SULFUR CHEMISTRY AND ISOTOPIC RATIOS IN THE STARBURST GALAXY NGC 2531, 2

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ABSTRACT

On the basis of observations of the most abundant sulfur-bearing molecules (H$_2$S, CS, NS, SO, H$_2$CS, OCS, and SO$_2$) carried out with the IRAM 30 m telescope and the Swedish-ESO Submillimetre Telescope (SEST), we present the first analysis of the sulfur chemistry of an extragalactic source, the nuclear region of the starburst galaxy NGC 253. This is the first time that H$_2$S and, tentatively, H$_2$CS are detected toward the nucleus of a starburst galaxy. Source-averaged fractional abundances of these molecules are a few times 10$^{-5}$, except for CS and OCS, which are more abundant (10$^{-3}$). Sulfur isotopic ratios, $^{32}$S/$^{34}$S $\sim$ 8 $\pm$ 2 and $^{34}$S/$^{33}$S $>$ 9, are measured through observations of $^{13}$CS, $^{34}$S, and $^{33}$S. A comparison with the observed relative abundances toward different prototypical Galactic sources suggests that the chemical composition of NGC 253 is similar to that found toward molecular cloud complexes like Sgr B2 in the nuclear region of the Milky Way. The large overabundance of OCS compared with the predictions of time-dependent sulfur chemistry models supports the idea that OCS is likely to have been injected into the gas phase from grain mantles by low-velocity shocks.

Subject headings: galaxies: abundances — galaxies: active — galaxies: individual (NGC 253) — galaxies: ISM — galaxies: nuclei — galaxies: starburst

1. INTRODUCTION

The formation and evolution of stars strongly affects the chemistry of their molecular environment. In particular, sulfur-bearing molecules show enhanced abundances in hot molecular cores, the condensations associated with massive protostars. The most accepted idea is that during the collapse of a star-forming cloud, a large fraction of the available sulfur freezes out by accretion onto grain mantles and hydrogenates in the form of H$_2$S. The high temperatures and turbulent motions in these objects produced by the newly formed stars induce the evaporation and disruption of grain mantles, releasing the H$_2$S into the gas phase. After evaporation, this molecule is believed to drive a fast high-temperature gas-phase chemistry leading to the formation first of SO and SO$_2$ and subsequently of other sulfur-bearing molecules such as CS and H$_2$CS (Charnley 1997; Hatchell et al. 1998). It is still uncertain whether the release of H$_2$S is caused exclusively by thermal evaporation or whether shocks play a role in the disruption of the grain mantles (Hatchell & Viti 2002). In low-mass star-forming regions, where the temperatures are not high enough to evaporate the grain mantles, there is evidence that shocks may be responsible for injecting the H$_2$S from ices into the gas phase (Buckle & Fuller 2003). Sulfur-bearing molecules are considered to be an important tool for studying the presence of shocks within massive star-forming regions. Time-dependent chemical models have roughly succeeded in reproducing the observed abundances of the most common sulfur-bearing species both in high- and low-mass star-forming regions (Hatchell et al. 1998; Buckle & Fuller 2003)

In starburst galaxies like NGC 253, only the most abundant sulfur-bearing molecules have been detected so far, namely, CS, OCS, SO (Henkel & Bally 1985; Mauersberger et al. 1995; Putuchowski & Bennet 1992), and recently also SO$_2$ and NS (Martín et al. 2003). Extragalactic H$_2$S has only been detected toward the Large Magellanic Cloud, where H$_2$CS is also tentatively detected (Heikkilä et al. 1999). In this paper we present the first detection of H$_2$S and the tentative detection of H$_2$CS in NGC 253, allowing us to investigate for the first time the sulfur chemistry in its nuclear region using a set of the most abundant sulfur-bearing species.

2. OBSERVATIONS

Most of the observations of the molecular species listed in Table 1 were carried out with the IRAM 30 m telescope on Pico Veleta, Spain. The measurements were made in symmetrical wobbler switching mode with a frequency of 0.5 Hz and a beam throw of 4$^\prime$ in azimuth. As spectrometers, we used two 256 $\times$ 4 MHz
Sulfur Chemistry and Isotopic Ratios in NGC 253

Table 1
Parameters Derived from Gaussian Fits to the Observed Features

| Molecule | $\nu$ (MHz) | Transition $J$--$J'$ | $\int T_{\text{mb}} \, dv$ (mK km s$^{-1}$) | $v_{\text{LSR}}$ (km s$^{-1}$) | $\Delta v/2$ (km s$^{-1}$) | $T_{\text{mb}}$ (mK) | rms$^a$ (mK) |
|----------|------------|---------------------|-------------------------------|-------------------|------------------|---------------|-----------|
| H$_2$S..... | 168762.8   | $1_{0,0}^{10,10}$  | 1520 ± 180                    | 180               | 100              | 14.3          | 4.7       |
| CS......... | 97981.0    | 2–1                 | 2250 ± 80                     | 275               | 88               | 23.9          |           |
| CS......... | 146969.0   | 3–2                 | 4400 ± 500                    | 172               | 96               | 43.4          | 5.2       |
| CS......... | 195954.2   | 4–3                 | 11500 ± 400                   | 288               | 171              | 110.3         |           |
| CS......... | 244935.6   | 5–4                 | 13400 ± 500                   | 185               | 100              | 111.2         | 4.1       |
| C$^{34}$S. | 144617.1   | 3–2                 | 3000 ± 300                    | 188               | 105              | 27.1          | 1.4       |
| C$^{33}$S. | 138739.3   | 3–2                 | 1500 ± 300                    | 284               | 86               | 16.1          |           |
| C$^{33}$S. | 145755.8   | 3–2                 | 550 ± 70                      | 188               | 70               | 7.4           | 1.9       |
| SO......... | 138178.6   | $4_2^{13}--3_2^{13}$ | 1100 ± 200                   | 274               | 88               | 11.6          |           |
| SO......... | 158971.8   | $3_2^{13}--3_2^{13}$ | 700 ± 200                    | 180$^b$           | 92               | 7.2           | 2.9       |
| H$_2$CS.... | 135297.8   | $4_1^{14}--3_1^{13}$ | 1000 ± 200                   | 274$^b$           | 84               | 11.4          |           |
| H$_2$CS.... | 139483.4   | $4_1^{13}--3_1^{13}$ | 1340 ± 150                   | 221               | 158              | 6.2           | 1.4       |
| OCS......... | 85139.1    | 7–6                 | 1100 ± 300                    | 212$^b$           | 210$^b$         | 5.1           | 2.7       |
| OCS......... | 97301.2    | 8–7                 | 1080 ± 120                    | 214               | 219              | 4.6           | 1.8       |
| OCS......... | 133785.9   | 11–10              | 1220 ± 130                    | 212               | 200              | 5.8           | 1.3       |
| OCS......... | 145946.8   | 12–11              | 580 ± 170                     | 212$^b$           | 210$^b$         | 2.6           | 1.4       |

$^a$ The rms values in $T_{\text{mb}}$ and smoothed to a 10 km s$^{-1}$ channel width.

$^b$ Fixed parameter.

Filter banks for the transitions at 2 mm and two $512 \times 1$ MHz filter banks for those at 3 mm. The $J = 2$–1 and 5–4 transitions of CS were measured with the 15 m Swedish-ESO Submillimetre Telescope (SEST) at La Silla, Chile. Observations were done in wide dual beam switch mode, with 11/8 beam throw in azimuth. Acousto-optical spectrometers were used as back ends with a resolution of 1.4 MHz. Beam sizes ranged from 29″ (at 85 GHz) to 12″ (at 196 GHz) for the 30 m telescope and from 51″ (at 98 GHz) to 21″ (at 244 GHz) for SEST. In both telescopes, receivers were tuned to single sideband with an image band rejection larger than 10 dB. The spectra were calibrated with a dual load system.

Figure 1 shows the observed line profiles of CS and two of its isotopic substitutions ($^{13}$CS and $^{34}$S), H$_2$S, SO, H$_2$CS, and OCS, as well as the corresponding Gaussian fits.

3. RESULTS

For most of the observed transitions, we identify two velocity components, which arise from molecular complex clouds at two opposing sides of the nucleus (Mauersberger et al. 1996) located at $\sim 5''$ northeast (the 180 km s$^{-1}$ component) and $\sim 5''$ southwest (the 280 km s$^{-1}$ component), as revealed by interferometric maps (Peng et al. 1996; Garcia-Burillo et al. 2000).

The derived parameters from the Gaussian fits to the observed profiles are shown in Table 1. While most of the transitions of the main isotopic species of CS have already been reported (Mauersberger & Henkel 1989; Henkel et al. 1993), the improved signal-to-noise ratios of our data allow us for the first time to separate the two main velocity components in the line profiles. Unfortunately, the 2 mm lines of H$_2$CS appear to be blended with other lines. The $4_1^{14}--3_1^{13}$ transition is blended with the H36$^a$ recombination line, and the $4_1^{13}--3_1^{12}$ transition is contaminated by a contribution of the CS $J = 3$–2 line from the image band. In order to perform the Gaussian fits to the H$_2$CS lines, we have, respectively, subtracted a Gaussian profile similar to that observed for the H34$^a$ line measured at 160 GHz and one similar to the CS $J = 3$–2 emission measured in the signal band corrected by the corresponding image gain. As seen in the bottom panel of the H$_2$CS lines in Figure 1, the CS and the H$_2$CS lines do not fully account for the observed feature. The extra emission could be due to the presence of another unidentified line. In spite of the uncertainties due to the blending, both resulting H$_2$CS profiles are self-consistent, since they are expected to have similar intensities. Nevertheless, this detection must be regarded as tentative. Similarly, the OCS $J = 7$–6 transition appears blended with the $J = 1$–0 line of HC$^{18}$O$^+$. Additional observation of the HC$^{18}$O$^+$ $J = 2$–1 transition at 170 GHz allowed us to estimate and subtract the contribution of this species to the observed feature by assuming local thermodynamic equilibrium (LTE) with an excitation temperature $T_{ex} \sim 12$ K.

3.1. Molecular Abundances and Excitation Temperatures

In order to derive the physical properties of the molecular material, we need to make an assumption on the total emission extent of the molecular emitting region. By smoothing the interferometric CS data from Peng et al. (1996), Mauersberger et al. (2003) derived the dependence of the observed line intensity on the beam size. This dependence indicates an equivalent source size of $\sim 20''$ for the CS emitting region. The interferometer maps of CS only miss 36% of the flux (Peng et al. 1996), suggesting that the extent of the CS emission is not much larger than this estimate. As we have no additional information on the extent of the emission of the other, rarer species, we assume...
them to be similar to that of CS. This assumption is supported by the comparison of the high angular resolution maps of the CS emission with those of species with a fairly different chemistry, such as SiO, H13CO+ (García-Burillo et al. 2000), and NH3 (M. Lebron 2004, private communication), where the morphology of the emission seems to be similar.

We have derived source-averaged column densities by correcting the measured line intensities for the estimated source size of 20" assuming optically thin emission. The corresponding population diagrams for CS, SO, and OCS are shown in Figure 2. For CS we show the population diagrams for the two velocity components at 180 and 280 km s⁻¹, and we derive a rotational temperature $T_{\text{rot}} \approx 10$ K for both components. In these diagrams, the population in the $J = 2$ level, clearly above the linear fit, shows evidence for the presence of a lower excitation temperature component with $T_{\text{rot}} \approx 5$ K, which can be explained by the much larger region observed by the 51" beam of SEST. As derived below, the CS emission is moderately optically thick. The effect of the opacity on the population diagram would result in a slight increase of the derived excitation temperatures. Thus, we would get temperatures of $\approx 13$ and $\approx 8$ K for the two components. To derive the CS column density in Table 2 we have used the optically thin emission of one of its isotopes, $^{13}$CS. For OCS we derive $T_{\text{rot}} = 16$ K. Our estimate of the OCS column density in Table 2 is in agreement with that derived by Mauersberger et al. (1995) when the differences in the
assumed source size are taken into account. For the 180 km s$^{-1}$ component of SO we obtain $T_{\text{rot}} = 23$ K. As seen in Figure 2, the 280 km s$^{-1}$ component of the SO $3_4-2_3$ transition ($E_u/k \sim 29$ K) has a higher intensity than expected if we assume, from the CS results, both components to have a similar rotational temperature (Fig. 2). This may be due to the contamination of this component by the emission feature observed at a velocity of $\sim 400$ km s$^{-1}$, which we tentatively identify as the $81,8-71,7$ transition of NH$_2$CN (cyanamide). The measured integrated intensity has been then considered as an upper limit, as shown in Figure 2. We have therefore assumed a similar excitation temperature of 23 K for both velocity components to compute the column density of the 280 km s$^{-1}$ component of SO. Since we have only one transition for H$_2$S and the two observed lines of H$_2$CS have the same upper level energy, we need to make an assumption on the excitation temperature of these species. As the Einstein coefficients of these transitions are similar to those of CS and SO$_2$, we take an excitation temperature of 12 K for both species, according to that derived from CS in this work and from SO$_2$ by Martín et al. (2003).

Table 2 shows the derived source-averaged column densities, rotational temperatures, and fractional abundances relative to H$_2$ for all the sulfur-bearing molecules detected toward the nucleus of NGC 253. The main sources of uncertainty in the derived abundances are those from the assumed extent of the emitting region and the H$_2$ column density, which are assumed to be the same for all the species. Assuming the extreme case in which the molecular emission is confined to a much smaller region of $\sim 10''$, the derived source-averaged column densities will be larger by less than a factor of 2. However, these uncertainties are expected to be even smaller when column density ratios between different species are considered. A similar argument also applies to the uncertainties in the derived fractional abundances introduced by the assumed H$_2$ column density if, as already discussed, the spatial distribution among different species does not vary substantially. Since we focus our discussion on the molecular abundance ratios between different species, these uncertainties do not affect our conclusions.

Given that the $J = 3-2$ transitions of CS, $^{13}$CS, and C$^{34}$S were observed with the same telescope, we can compare the observed $^{12}$CS/$^{13}$CS line intensity ratio of 21 $\pm$ 3 with the $^{12}$C/$^{13}$C ratio of $40 \pm 10$ estimated by Henkel et al. (1993). Assuming that the $^{12}$CS/$^{13}$CS intensity ratio reflects the $^{12}$C/$^{13}$C abundance ratio, we derive an optical depth for the $^{12}$CS,$J = 3-2$ transition of $\sim 1.4$. Therefore, from the measured $^{13}$CS/C$^{34}$S line intensities and the $^{12}$C/$^{13}$C ratio mentioned above we derive a $^{32}$S/$^{34}$S abundance ratio of $8 \pm 2$. From our nondetection of the C$^{33}$S line, it is possible to give a 3 $\sigma$ lower limit to the $^{34}$S/$^{33}$S ratio of 9.

The line intensities corrected for beam dilution of the four observed transitions of CS and the $J = 3-2$ lines of $^{13}$CS and C$^{34}$S have been compared with the results of model calculations for the excitation of CS in which the large velocity gradient approximation has been used. A line width of 100 km s$^{-1}$ and a kinetic temperature $T_{\text{kin}} = 100$ K (similar to the rotational temperature of 100–142 K derived from NH$_3$ measurements by Mauersberger et al. 2003) have been considered in these non-LTE calculations. Figure 3 shows the results of this model for the observed line intensities and line ratios. The gray region corresponds to the best fit to the observed CS main isotope line intensities, calculated by minimizing the reduced $\chi^2$ function, as described by Nummelin et al. (2000). The best fit gives a CS column density $N$(CS) = $5.7 \times 10^{13}$ cm$^{-2}$ and a molecular hydrogen density $n$(H$_2$) = $2.2 \times 10^5$ cm$^{-3}$ for the velocity component at 180 km s$^{-1}$ and $N$(CS) = $5.7 \times 10^{13}$ cm$^{-2}$ and $n$(H$_2$) = $2.4 \times 10^5$ cm$^{-3}$ for that at 280 km s$^{-1}$. These column densities are a factor of 2 lower than those in Table 2 derived from the isotopomer $^{13}$CS assuming LTE conditions. The H$_2$ density derived from this analysis depends on the assumed kinetic temperature. Therefore, a $T_{\text{kin}}$ of 50 or 25 K would lead to H$_2$ densities a factor of 2 and 4 higher, respectively. The choice of $T_{\text{kin}}$ has, however, almost no effect on the column density determination.

As Figure 3 shows, the best-fit contour does not cover the $J = 2-1$ data at a probability level of 99.5%. This fact suggests that the CS emission is best explained if one considers several gas components in the region covered by the telescope beam.

![Fig. 2.—Population diagrams for the CS, SO, and OCS molecules. The 180 km s$^{-1}$ component is represented by squares and continuous lines; the 280 km s$^{-1}$ component is shown with triangles and dashed lines.](image-url)
These components are related to the need for two different excitation temperatures to fit the population diagram. The \( J = 2-1 \) to \( 1-0 \) ratio of 1.5 derived by Paglione et al. (1995), also plotted in Figure 3, supports this scenario. For the 180 km s\(^{-1}\) velocity component (Fig. 3a) a higher density component [\( n(H_2) \sim 4 \times 10^4 \text{ cm}^{-3} \)] explains the \( J_u = 5, 4 \), and 3 transitions, and a lower density component [\( n(H_2) \sim 6 \times 10^3 \text{ cm}^{-3} \)], with a column density 3 times higher, explains the lower \( J \) transitions. Similar results, within the errors, can be derived for the 280 km s\(^{-1}\) component.

From the non-LTE calculations we derive \( C_3^{2S}/C_3^{4S} \) ratios of 4–9 and \( ^{12}C^{13}S/^{13}C^{13}S \) ratios of 22–35 for the 180 and 280 km s\(^{-1}\) velocity components, respectively. The \( ^{12}C^{13}S/^{13}C^{13}S \) intensity ratio obtained for the 180 km s\(^{-1}\) component is half of the \( ^{12}C/^{13}C \) ratio estimated by Henkel et al. (1993), while that obtained for the 280 km s\(^{-1}\) component is closer to their value. This may be explained by the fact that the \(^{13}S\) observation by Henkel et al. (1993) was made toward a position \( \sim 6'' \) closer to the emission peak of the 280 km s\(^{-1}\) component.

4. DISCUSSION

4.1. Molecular Fractional Abundances

We find that most of the sulfur-bearing species detected toward the nuclear region of NGC 253 show similar fractional abundances of a few times \( 10^{-9} \) (Table 2). Only CS and OCS have abundances a factor of \( \sim 5 \) higher. In order to understand the mechanism that dominates the chemistry in the nuclear environment of NGC 253, we summarize in Table 3 the fractional abundances of all the sulfur-bearing molecules detected toward this starburst galaxy and those observed toward selected Galactic sources (hot cores, Galactic center clouds, dark clouds, photodissociation regions (PDRs), and shocks driven by massive protostars) that are dominated by different kinds of chemistry. The

| TABLE 3 | RELATIVE ABUNDANCES OF S-BEARING MOLECULES IN DIFFERENT ENvironments |
|---|---|---|---|---|---|---|
| MOLECULE | HOT CORES | | | | | |
| | NGC 253 | SGR B2 (N) | Orion KL | | | |
| H$_2$S | 4 | 0.2$^a$ | 5000$^b$ | ... | 1.5 | 0.8 | <0.5 | 6 | 4000$^b$ |
| CS | 20 | ... | 6 | ... | 11 | 1 | 10 | 20 | 4 |
| NS | 3$^f$ | 10 | 0.4$^f$ | ... | 2.1 | 0.4$^g$ | 1$^k$ | ... | ... |
| SO | 4 | 20 | 190 | 4.4 | 6 | 5 | 20 | 5 | 9 | 200 |
| H$_2$CS | 3 | 20 | 0.8 | 6 | 5 | 0.6 | 3 | ... | 8 |
| OCS | 15 | 2 | 11 | 21 | 53 | 2 | 2 | ... | 10 |
| SO$_2$ | 4$^c$ | 30 | 120 | 5.8 | 5.4 | 4 | \( <1 \) | 0.1 | 100 |
| H$_2$S/SO$_2$ | 1 | 0.01 | 26 | ... | 0.25 | 0.04 | \( <0.1 \) | 0.7 | 20 |
| CS/SO$_2$ | 5 | ... | 0.005 | ... | 2 | 0.25 | \( <10 \) | 200 | 0.04 |
| SO$_2$/SO | 1 | 1.5 | 0.6 | 1.3 | 0.9 | 0.2 | \( <0.2 \) | 0.01 | 0.5 |
| OCS/SO$_2$ | 3.75 | 0.1 | 0.06 | 4.8 | 8.8 | 0.1 | 0.4 | ... | 0.05 |
| CS/H$_2$S | 5 | ... | 0.001 | ... | 7.3 | 1.25 | \( >20 \) | 3.3 | 0.001 |

Note.—Units of \( 10^{-9} \) are used.

$^a$ Nummelin et al. (2000).

$^b$ Sutton et al. (1995).

$^c$ Cummins et al. (1986) assuming \( N(H_2) = 1 \times 10^{23} \text{ cm}^{-2} \).

$^d$ S. Martin et al. (in preparation).

$^e$ Ohishi et al. (1992).

$^f$ Jansen et al. (1995).

$^g$ Minh et al. (1991).

$^h$ Minh et al. (1990).

$^i$ Martin et al. (2003).

$^j$ McGonagle & Irvine (1997).

$^k$ McGonagle et al. (1994).
abundance ratios discussed in this section are also shown in Table 3.

The SO$_2$ abundance in PDRs is much lower, by a factor of 40, than that found in NGC 253. Thus, abundance ratios such as H$_2$S/SO$_2$ and CS/SO$_2$ can be used to establish the role of photodissociation in the chemistry of NGC 253. Particularly instructive is the SO/SO$_2$ abundance ratio. A ratio of SO/SO$_2$ $\sim$ 100 toward PDRs is about 2 orders of magnitude larger than that in NGC 253, which suggests that photodissociation does not play a major role in the chemistry of its nuclear region.

A comparison with dark clouds shows a clearly lower abundance of OCS than that observed toward NGC 253. The OCS/SO ratio is 0.1 and 0.4 in L134N and TMC-1, respectively, while we measure $\sim$4 in NGC 253. The abundance ratios of SO$_2$/SO and H$_2$S/SO$_2$ of $\sim$0.2 and $\sim$0.05, respectively, measured toward these dark clouds are also much smaller than the corresponding ratios of $\sim$1 observed toward NGC 253. Therefore, dark molecular clouds like L134N and TMC-1 do not seem to dominate the molecular composition near the nucleus of NGC 253.

Chemistry driven by high-velocity shocks in molecular outflows also differs significantly from the chemistry found in NGC 253. The OCS/SO ratio measured toward these sources is 2 orders of magnitude smaller than that in NGC 253, while CS/H$_2$S is 3 orders of magnitude lower. The large abundance of H$_2$S, as well as the low abundance of molecules such as CS, OCS, and H$_2$CS in local molecular outflows, is not observed in NGC 253.

As far as the hot cores are concerned, the molecular abundances vary significantly between Galactic sources. Different evolutionary states may account for these observed differences. As seen in Table 3, the abundance ratios in the Orion hot core mostly disagree with those in NGC 253. The relative abundances of most of the species toward SGR B2 (N) are similar to what we find in NGC 253, except for the underabundance of H$_2$S and OCS with respect to the other molecules. The ratio OCS/SO is almost 2 orders of magnitude lower in both hot cores than in NGC 253. In addition, the low rotational temperatures ($T_{\text{rot}} < 25$ K) derived for all the sulfur-bearing species in NGC 253 suggest that the observed emission cannot be due to hot cores, where much higher rotational temperatures are expected ($T_{\text{kin}} > 70$ K).

Martin et al. (2003) pointed out that the molecular abundances of SO$_2$, NO, and NS are similar to those found in the envelope of the SGR B2 molecular complex. Table 3 also includes a comparison with two different clouds in the envelope of SGR B2. The first position, labeled SGR B2 (OH), is located 30" south of SGR B2 M, and the second one, 100" northeast of SGR B2 M. SO$_2$, SO, and H$_2$CS abundances in the Galactic center clouds agree well with those observed toward NGC 253. OCS/SO abundance ratios of 5 and 9 are similar to the ratio of $\sim$4 found in NGC 253.

Our study of the sulfur chemistry toward the nuclear region of NGC 253 seems to indicate a chemistry similar to that of the envelope of SGR B2, where low-velocity shocks are thought to be the main heating mechanism of the molecular material (Flower et al. 1995; Martin-Pintado et al. 1997, 2001). The low rotational temperatures derived for NGC 253 are also in agreement with those derived by Cummins et al. (1986) in the SGR B2 envelope. These results support the idea of large-scale low-velocity shocks driving the chemistry of the inner molecular material in the nucleus of NGC 253, which is consistent with the high rotational temperatures derived from NH$_3$ and the large observed SiO abundances (Garcia-Burillo et al. 2000; Mauersberger et al. 2003).

4.2. Chemical Models

In order to get an insight into the dominant chemistry around the central region of NGC 253, we compare our results with those available from chemical models (Millar et al. 1997; Charnley 1997; Hatchell et al. 1998; Buckle & Fuller 2003). For this we assume that the whole nuclear region of NGC 253 can be described as a single molecular cloud. This is not likely, as we are observing a 200 pc region in which a number of unresolved molecular complexes with different physical and chemical properties coexist. Nevertheless, the dominant observed chemistry in the nuclear region of NGC 253 could be characterized by a single giant cloud, as observed for the envelope of SGR B2, which has a size of $\sim$30 pc. The SiO mapping of the Galactic center region shows molecular cloud complexes extended over even larger scales (Martin-Pintado et al. 1997).

We have compared the observed molecular abundances in NGC 253 with the time-dependent models used by Hatchell et al. (1998) and Buckle & Fuller (2003) to describe the chemistry of hot cores and low-mass protostars, respectively. These models assume the release of H$_2$S from grain mantles as the main precursor of the sulfur chemistry. Models with $T_{\text{kin}} \leq 50$ K and $n(H_2) < 10^5$ cm$^{-3}$ seem to best reproduce the abundances measured for SO$_2$, SO, H$_2$S, and H$_2$CS shown in Table 3. This result is in agreement with the idea that the emission from the nuclear region of NGC 253 is dominated by a low excitation temperature and moderately dense molecular clouds similar to those found in the Galactic center clouds.

However, current chemical models fall short of accounting for the observed abundances of OCS by more than 1 order of magnitude. It has been pointed out by Hatchell et al. (1998) and van der Tak et al. (2003) that OCS may play an important role in the chemistry of sulfur-bearing molecules. Near-IR observations of massive protostars (Geballe et al. 1985; Tielens 1989; Palumbo et al. 1995) show that sulfur may freeze out onto grains not only in the form of H$_2$S but also in the form of OCS. In fact, OCS is the only sulfur-bearing molecule detected so far in icy grain mantles. This would imply that OCS is also sputtered from grains by shocks. Hatchell et al. (1998) revised the chemical model by including an initial large abundance of OCS as well as reducing that of H$_2$S, assuming that these species are initially injected into the gas phase. These models, depending on the initially injected H$_2$S and OCS (Wakelam et al. 2004), may account for the high OCS abundance observed in the nuclear region of NGC 253.

4.3. Sulfur Isotopic Ratios

The $^{32}$S/$^{34}$S abundance ratios of 8 $\pm$ 2 and 13.5 $\pm$ 2.5 observed toward the nuclear starburst environment of NGC 253 ($\S$3) and NGC 4945 (Wang et al. 2004), respectively, are similar to those found within the Galactic inner 3 kpc region but considerably lower than the value of $\sim$24 measured in the Galactic disk (Chin et al. 1996). The estimated lower limit of the $^{34}$S/$^{32}$S ratio toward NGC 253 is higher than the abundance of $\sim$6 measured toward most of the Galactic sources studied by Chin et al. (1996).

Massive stars, as well as Type Ib/c and II supernovae, appear to slightly overproduce $^{34}$S and underproduce $^{32}$S compared to $^{32}$S (see Chin et al. 1996 and references therein). Thus, the compact stellar clusters observed near the center of NGC 253 (Watson et al. 1996) and the estimated overall star formation rate of 3.6 $M_\odot$ yr$^{-1}$ (Strickland et al. 2004) and supernova rate of 0.05–0.3 yr$^{-1}$ (Mattila & Meikle 2001; Ulvestad
& Antonucci 1997) might account for the low $^{32}\text{S}/^{34}\text{S}$ as well as the enhanced $^{34}\text{S}/^{35}\text{S}$ ratios in NGC 253. This fact is supported by the high massive star formation rate of $\sim 0.1 \, M_{\odot} \text{yr}^{-1}$ estimated by Forbes et al. (1993) for the inner 6 of this starburst.

The uncertainties are large enough that the $^{32}\text{S}/^{34}\text{S}$ ratio observed toward NGC 253 may not significantly differ from that in NGC 4945, where slightly higher star formation and supernova rates (Strickland et al. 2004) might also have induced an overproduction of $^{34}\text{S}$ in its nuclear region.

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