, Fig. 1, and Table 1). The fitted parameters were the column density, line width, and the centroid velocity, under the assumption that the excitation temperature is equal to the temperature of the cosmic microwave background (2.73 K).

We selected four continuum peaks inside Sgr B2(N) (Fig. 1). We excluded the two strong continuum peaks at which the

### Table 3. Summary for our carbon and sulphur column density ratio calculations in the +50 km s\(^{-1} \) Cloud.

| \( \text{Column Density Ratio} \) | \( J = 2–1 \) | \( J = 2–1\)/\( J = 6–5 \) | \( J = 2–1 \) | \( J = 2–1 \) |
|---|---|---|---|
| \( ^{12}\text{C} \) | \( ^{13}\text{C} \) | \( ^{32}\text{S} \) | \( ^{34}\text{S} \) | \( ^{34}\text{S} \) |
| \( ^{12}\text{C}/^{13}\text{C} \) | \( ^{32}\text{S}/^{34}\text{S} \) | \( ^{32}\text{S}/^{34}\text{S} \) | \( ^{32}\text{S}/^{34}\text{S} \) | \( ^{34}\text{S}/^{34}\text{S} \) |
| \( J = 2–1 \) | \( J = 2–1\)/\( J = 6–5 \) | \( J = 2–1 \) | \( J = 2–1 \) |
| \( 22.1^{+3.3}_{-2.4} \) | \( 16.3^{+3.0}_{-2.4}/15.8^{+2.4}_{-3.4} \) | \( 16.3^{+2.1}_{-1.7} \) | \( 4.3 \pm 0.2 \) |

Notes. (a) From \( N(^{13}\text{CS})/N(^{13}\text{CS}) \) \( J = 2–1 \) lines, as described in Sect. 4.1. (b) Through the double isotope method in Sect. 4.1.1. (c) From direct observations in Sect. 4.1.2. (d) See Sect. 4.1.4.
Table 4. Isotopic ratios determined in the envelope of Sgr B2(N) ($^{34}$CS/$^{34}$S and C$^{34}$S/$^{34}$C) and in GC clouds along the line of sight to Sgr B2(N) (C/C$^{34}$S) using absorption lines of CS isotopologues.

| $\Delta x$ | $\Delta y$ | $V_{LSR}$ | $N(C^{34}S)$ | $N(^{13}CS)$ | $N(^{13}C^{34}S)$ | FWHM | $^{34}$CS/$^{34}$S | C$^{34}$S/$^{34}$C |
|------------|------------|-----------|--------------|---------------|-----------------|-------|----------------|-----------------|
| 1.8        | 11.1       | -73.3     | 26.0 ± 0.7   | 1.4 ± 0.5     | 3.5             | 18.6 ± 6.3 |
| 1.8        | 11.1       | -81.2     | 45.0 ± 0.9   | 2.5 ± 0.6     | 5.0             | 18.0 ± 4.0 |
| 1.8        | 11.1       | -104.2    | 58.0 ± 1.0   | 3.0 ± 0.6     | 5.0             | 19.3 ± 3.6 |
| 9.3        | 1.8        | -82.5     | 16.0 ± 0.7   | 1.4 ± 0.4     | 2.5             | 11.4 ± 3.7 |
| 9.3        | 1.8        | -92.6     | 20.0 ± 0.7   | 1.2 ± 0.5     | 2.5             | 16.7 ± 7.3 |
| 9.3        | 1.8        | -104.7    | 63.0 ± 1.1   | 3.0 ± 0.7     | 6.5             | 21.0 ± 4.9 |
| 6.6        | 3.3        | -71.8     | 65.0 ± 1.5   | 7.2 ± 0.8     | 5.5             | 9.0 ± 1.0  |
| 6.6        | 3.3        | -79.8     | 29.0 ± 1.0   | 1.8 ± 0.6     | 4.0             | 16.1 ± 5.8 |
| Average    |            |           |              |               |                 | 16.3 ± 3.8 |

Isotopic ratios determined in GC clouds along the line of sight to Sgr B2(N)

| $\Delta x$ | $\Delta y$ | $V_{LSR}$ | $N(CS)$   | $N(^{13}C^{34}S)$ | FWHM | CS/C$^{34}$S |
|------------|------------|-----------|------------|----------------|-------|---------------|
| 1.8        | 11.1       | -73.3     | 26.0 ± 0.7 | 1.4 ± 0.5     | 3.5   | 18.6 ± 6.3   |
| 1.8        | 11.1       | -81.2     | 45.0 ± 0.9 | 2.5 ± 0.6     | 5.0   | 18.0 ± 4.0   |
| 1.8        | 11.1       | -104.2    | 58.0 ± 1.0 | 3.0 ± 0.6     | 5.0   | 19.3 ± 3.6   |
| 9.3        | 1.8        | -82.5     | 16.0 ± 0.7 | 1.4 ± 0.4     | 2.5   | 11.4 ± 3.7   |
| 9.3        | 1.8        | -92.6     | 20.0 ± 0.7 | 1.2 ± 0.5     | 2.5   | 16.7 ± 7.3   |
| 9.3        | 1.8        | -104.7    | 63.0 ± 1.1 | 3.0 ± 0.7     | 6.5   | 21.0 ± 4.9   |
| 6.6        | 3.3        | -71.8     | 65.0 ± 1.5 | 7.2 ± 0.8     | 5.5   | 9.0 ± 1.0    |
| 6.6        | 3.3        | -79.8     | 29.0 ± 1.0 | 1.8 ± 0.6     | 4.0   | 16.1 ± 5.8   |
| Average    |            |           |            |                | 16.3 ± 3.8 |               |

Notes. (a) The offset positions ($\Delta x$, $\Delta y$) in units of arcseconds: (1.8, 11.1), (9.3, 1.8), (4.8, 9.3), and (6.6, 3.3), correspond to K4, K6$^{sh}$, K5$^{sh}$, and K6$^{sh}$, in Fig. 1, respectively. See the caption to Fig. 1 and the green crosses in the image. (b) Column densities determined using Weeds. It is assumed that all isotopologues have the same FWHM. The average isotope ratios presented by the lowest line of each panel are unweighted and provide the standard deviation of an individual measurement (without dividing by the square root of the number of ratios).

main hot cores N1 and N2 are located because at these positions the spectra are full of emission lines of organic molecules (e.g. Bonfand et al. 2017) contaminating the carbon monosulfide absorption features. The offsets to the centre of the observed field are (1° 8, 11° 1), (9° 3, 1° 8), (4° 8, 9° 3), and (6° 6, 3° 3) (see Fig. 1 and Table 4). The observed absorption profiles and the corresponding Weeds models for the four isotopologues and the four positions are shown in Fig. 3. Using their results for the column densities, we determined the isotopic ratios CS/C$^{34}$S, $^{13}$CS/$^{13}$C$^{34}$S, and C$^{34}$S/$^{13}$C$^{34}$S. We determined those ratios separately for the envelope of Sgr B2(N) and some GC clouds along the I.o.s. to Sgr B2(N), the latter with velocities lower than $-50$ km s$^{-1}$. We only determine the ratio CS/C$^{34}$S in those cases where the absorption caused by CS is not optically thick.

The resulting unweighted average values of the isotopic ratios are listed in Table 4, namely a $^{32}$S/$^{34}$S isotope ratio of 16.3 ± 3.8 in the GC I.o.s. clouds towards Sgr B2(N) and 17.9 ± 5.0 in the envelope of Sgr B2(N). For this envelope we obtain a $^{12}$C/$^{13}$C ratio of 27.6 ± 6.5. It should be noted that our uncertainties correspond to the standard deviation for independent measurements, i.e. without dividing it by the square root of the number of studied spectral components.

4.3. Discussion on the validity of using C$^{32}$S/C$^{34}$S as a proxy for $^{32}$S/$^{34}$S

Chin et al. (1996) estimated that sulphur fractionation is marginal for CS isotopic ratios. If the bulk of the CS emission, which allows us to measure rare isotopes, arises from the densest parts of the molecular clouds only, the heating from the massive stars should inhibit significant fractionation (Chin et al. 1996). In that case, CS emission can be used directly to determine sulphur isotope ratios from such sources.

In their oxygen fractionation study, Loison et al. (2019) analyse sulphur fractionation including CS. Some sulphur fractionation is induced at low temperature by the $^{33}$S$^+$ → $^+$ + C$^{34}$S reaction. To determine the potential fractionation of sulphur, we used the network from Loison et al. (2019) in the $+50$ km s$^{-1}$ Cloud, the I.o.s. clouds towards Sgr B2(N) and the envelope of Sgr B2(N), with realistic physical conditions for these objects, in particular a much higher value of the cosmic-ray ionization rate (CIR) than the usual value in more local dense molecular clouds. Some typical results are shown in Fig. 4 and are described below.

In the simulations, all elements with an ionization potential below the maximum energy of ambient UV photons (13.6 eV)
are assumed to be initially in an atomic, singly ionized state. We considered all sulphur in the $S^+$ form without depletion, and we performed some tests to quantify the effect of depletion, which is low (see below). Hydrogen, with its high degree of self-shielding, is taken to be entirely molecular. The initial abundances are similar to those in Table 1 of Hincelin et al. (2011), the C/O elemental ratio being equal to 0.7 in our study. We verified that the initial state of carbon and nitrogen ($C^+$ versus CO and $N$ versus $N_2$) have very little influence on sulphur fractionation (less than 4% for the typical ages considered: $10^{5-6}$ yr). The estimation of the dense cloud ages is deduced from clouds with similar density ($10^4$ to a few $10^5$ cm$^{-3}$) for which the age is given by the best agreement between calculations and observations for key species given by the so-called distance of disagreement (Wakelam et al. 2006). By key species we mean species typically encountered in molecular clouds such as HCN, HNC, CN, CH, C$_2$H, $c$-C$_3$H, $c$-$c$-C$_3$H$_2$, CO, H$_2$CO, CH$_3$OH, NO, SO, CS, HCS$^+$, and H$_2$CS (see e.g. Wakelam et al. 2010; Agúndez & Wakelam 2013; Agúndez et al. 2019).

For Fig. 4a, which represents conditions in the +50 km s$^{-1}$ Cloud, we adopted a density of $10^5$ cm$^{-3}$ and a CRIR of $\zeta_{H_2} = 7 \times 10^{-16}$ s$^{-1}$ based on measurements in hot cores of Sgr B2(N) by using COMs (Bonfand et al. 2019). For Figs. 4b and c, which represent the conditions for the envelope of Sgr B2(N) and the l.o.s. clouds towards Sgr B2(N), respectively, we chose a density of $10^4$ cm$^{-3}$, an upper limit for the volume density in those regions (see Thiel et al. 2019, their Table 12), in order to avoid possible UV heating in our models. Due to this high density, we have adopted a CRIR of $\zeta_{H_2} = 3 \times 10^{-15}$ s$^{-1}$, i.e. one order of magnitude lower than the value usually obtained in the l.o.s. of translucent and diffuse clouds towards the Galactic centre, but within the range obtained for the nuclear $\sim 100$ pc of our Galaxy (Indriolo et al. 2015; Le Petit et al. 2016). The $^{32}S/^{34}S$ isotope ratio chosen for each simulation is that obtained from
Fig. 4. Calculated abundance ratios of gas phase species $^{32}\text{S}/^{34}\text{S}$ as a function of cloud age for conditions in (a) the $+50\text{ km s}^{-1}$ Cloud, (b) the envelope of Sgr B2(N), and (c) I.o.s. clouds towards Sgr B2(N) (see Sect. 4.2 for details). Low values for the gas temperatures were chosen to illustrate an upper limit for fractionation. The vertical grey loci represent values given by the most probable chemical age. The observational results from this study are illustrated as horizontal light grey rectangles (including the uncertainties).

Some measurements using the double-isotope ratio method (see Sect. 4.1.1), which take the $^{32}\text{C}^{13}\text{C}$ ratio into account, may induce a bias since CS may show a non-negligible fractionation into $^{13}\text{C}$. There is no specific study of the $^{13}\text{C}$ fractionation of CS, but the reactivity of $^{13}\text{C}$ and C, in particular with CO and CN (but also with CS), can induce an enrichment or depletion in $^{13}\text{C}$ of carbonaceous species including CS (Smith & Adams 1980; Roueff et al. 2015). In that case, the good agreement between the sulphur fractionation measurements using $^{32}\text{S}/^{34}\text{S}$ and the values obtained using the double-isotope method also suggests a low $^{13}\text{C}$ fractionation of CS. This result is interesting and could initiate future studies on the modelling of $^{13}\text{C}$ fractionation in CS.

5. Our results in the light of previous studies

If we assume that the gradient proposed by Chin et al. (1996) would also be valid in the Galactic centre region, the $^{32}\text{S}^{13}\text{S}$ ratio would decrease to values of $4.1 \pm 3.1$ at the centre of our Galaxy, i.e. to a very low value, only 1/4 of the solar system ratio. This value is less than one fourth of the value derived from integrated intensities in this work, $18.6^{+2.2}_{-4.1}$. This difference can be explained in terms of the $^{12}\text{C}^{13}\text{C}$ ratios assumed in Chin et al. (1996), required to obtain the $^{32}\text{S}^{13}\text{S}$ ratio through the double-isotope method by using the formalism of Eq. (5) (although using intensities instead of column densities). The $^{12}\text{C}^{13}\text{C}$ ratios were derived from the relation found by Wilson & Rood (1994) of $^{12}\text{C}^{13}\text{C} = (7.5 \pm 1.9) (\text{D}_{\text{abs}}/\text{Kpc}) + (7.6 \pm 1.9)$, which gives a value of $7.6^{+2.9}_{-1.7}$ for the Galactic centre, although the authors claimed a value of $\approx 20$ near the Galactic nucleus (Wilson & Rood 1994, Sect 5.1). This provides an idea of the large uncertainty in this relation.

On the other hand, we are confident about our $^{12}\text{C}^{13}\text{C}$ ratio of $22.1^{+3.1}_{-2.0}$ (Sect. 4.1) for two reasons: first, the agreement between the $^{32}\text{S}^{13}\text{S}$ ratio obtained through the double-isotope method (Sect. 4.1.1), which makes use of the $^{12}\text{C}^{13}\text{C}$ ratio, and the $^{32}\text{S}^{13}\text{S}$ ratio obtained directly from $^{13}\text{C}^{13}\text{S}$ (Sect. 4.1.2), i.e. independently of the carbon ratio (this also indicates that the carbon fractionation is low, as described in Sect. 4.3) and second, its proximity to the ratio obtained through decades of observations in the nuclear regions of our Galaxy ($^{13}\text{C}^{13}\text{C} = 17.25$, Freking et al. 1980; Wilson & Rood 1994; Milam et al. 2005; Müller et al. 2008; Corby et al. 2018), including LTE modelling of complex organic molecules.
Recently, Corby et al. (2018) found $^{32}\text{S}/^{34}\text{S}$ ratios mostly in the 5–10 range, based on $^{32}\text{S}$ and $^{34}\text{S}$ $J = 1$–0 absorption lines from diffuse clouds near the GC, with a resolution of $\sim 15''$. Considering their data in the $73$ to $106$ km s$^{-1}$ velocity range, corresponding to our GC l.o.s. clouds towards Sgr B2(N), their observations reach values between $6.6 \pm 6$ and $29 \pm 14$, consistent with our values between $9.0 \pm 1.0$ and $21.0 \pm 4.9$ (Table 4, lower panel).

In addition, Armijos-Abendaño et al. (2015), with a resolution of $\sim 30''$–$39''$, found values of $\geq 22$ and $8.7 \pm 1.3$ for $^{32}\text{S}/^{34}\text{S}$ isotope ratios in l.o.s. clouds towards Sgr A and Sgr B2, respectively, consistent with previous estimations (Frerking et al. 1980). However, their sulphur ratios were obtained from OCS/OC$^{34}$S, with OCS being potentially optically thick and OC$^{34}$S spectra being badly affected by band pass ripples, possibly providing only tentative detections. So we propose a more conservative lower limit for the l.o.s. clouds towards Sgr A of $\sim 10$ and we suggest that the uncertainty for their ratio in Sgr B2 was underestimated.

Both Corby et al. (2018) and Armijos-Abendaño et al. (2015) employed integrated column density ratios, so we should compare those measurements with our normal $^{32}\text{S}/^{34}\text{S}$ isotope ratio estimation, that is $16.3^{+1.7}_{-1.7}$ for the $+50$ km s$^{-1}$ Cloud (as an approximation for the l.o.s. clouds towards Sgr A) and $16.3 \pm 3.8$ for the l.o.s. clouds towards Sgr B2 (see Table 4). Our data represent a significant improvement in terms of accuracy and precision with respect to those previous observations. In addition, our estimation of $17.9 \pm 5.0$ for the envelope of Sgr B2(N) agrees with both estimations for the $+50$ km s$^{-1}$ Cloud and also with previous calculations for the whole Sgr B2 region: $\sim 16$, from the OCS/OC$^{34}$S ratio, which is claimed to be derived from optically thin lines (Goldsmith & Linsky 1981).

Cutting-edge model calculations performed by Kobayashi et al. (2011) relate sulphur isotope ratios ($^{32}\text{S}/^{34}\text{S}$) to metallicity ([Fe/H]). We can use this relation in combination with a given metallicity gradient along the Milky Way ([Fe/H]) part of our Galaxy. Then, to relate $^{32}\text{S}/^{34}\text{S}$ with a given metallicity gradient along the Milky Way ([Fe/H]) of our Galaxy (see also Kovtyukh et al. 2019). Their measurements are $[\text{Fe/H}] = 0.1 \pm 0.2$ and $-0.06 \pm 0.2$, respectively, and we converted them to $^{32}\text{S}/^{34}\text{S}$ ratios of $21.2 \pm 4$ and $24.4 \pm 4$ by applying Eq. (9).

In summary, the relations of both Bovy et al. (2014) and Genovali et al. (2014), through Eq. (9), give results closer to those obtained from the double-isotope method (Eq. (5)), considering $^{12}\text{C}/^{13}\text{C}$ ratios by Yan et al. (2019) in combination with the $^{13}\text{C}/^{32}\text{S}/^{34}\text{S}$ ratios from Chin et al. (1996), as can be seen in Fig. 5 (dotted blue line). In the nuclear region of the Galaxy the Davies et al. (2009) and Najarro et al. (2009) observations, when accounting for Eq. (9), are both consistent with our measurements for the $+50$ km s$^{-1}$ Cloud and the envelope of Sgr B2(N).

6. Discussion

Among the four stable sulphur isotopes ($^{32}\text{S}$, $^{33}\text{S}$, $^{34}\text{S}$, and $^{36}\text{S}$), $^{32}\text{S}$ is a primary nucleus which could be synthesized in a single generation of massive stars. $^{32}\text{S}$ is mostly formed during stages of hydrostatic and explosive oxygen-burning (Wilson & Matteucci 1992) either preceding a Type II supernova event or in a Type Ia supernova, where two $^{16}\text{O}$ nuclei collide to form $^{32}\text{S}$ and $^{4}\text{He}$, with these products subsequently fusing to yield $^{32}\text{S}$. Type II supernovae synthesize around ten times more $^{32}\text{S}$ than Type I supernovae, and occur roughly 5 times as often as those of Type I (Hughes et al. 2008). $^{32}\text{S}$ is partly a secondary isotope because it can be formed by neutron capture from newly made $^{32}\text{S}$ if the star not only has hydrogen and helium, but also carbon and oxygen in its initial composition (Clayton 2007). It is synthesized in hydrostatic and explosive oxygen- and neon-burning, also produced in massive stars. $^{34}\text{S}$ is partly a secondary product because it can be formed from newly made $^{32}\text{S}$ and $^{33}\text{S}$ by neutron capture, but also during oxygen burning in supernovae like the primary isotope, $^{32}\text{S}$ (Hughes et al. 2008, and references therein). While the comprehensive calculations of Woosley & Weaver (1995) identify $^{32}\text{S}$ as a primary isotope, the same study also found that $^{34}\text{S}$ is not a clean primary isotope; its yields decrease with decreasing metallicity. However, they identify $^{33}\text{S}$ as a primary isotope, in contradiction with later findings (Clayton 2007). $^{36}\text{S}$ is probably the only purely secondary sulphur isotope, being produced by s-process nucleosynthesis in massive stars (Thielemann & Arnett 1985; Mauersberger et al. 1996) and also by explosive C and He burning and via direct neutron capture from $^{34}\text{S}$, according to models (Pignatari et al. 2016). $^{36}\text{S}$ could be the only S isotope not only produced from massive stars but also, to a lesser extent, from AGB stars (Pignatari et al. 2016). However, lines from C$^{36}\text{S}$ are too weak to be detected in this study. Massive stars, as well as Type Ib/c and II supernovae, appear to slightly overproduce $^{34}\text{S}$ and underproduce $^{33}\text{S}$ compared to $^{32}\text{S}$, relative to the solar vicinity (Timmes et al. 1995).

The main result of our study is that the previous trend observed by Chin et al. (1996) is broken near the centre of our Galaxy. In other words, the increase in $^{32}\text{S}/^{34}\text{S}$ with $D_{\text{GC}}$ is not valid in the Galactic centre region. The values of $16.3^{+1.5}_{-1.7}$ from the $+50$ km s$^{-1}$ Cloud and $16.3 \pm 3.8$ and $17.9 \pm 5.0$ Equations (12) and (13) are plotted in Fig. 5 as hatched-shaded regions. As described in the legend, their extrapolations down to 2.53 kpc, following Inno et al. (2019), their Fig. 11, for both Eqs. (10) and (11), are indicated as hatched regions only.

Additionally, we have accounted for iron abundances obtained from high-resolution near-infrared observations by Davies et al. (2009) and Najarro et al. (2009) in the inner 30 pc of the Galaxy (see also Kovtyukh et al. 2019). Their measurements are $[\text{Fe/H}] = 0.1 \pm 0.2$ and $-0.06 \pm 0.2$, respectively, and we converted them to $^{32}\text{S}/^{34}\text{S}$ ratios of $21.2 \pm 4$ and $24.4 \pm 4$ by applying Eq. (9).

Where $[\text{Fe/H}] = \log_{10}(N_{\text{Fe}}/N_{\text{H}})_{\text{sun}} - \log_{10}(N_{\text{Fe}}/N_{\text{H}})_{\text{sun}}$.5

A222, page 10 of 15
Fig. 5. Sulphur isotope $^{32}\text{S}/^{34}\text{S}$ ratio variation when accounting for different carbon $^{12}\text{C}/^{13}\text{C}$ ratios as a function of galactocentric radius, $D_{\text{GC}}$ (e.g. Wilson & Rood 1994; Haffner et al. 2017; Milam et al. 2005; Yan et al. 2019) for the implemented $^{12}\text{C}/^{32}\text{S}/^{34}\text{S}$ ratios, see Chin et al. 1996). The $^{32}\text{S}/^{34}\text{S}$ to $D_{\text{GC}}$ relations obtained from a linear least-squares fit to weighted data (taken as $1/\sigma$, see Sect. 5) are shown and plotted as lines with different styles (see legend). The $^{32}\text{S}/^{34}\text{S}$ ratios from this work are shown in orange, cyan, and light green. All ratios were gleaned from integrated intensity ratios except for Sgr B2(N) (see Fig. 3), where our derived integrated column density ratios are used. Possible differences between integrated column density ratios and line intensity ratios for the mean values in Sgr B2(N) fall inside the error bars. For the case of the GC l.o.s. clouds towards Sgr B2(N), their distances are uncertain and they are believed to be located within $1$ kpc from the GC (see Sect. 3). As described in Sect. 5, the purple and yellow hatched-shaded loci are derived from [Fe/H] vs $D_{\text{GC}}$ relations obtained by Bovy et al. (2014) and Genovali et al. (2014), after accounting for the models of Kobayashi et al. (2011); hatched-only loci correspond to an extrapolation of those relations, following Inno et al. (2019). Using the same models, two $^{32}\text{S}/^{34}\text{S}$ ratios are included. These ratios are derived from iron abundances measured in the central 30 pc of the Galaxy by Davies et al. (2009) and Najarro et al. (2009). A zoom on the results of our study displayed in the left part of the figure is shown in Fig. C.1.

from the GC l.o.s. clouds towards Sgr B2(N) and its envelope, respectively, contrast with the expected $\sim 5–10$ regardless of the value of $^{12}\text{C}/^{13}\text{C}$ adopted (see Fig. 5) when accounting for the $^{12}\text{C}/^{32}\text{S}/^{34}\text{S}$ ratios used in Chin et al. (1996). It is also worth mentioning that our $^{32}\text{S}/^{34}\text{S}$ isotope ratios derived from absorption lines from diffuse or translucent clouds (Sgr B2(N)) are consistent with values derived from emission lines from a prominent star-forming region with dense molecular gas (the +50 km s$^{-1}$ Cloud), even though the chemistry for CS formation is completely different in those regions (see Appendix A).

Ferking et al. (1980), even before the $^{32}\text{S}/^{34}\text{S}$ slope was found, suggested values for $^{32}\text{S}/^{34}\text{S}$ of $\sim 22$ for the Galactic centre. Therefore, the sulphur ratio seems to be constant, or even increases with decreasing $D_{\text{GC}}$, within the inner 2.9 kpc of the Milky Way, in contrast to $^{12}\text{C}/^{13}\text{C}$ (e.g. Yan et al. 2019), $^{14}\text{N}/^{15}\text{N}$ (e.g. Adande & Ziurys 2012), and $^{18}\text{O}/^{17}\text{O}$ (Wouterloot et al. 2008; Zhang et al. 2015). Intriguingly, $^{32}\text{S}/^{34}\text{S}$ behaves in a similar way to $^{18}\text{O}/^{16}\text{O}$ (Polehampton et al. 2005), two nuclei with the bulk of their formation taking place in massive stars ($\geq 10 \text{M}_\odot$) (Clayton 2007). This is surprising because $^{34}\text{S}$ is a tracer of secondary processing as $^{15}\text{C}$ and $^{17}\text{N}$, and therefore its abundance is expected to increase in the same manner as observed for those isotopes.

The fact that sulphur traces late evolutionary stages of massive stars can give a clue to this difference in comparison to C and N, which give information on CNO and helium burning (Chin et al. 1996). Due to their short lives, the star formation rate of massive stars can be traced by their SN rate. Although the amount of $^{34}\text{S}$ is related to metallicity, which decreases with increasing galactocentric radius especially in spiral galaxies (e.g. as observed from oxygen, Henry & Worthey 1999), leading to a trend similar to C and N, the production of $^{34}\text{S}$ is mostly related to SNe II, which show a dip in the inner regions of our Galaxy and other spiral galaxies (Anderson & James 2009), in good agreement with our higher than expected $^{32}\text{S}/^{34}\text{S}$ ratios in the Galactic centre. However, these results are still under debate (see e.g. Hakobyan et al. 2009) and more observations are needed.

Another argument in favour of the above could be that metallicities traced by iron (Genovali et al. 2014; Kovtyukh et al. 2019) instead of oxygen (Henry & Worthey 1999) show a trend in good agreement with our observations (after converting [Fe/H] to $D_{\text{GC}}$/kpc not only outside the central 2.53 kpc as in Fig. 5, but also in the GC region itself). This could also indicate a drop in the production of massive stars at the Galactic centre compared to the rest of the Galaxy and to less massive stars.

Our $^{32}\text{S}/^{34}\text{S}$ isotope ratio of $16.3_{-1.4}^{+1.7}$ can constrain opacity estimates of sulphur-bearing molecules in the Galactic centre region and will considerably augment the confidence in theoretical modelling of dense molecular clouds (e.g. Loison et al. 2019). Such results can then be used as initial inputs to reproduce hot core conditions (Charnley 1997; Viti et al. 2004; Vidal et al. 2018).
Our new value for this ratio can also improve synthetic spectral fitting and subsequent line identification, giving better estimations to sulphur-bearing molecules. As a prime example, we mention the recent work of Zakharenko et al. (2019): the canonical ratio of $^{32}\text{S}/^{34}\text{S} = 22.5$ (Ferking et al. 1980) is insufficient to reproduce their data, as can be seen in their Fig. 4. Our value of $16.3^{+2.1}_{-1.3}$ leads to an enhancement of the $^{34}\text{S}$ isotope by a factor of 1.4 in their fit (red line), better reproducing the lines detected at 99.512 and 99.520 GHz, and thus increasing the confidence in the identification of CH$_3$SH in the hot core Sgr B2(N2).

7. Summary and conclusions

From our analysis of the emission line profiles of CS, $^{13}\text{CS}$, $^{33}\text{S}$, $^{13}\text{C}^{33}\text{S}$ J = 2–1, of CS and $^{34}\text{S}$ J = 3–2, and of $^{13}\text{CS}$ and $^{34}\text{S}$ J = 6–5 in the +50 km s$^{-1}$ Cloud and CS, $^{13}\text{CS}$, $^{34}\text{S}$, $^{13}\text{C}^{34}\text{S}$ J = 2–1 observed in absorption towards Sgr B2(N), we obtain the following main results:

- From measurements of the J = 2–1 lines of $^{12}\text{C}^{34}\text{S}$ J = 2–1 and $^{13}\text{CS}$ J = 2–1, we have obtained a $^{12}\text{C}/^{13}\text{C}$ isotope ratio of 22.1$^{+3.3}_{-2.4}$. Near the centre of our Galaxy, in good agreement with previous estimates.

- For the +50 km s$^{-1}$ Cloud we obtain a $^{34}\text{S}/^{32}\text{S}$ ratio of 4.3$^{+0.2}_{-0.2}$, derived from $^{34}\text{S}$ J = 2–1 and $^{13}\text{CS}$ J = 2–1 column densities. If we take the integrated intensities instead, this ratio would be 4.2$^{+0.2}_{-0.2}$, consistent with the lower end of the range of ratios obtained by Chin et al. (1996), who derived $^{34}\text{S}/^{32}\text{S}$ ratios between 4.38 and 7.53, irrespective of Galactic radius. This might be a first indication of a gradient with rising ratios as a function of increasing galactocentric distance, but data from the Galactic disc have to become more precise for a definite result.

- From the J = 2–1 $^{13}\text{CS}$ and $^{13}\text{C}^{34}\text{S}$ emission lines in the +50 km s$^{-1}$ Cloud, we derive, for the first time in a direct way, a $^{32}\text{S}^{12}\text{O}$ column density ratio of 16.3$^{+1.7}_{-1.3}$, which is consistent with the $^{32}\text{S}^{12}\text{O}$ ratio derived from the J = 6–5 and J = 2–1 $^{13}\text{CS}$ and $^{34}\text{S}$ isotopologues when accounting for the above-mentioned $^{12}\text{C}$/^{13}\text{C}$ ratio. Due to possible CS fractionation, the above ratio might be underestimated by less than ~10%.

- We were able to directly obtain a $^{32}\text{S}^{14}\text{O}$ ratio of 17.9$^{+5.0}_{-5.0}$ for the envelope of Sgr B2(N), from the isotopologues $^{13}\text{CS}$ and $^{13}\text{C}^{34}\text{S}$ in the J = 2–1 lines. Moreover, we have obtained a $^{32}\text{S}^{18}\text{O}$ ratio of 16.3$^{+3.8}_{-3.8}$ for the GC l.o.s. clouds towards Sgr B2(N) through the CS and $^{34}\text{S}$ J = 2–1 isotopologue lines, when CS is not optically thick. Those ratios are prone to increase by up to ~15%, when taking CS fractionation effects into account.

- Making use of the network presented in Loison et al. (2019), we significantly improved CS fractionation estimations under conditions similar to those taking place in massive molecular clouds, young stellar objects, and diffuse or translucent cold molecular clouds.

- Comparing the sulphur ratios from this work with data available in the literature that were obtained from larger distances to Sgr A* and showed a decrease in $^{32}\text{S}^{14}\text{O}$ towards the Galactic centre, we can confidently establish that this decrease terminates at least at a distance of 100 pc to Sgr A*, at the position of Sgr B2(N) (Reid et al. 2009). This is different from trends previously reported for $^{12}\text{C}^{18}\text{O}^{14}\text{N}/^{15}\text{N}$, and $^{18}\text{O}^{16}\text{O}$.

- Our improved $^{32}\text{S}^{14}\text{O}$ isotope ratio will considerably augment the confidence in theoretical modelling for hot cores and in synthetic spectral fitting and subsequent line identification, giving better constraints for the intensities of sulphur-bearing molecules.

Overall, our results suggest that processes occurring at late evolutionary stages of massive stars could be better traced by sulphur isotopologues instead of the most commonly studied CNO isotopes. Further observations targeting isotopologue ratios with distinct nucleogenesis like $^{32}\text{S}^{13}\text{S}$ (i.e. primary species versus secondary isotopologues) produced in advanced massive stars and SNe II can lead to a better understanding of environmental discrepancies between the solar neighbourhood and the inner Galaxy. This will allow, for example, a connection between metallicity gradients traced by iron (Genovali et al. 2014; Kovtyukh et al. 2019) and observations of SNe II (Anderson & James 2009). The above could be also extrapolated to external galaxies, especially with the advent of a new generation of facilities.

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References

Adande, G. R., & Ziurys, L. M. 2012, ApJ, 744, 194
Adrians, D. A., Goumans, T. P. M., Catlow, C. R. A., & Brown, W. A. 2010, J. Phys. Chem. C, 114, 1892
Agúndez, M., & Wakelam, V. 2013, Chem. Rev., 113, 8710
Agúndez, M., Marcelino, N., Cernicharo, J., Roueff, E., & Tafalla, M. 2019, A&A, 625, A147
Anderson, J. P., & James, P. A. 2009, MNRAS, 399, 559
Ao, Y., Henkel, C., Menten, K. M., et al. 2013, A&A, 550, A135
Armijos-Abendaño, J., Martín-Pintado, J., Requena-Torres, M. A., Martín, S., & Rodríguez-Franco, A. 2015, MNRAS, 446, 3842
Bayet, E., Viti, S., Williams, D. A., & Rawlings, J. M. C. 2008, ApJ, 676, 978
Bayet, E., Aladro, R., Martín, S., Viti, S., & Martín-Pintado, J. 2009, ApJ, 707, 126
Belloche, A., Müller, H. S. P., Menten, K. M., Schilke, P., & Comito, C. 2013, A&A, 559, A47
Belloche, A., Müller, H. S. P., Garrod, R. T., & Menten, K. M. 2016, A&A, 587, A91
Bonfill, B., Belloche, A., Menten, K. M., Garrod, R. T., & Müller, H. S. P. 2017, A&A, 604, A60
Bonfield, M., Belloche, A., & Garrod, R. T., et al. 2019, A&A, 628, A10
Bovy, J., Nidever, D. L., Rix, H.-W., et al. 2014, ApJ, 790, 127
Charnley, S. B. 1997, ApJ, 481, 396
Chen, Y. N., Henkel, C., Whiteoak, J. B., Langer, N., & Churchill, E. B. 1996, A&A, 305, 960
Clayton, D. 2007, Handbook of Isotopes in the Cosmos (Cambridge: Cambridge University Press)
Corby, J. F., McGaugh, B. A., Herbst, E., & Remijan, A. J. 2018, A&A, 610, A10
Dale, D. A., Kaastra, J. S., & Longmore, S. N. 2019, MNRAS, 486, 3307
Davies, B., Orígala, L., Kudritzki, R. P., et al. 2009, ApJ, 694, 46
Durla, K., Knapp, G. R., & van Dishoeck, E. F. 1989, ApJ, 345, 815
Endres, C. P., Schlemmer, S., Schilke, P., Stutzki, J., & Müller, H. S. P. 2016, J. Mol. Spectr., 327, 95
P. K. Humire et al.: Sulphur and carbon isotopes towards Sgr A

Molinari, S., Bally, J., Glover, S., et al. 2014, in Protostars and Planets VI, eds. H. Beuther, R. S. Klessen, P. C. Dullemond, & T. Henning, 125 Montaigne, H., Geppert, W. D., Semanak, J., et al. 2005, ApJ, 631, 653 Müller, H. S. P., Schlöder, F., Stutzki, J., & Winnewisser, G. 2005, J. Mol. Struct., 418 Müller, S., Guélin, M., Dunke, M., Lucas, R., & Combes, F. 2006, A&A, 458, 417 Müller, H. S. P., Belloche, A., Menten, K. M., Comito, C., & Schilke, P. 2008, J. Mol. Spectrosc., 251, 319 Najarro, F., Figuer, D. F., Hillier, D. J., Geballe, T. R., & Kudritzki, R. P. 2009, ApJ, 691, 1836 Nummelin, A., Bergman, P., Hjalmarson, Å., et al. 1998, ApJS, 117, 427 Pignatari, M., Herwig, F., Hirschi, R., et al. 2016, ApJS, 225, 24 Polehampton, E. T., Baluteau, J. P., & Swinyard, B. M. 2005, A&A, 437, 959 Rau, M. J., Menten, K. M., Zheng, X. W., Brunthaler, A., & Xu, Y. 2009, ApJ, 705, 1548 Remijan, A. J., Hollis, J. M., Lovas, F. J., et al. 2008, ApJ, 675, L85 Requena-Torres, M., Martín-Pintado, J., Martín, S., & Morris, M. R. 2008, ApJ, 672, 352 Rüdiger, A. M., Federman, S. R., & Lambert, D. L. 2011, ApJ, 728, 36 Roueff, E., Loison, J. C., & Hickson, K. M. 2015, A&A, 576, A99 Ruze, J. 1966, IEEE Proc., 54, 633 Sánchez-Monge, Á., Chibueze, P., Schmiedeke, A., et al. 2017, A&A, 604, A6 Sandqvist, A., Larsson, B., Hjalmarson, Å., et al. 2008, A&A, 482, 849 Sandqvist, A., Larsson, B., Hjalmarson, Å., et al. 2015, A&A, 584, A118 Schmiedeke, A., Chibueze, P., Möller, T., et al. 2016, A&A, 588, A143 Schöller, A., Sánchez-Monge, Á., Chibueze, P., et al. 2019, A&A, 628, A6 Smith, D., & Adams, N. G. 1980, ApJ, 242, 424 Thiel, V. 2019, PhD thesis, University of Bonn, Germany Thiel, V., Belloche, A., Menten, K. M., et al. 2019, A&A, 623, A68 Thielemann, F. K., & Arnett, W. D. 1985, ApJ, 295, 604 Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617 Tsuboi, M., Handa, T., & Uchida, N. 1999, ApJS, 213, 157 Uehara, K., Tsuboi, M., Kitamura, Y., Miyawaki, R., & Miyazaki, A. 2019, ApJ, 872, 121 van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, A&A, 468, 627 van Dishoeck, E. F., & Blake, G. A. 1998, ARA&A, 36, 317 Vastel, C. Quénard, D., Le Gal, R., et al. 2018, MNRAS, 478, 5599 Vidal, T. H. G., Loison, J.-C., Jaziri, A. Y., et al. 2018, MNRAS, 469, 435 Viti, S. 2016, IAU Symp., 17 Viti, S., Collings, M. P., Dever, J. W., McCoustra, M. S. R., & Williams, D. A. 2004, MNRAS, 354, 1141 Vollmer, B., Duschl, W. J., & Zylka, R. 2003, Astron. Nachr. Suppl., 324, 613 Wakelam, V., Herbst, E., & Segura, J. 2006, A&A, 458, 5777 Wakelam, V., Smith, I. W. M., Herbst, E., et al. 2010, A&A, 519, 83 Wagner, M., Henkel, C., Chin, Y. N., et al. 2004, ApJ, 612, 1141 Wang, K. S., Bourke, T. L., Hogerheijde, M. R., et al. 2013, A&A, 558, A69 Whiteoak, J. B., & Gardner, F. F. 1979, MNRAS, 188, 445 Wilson, T. L., & Mattucci, F. 1992, ARA&A, 4, 1 Wilson, T. L., & Rood, R. J. 1994, ARA&A, 32, 191 Woörmann, E. B., Bergman, P., Black, J. H., et al. 2010, A&A, 522, A19 Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181 Wouterloot, J. G. A., Henkel, C., Brand, J., & Davis, G. R. 2008, A&A, 487, 237 Yan, Y. T., Zhang, J. S., Henkel, C., et al. 2019, ApJ, 877, 154 Zakharenko, O., Lewen, F., Illuyshin, V. V., et al. 2019, A&A, 627, A41 Zhang, J. S., Sun, L. L., Riquelme, D., et al. 2015, ApJS, 219, 28 Zuckerman, B., Turner, B. E., Johnson, D. R., et al. 1975, ApJ, 196, L99
Appendix A: Chemical aspects

In diffuse clouds, it has been suggested that CS forms mainly by exothermic ion-molecule reactions of $^3$S$^+$ with CH and C$_2$ (Drdla et al. 1989; van Dishoeck & Blake 1998). However, these species require to be one order of magnitude more abundant than currently observed in order to reproduce the observed quantities of CS (Lucas & Liszt 2002). Currently, CS formation is believed to be dominated by the exothermic reaction (Drdla et al. 1989; Lucas & Liszt 2002; Montaigne et al. 2005; Laas & Caselli 2019)

\[
{\text{HCS}}^+ + e^- \rightarrow \text{CS} + \text{H}. \quad (A.1)
\]

Subsequently, the dominant destruction route of CS is photodissociation, with destruction by He$^+$ being only significant in denser clouds (Drdla et al. 1989).

At higher densities, CS is mainly produced through neutral–neutral reactions with atomic sulfur such as (Fuente et al. 2016; Vidal et al. 2018; Laas & Caselli 2019)

\[
\begin{align*}
\text{S} + \text{CH} & \rightarrow \text{CS} + \text{H} \quad \text{(A.2a)} \\
\text{S} + \text{C}_2 & \rightarrow \text{CS} + \text{C}, \text{ and} \\
\text{SO} + \text{C} & \rightarrow \text{CS} + \text{O}. \quad \text{(A.2c)}
\end{align*}
\]

The dissociative recombination (DR) of HCS$^+$ becomes the main path for CS destruction at low temperatures because HCS$^+$ is mainly produced through protonation of CS and its DR leads mainly to S+CH and not to CS+H (Montaigne et al. 2005).

At higher temperatures, such as in hot cores and hot corinos for which recent models suggest some changes in sulfur chemistry (Vidal et al. 2018), CS is also destroyed by atomic oxygen:

\[
\text{CS} + \text{O} \rightarrow \text{CO} + \text{S}. \quad (A.3)
\]

This reaction is supposed to be negligible at low temperature due to the presence of a barrier (Lilienfeld & Richardson 1977; González et al. 1996). However, the value of the barrier is questionable (Adriaens et al. 2010) so that this reaction may not be completely negligible at low temperature. Apart from this reaction, and despite the recent advances in the investigation of sulfur species in the interstellar medium (Fuente et al. 2016; Vidal et al. 2018; Laas & Caselli 2019), there are still large uncertainties with respect to CS and HCS$^+$ chemistry.

Recent studies agree with the above reactions, but indicate that the dominant mechanism also depends on the cosmic ray ionization rates (CRIR). At high CRIR, which may be typical of the central parts of giant spiral galaxies, reactions (A.2c) and (A.3) dominate CS formation and destruction, but at lower CRIR the following reaction (route (A.4)) becomes dominant for the destruction of CS (Kelly et al. 2015; Viti 2016):

\[
\text{H}_2\text{O}^+ + \text{CS} \rightarrow \text{HCS}^+ + \text{H}_2\text{O}. \quad (A.4)
\]

In hot cores and corinos, recent models suggest some deviations from the above-mentioned routes of sulfur chemistry (Vidal et al. 2018). Specifically for CS, the main paths for its formation and destruction continue being Eqs. (A.2c) and (A.3), respectively. CS is initially destroyed by atomic oxygen (Eq. (A.3)) both at 100 and 300 K, on timescales of $10^4$ and $10^3$ yr, respectively. Nevertheless, CS is then also produced by

\[
\begin{align*}
\text{S} + \text{CH}_2 & \rightarrow \text{HCS} + \text{CS}_2 \\
\text{S} & \rightarrow \text{CS}.
\end{align*}
\]

Appendix B: Excitation temperatures

![Excitation temperatures](https://pypi.org/project/ndradex/)

Fig. B.1. Excitation temperatures ($T_{ex}$) as a function of opacity ($\tau$) for $^{13}$CS $J=2–1$ (top) and $^{34}$S$^+ J=3–2$ (bottom). Molecular column densities range between $10^{11}$ and $10^{15}$ cm$^{-2}$, and the kinetic temperature is 80, 200, and 400 K, represented by blue, green, and red lines, respectively. $\Delta(T_{ex})$ refers to the $T_{ex}$ maximum variation between $\tau=0.04$ and 0.15 (delineated by dashed vertical red lines).

As mentioned in Sects. 4.1 and 4.1.3, we assumed the same excitation temperatures ($T_{ex}$) in all our opacity calculations. This is argued by the low opacity of the isotopologues used to make such calculations.

Let us take an opacity ($\tau$) ranging between 0.04 and 0.15 (see Table 2) for both $^{13}$CS $J=2–1$ and $^{34}$S$^+ J=3–2$ with which we obtained the opacity for $^{12}$CS $J=2–1$ and $J=3–2$, respectively. As can be seen in Fig. B.1, the variations in $T_{ex}$ within this range falls below 0.64 K. Considering that this temperature will be inside an exponential as denominator of a fraction and, furthermore, multiplied by the Boltzmann constant (see Eq. (80) in Mangum & Shirley 2015), is reasonable to assume that $T_{ex}$ variations are negligible for the scope of this work.

Calculations were done with a python version$^6$ of RADEX (van der Tak et al. 2007), a statistical equilibrium molecular radiative transfer code. Our inputs were a kinetic temperature of 80, 200, and 400 K; 100 equally spaced values for the column density from $10^{11}$ to $10^{15}$ cm$^{-2}$; and a H$_2$ volumetric density of $5 \times 10^4$ cm$^{-3}$, in an attempt to emulate the conditions of the $+50$ km s$^{-1}$ Cloud (see Sect. 3). $^{13}$CS and $^{34}$S$^+$ collision rates were taken from the Leiden Atomic and Molecular Database (LAMDA, Schwörer et al. 2019), which in turn uses calculations made by Lique et al. (2006).

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$^6$ See https://pypi.org/project/ndradex/ for a full description. We have used the Grid RADEX run option.
Appendix C: Zoom in for Fig. 5

We plot our own data from Fig. 5 in a magnified way. Data values for the l.o.s. clouds towards Sgr B2(N) and its envelope are given in Table 4. The integrated intensity $^{32}\text{S}/^{34}\text{S}$ ratio of the $+50$ km s$^{-1}$ Cloud (18.6$^{+2.2}_{-1.8}$) comes from Sect. 4.1.2.

Appendix D: Gaussian fitting

We preferred to use the lmfit package instead of Gildas, for example, because the former has some improvements related to uncertainty calculations. While both use minimization, Simplex and Gradient methods, because of the use of the Minimize package, lmfit has additional functions and packages to ensure a proper uncertainty estimation “even in the most difficult cases”. We compared the uncertainties from Gildas and lmfit; those derived based on Gildas are lower than those from lmfit by a small percentage (well within the uncertainties), and at the same time the use of Gildas results in a less successful fit in certain cases (not shown). Given the rich available documentation for lmfit, we opted for the lmfit-based fitting and associated uncertainty determination.

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7 https://www.iram.fr/IRAMFR/GILDAS
8 https://lmfit.github.io/lmfit-py/fitting.html#the-minimize-function
9 https://lmfit.github.io/lmfit-py/