Sulphur-bearing species in the star forming region L1689N

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Abstract. We report observations of the expected main S-bearing species (SO, SO₂ and H₂S) in the low-mass star forming region L1689N. We obtained large scale (∼ 300″x200″) maps of several transitions from these molecules with the goal to study the sulphur chemistry, i.e. how the relative abundances change in the different physical conditions found in L1689N. We identified eight interesting regions, where we carried out a quantitative comparative study: the molecular cloud (as reference position), five shocked regions caused by the interaction of the molecular outflows with the cloud, and the two protostars IRAS16293-2422 and 16293E. In the cloud we carefully computed the gas temperature and density by means of a non-LTE LGV code, while in other regions we used previous results. We hence derived the column density of SO, SO₂ and H₂S, together with SiO and H₂CO - which were observed previously - and their relevant abundance ratios. We find that SiO is the molecule that shows the largest abundance variations in the shocked regions, whereas S-bearing molecules show more moderate variations. Remarkably, the region of the brightest SiO emission in L1689N is undetected in SO₂, H₂S and H₂CO and only marginally detected in SO. In the other weaker SiO shocks, SO₂ is enhanced with respect to SO. We propose a schema in which the different molecular ratios correspond to different ages of the shocks. Finally, we find that SO, SO₂ and H₂S have significant abundance jumps in the inner hot core of IRAS16293-2422 and discuss the implications of the measured abundances.

Key words. ISM: abundances – ISM: molecules – Stars: formation – ISM: individual: L1689N, IRAS16293-2422

1. Introduction

Low mass star forming regions are composed by at least three main ingredients: the molecular cloud from which protostars are born, the protostars themselves, and the shocked regions at the interface between the cloud and the outflows emanating from the protostars. These three regions have very different physical conditions, where temperature, density and also chemical abundances greatly differ (e.g. van Dishoeck & Blake 1998). This paper focuses on the abundance changes occurring to the S-bearing molecules and the relevant sulfur chemistry. Depending on the physical condition of the gas, it is believed that different types of reactions play a role in the formation of sulphur-bearing molecules. In molecular clouds, ion-molecule reactions are the most important (Oppenheimer & Dalgarno 1974; Prasad & Huntress 1982; Millar & Herbst 1990), whereas in the warm gas of the hot cores and shocks, neutral-neutral reactions play the major role in forming sulphur species (Pineau Des Forêts et al. 1993; Charnley 1997). And because of the relatively fast evolution of their chemistry, on time scale of tens of thousand years, they are good candidates to be chemical clocks to study the evolution of outflows (Bachiller et al. 2001) and hot cores (Charnley 1997; Hatchell et al. 1998). Overall, it is widely accepted that in star forming regions the formation of S-bearing molecules is largely determined during the cold collapse phase, when atomic sulphur freezes out on grains and probably forms H₂S. When the protostar starts to heat its environment, H₂S evaporates and it reacts with hydrogen atoms to give sulphur atoms. S rapidly reacts with OH and O₂ to form SO, that in turn gives SO₂ by reacting with OH (e.g. Charnley 1997).

In this paper, we present large scale maps of several transitions of SO, SO₂ and H₂S in the molecular cloud L1689N, a molecular cloud located in the ρ Ophiuchi cloud complex at 120 pc from the Sun (Knude & Hog...
Based on atomic oxygen observations, Caux et al. (1999) found that the gas temperature in this cloud is $(26 \pm 0.5)$ K and the H$_2$ density is larger than $3 \times 10^4$ cm$^{-3}$. L1689N harbors two young protostellar sources. The first one is IRAS16293-2422 (hereinafter IRAS16293), a Class 0 protostar ($15 L_\odot$) still in the accretion phase (Walker et al. 1986; Zhou 1995; Narayanan et al. 1998; Ceccarelli et al. 2000a). Like many other young protostars, IRAS16293 is a binary system with a total mass around 1.1 M$_\odot$ (Looney et al. 2000), whose two sources are separated by 5″, namely a projected separation of 600 AU. The structure of the envelope surrounding IRAS16293 has been reconstructed based on multifrequency H$_2$O, SiO, O and H$_2$CO line observations (Ceccarelli et al. 2000a). In the outer region ($r \geq 150$AU), the envelope gas shows molecular abundances typical of cold molecular clouds. In the inner region ($r \leq 150$AU, i.e. about 2″ in diameter) the abundances of H$_2$O, SiO and H$_2$CO jump to abundances typical of the hot cores around massive protostars. This structure has been recently confirmed by Schöier et al. (2002), who modeled the continuum and the line emission from several other molecules. The second protostar, 16293E, is a recently discovered low mass and very young Class 0 source situated South-East of IRAS16293. It was detected first by Mizuno et al. (1999) as a strong NH$_3$ peak emission. Its protostellar nature is discussed in Castets et al. (2001) hereinafter CCLCL01).

The L1689N region is complex and has long been known to house multiple outflows (Fukui et al. 1983; Wootten & Loren 1987; Mizuno et al. 1990; Hirano et al. 2001). The recent work by CCLCL01 claims that the two protostars IRAS16293 and 16293E drive three bipolar outflows. Two of them originate from each of the two components of IRAS16293, while the third outflow probably emanates from 16293E (Fig. 1). In the present article we will adopt the scheme outlined in CCLCL01 (Fig. 1), but our main conclusions are substantially unaffected by the actual evolutionary stage (pre-stellar or protostellar) of 16293E, questioned in Lis et al. (2002). What is important in the following discussion is the presence in L1689N of at least one protostar, IRAS16293, and six regions which shows an enhancement of SiO and/or H$_2$CO emission, and that are sites of shocked gas marked as E1, E2, HE1\textsuperscript{1}, HE2, W1 and W2 (Fig. 1). In particular, CCLCL01 found that the brightest site of SiO emission, E2, does not show up any H$_2$CO enhanced emission, whereas the brightest H$_2$CO emission site, E1, is also accompanied by strong SiO emission. HE2 and HE1 represent a third class, for only H$_2$CO emission is detected there and no SiO. The goal of the present work is to study how the abundances of S-bearing molecules change in all these sites, compared with the abundances in the IRAS16293 protostar and in the cloud.

The article is organized as follows. The observations are presented in Sect. 2, the results are presented in Sect. 3, and the column density determinations are detailed in Sect. 4. In Sect. 5 we discuss the results, i.e. the observed changes of SO, SO$_2$ and H$_2$S abundances with respect to the previously measured SiO and H$_2$CO abundances and what this may teach us.

### 2. Observations

Observations of large scale maps and specific positions inside the L1689N region were performed with the IRAM and SEST telescopes. We measured the emission of the following molecules: SO ($3_2 \rightarrow 2_1$ and $6_5 \rightarrow 5_4$ transitions), SO$_2$ ($5_1 \rightarrow 4_0$ transition) and H$_2$S ($2_2 \rightarrow 2_{1,1}$ and $1_1 \rightarrow 1_{0,1}$ transitions). We also observed the $^{34}$SO $3_2 \rightarrow 2_1$ line in a few positions in order to estimate the opacity of the main isotopic line. The coordinates $(\Delta \alpha, \Delta \delta)$ of all maps shown here are offsets relative to the position of the 16293B component of the binary system IRAS16293 at $\alpha(2000.0) = 16^{h}32^{m}22^{s}.6$, $\delta(2000.0) = -24^{\circ}28'33''$ (the 16293A component is located 4″ South and 2″ East from the B component - Looney et al. 2000).

In June 1997 we obtained a map covering 120″ × 100″ in the SO$_2$ molecular line with the IRAM-30m telescope. In November 2001, May and September 2002 we performed additional IRAM observations of the SO$_2$, $^{34}$SO and H$_2$S $1_{1,0} \rightarrow 1_{0,1}$ lines at some specific positions in L1689N, namely the shocked regions E1, E2, W1, W2 and HE2 (see Fig. 1 and the Introduction), the two protostars IRAS16293 and 16293E, and the molecular cloud (at the position $\Delta \alpha = 120^\circ$, $\Delta \delta = 0^\circ$). In the following we will refer to these eight positions as the “key” positions. The SEST telescope was used in July 1998 to map an area covering 300″ × 200″ in the SO molecular lines and to map a smaller area covering 120″ × 100″ in the H$_2$S molecular transition. Table I summarizes the different observed molecular transitions, together with their frequencies and upper level energies.

All data were obtained in the position switching mode with an OFF position located at $\Delta \alpha = -180^\circ$, $\Delta \delta = 0''$ from the center of IRAS16293. Using the frequency switching mode we checked that this position is free of any C$^{18}$O
and $^{13}$CO emission. Even though our observations are not Nyquist sampled, we smoothed our data to the largest beamsize when necessary, which is accurate enough, except in the case of pathological source morphologies. Both with the IRAM and SEST telescopes, pointing and focus was checked every 2 hours, using planets, maser sources and strong extragalactic continuum sources. The pointing corrections were found to be always smaller than 3" and 5" with the IRAM and SEST telescopes respectively. Polynomial baselines of order 3 or less have been subtracted from the spectra. The observing parameters for both telescopes are listed in Table 1. In the following, all intensities will be given in main-beam brightness temperatures. Below we give some information which are specific to the IRAM-30m and SEST observations.

**IRAM Observations:** The IRAM 30-meter telescope is located at an altitude of 2920 meters near the summit of Pico Veleta in Southern Spain. The $^{34}$SO $^2\text{S} \rightarrow ^1\text{S}$, SO$_2$ and H$_2$S molecular emissions were observed simultaneously with the 3, 2 and 1mm SIS receivers respectively, available at the IRAM-30m. The SO$_2$ emission observed in June 1997 was observed simultaneously with other molecular transitions not presented here. The image sideband rejections of all receivers were always higher than 10 dB. Typical system temperatures were in the range $T_{\text{sys}} \sim 300 \text{ – } 600 \text{ K}$. The three receivers were connected to units of the autocorrelator, set to provide spectral resolutions of 40, 40, and 80 kHz at 98, 136, and 217 GHz respectively. At those frequencies, the velocity resolutions are of the order of 0.1 – 0.2 km s$^{-1}$.

**SEST Observations:** The SEST telescope is a 15-meter single dish millimeter telescope operated jointly by ESO and a consortium of Swedish institutions. It is located at an altitude of about 2450 meters in La Silla (Chile). To obtain the SO and H$_2$S molecular emissions were observed simultaneously with the 3, 2 and 1mm SIS receivers respectively, available at the IRAM-30m. The SO$_2$ emission observed in June 1997 was observed simultaneously with other molecular transitions not presented here. The image sideband rejections of all receivers were always higher than 10 dB. Typical system temperatures were in the range $T_{\text{sys}} \sim 300 \text{ – } 500 \text{ K}$. This receiver was always connected to the high resolution acousto-optical spectrometer available at SEST, which provides 2048 channel of 43 kHz width giving a 86 kHz spectral resolution. At the frequencies considered here, that corresponds to a velocity resolution of 0.1 – 0.2 km s$^{-1}$, comparable to that of the IRAM data.

### 3. Results

Figure 2 shows the velocity-integrated intensity maps of the SO $^2\text{S} \rightarrow ^1\text{S}$, SO $^5\text{S} \rightarrow ^4\text{S}$ and SO$_2$ $^5\text{I}_{1,5} \rightarrow ^4\text{O}_{0,4}$ lines. The spectra (not smoothed) of the six transitions of Table 1 observed towards the “key” positions are displayed in Fig. 3 and the relevant line parameters are reported in Table 2. The SO $^2\text{S} \rightarrow ^1\text{S}$ lines. For example, the SO $^2\text{S} \rightarrow ^1\text{S}$ line in W1 which has an equivalent width of 2.5 km s$^{-1}$ (versus 1.3 km s$^{-1}$ in Table 2). On the contrary, the velocity-integrated intensity is the area integrated in the interval of velocities at the “zero-intensity” level. The velocity $v_{\text{LSR}}$ is the velocity at the peak or at the absorption dip for double-peaked profiles. They are roughly the same for each observed transition and position, with the exception of E2(HVC), whose emission is red-shifted by $\sim 6$ km s$^{-1}$.

The first remarkable result is that, against probably naive expectations, the shocked regions are not necessarily associated with evident enhancements of the emission of the observed SO, SO$_2$ and H$_2$S lines. For example, the E2 region, the brightest SiO 2-1 emission peak (see CCLCL01) is undetected in SO$_2$, and only marginally detected in the lowest SO transition.

The second result is that IRAS16293 is the only site where all the molecular lines have been detected, including the high-energy transition H$_2$S $^2\text{S}_2 \rightarrow ^2\text{S}_1$. Quite interestingly, we find that not only the line profiles are broader than in the cloud but their widths tend to increase with the upper energy level of the transition. We will discuss in the §5 the implication of this behavior.

We now discuss in more detail the results toward the eight “key” positions.

#### 3.1. SO emission

The SO $^2\text{S} \rightarrow ^1\text{S}$ emission is relatively bright (~ 3 K) all over the cloud (Figs. 2 and 3). All the line profiles are relatively narrow (with linewidths ranging between 1 and 2 km s$^{-1}$) and peak around the systemic cloud velocity at $v_{\text{LSR}} = 3.9$ km s$^{-1}$. The absorption dip around the systemic velocity seen towards IRAS16293 is probably due to the absorption by foreground material, as also seen in the H$_2$CO transitions (Loinard et al. 2001). On the other hand, the absorption dip seen in the $^{34}$SO towards W1 may point to a very large SO column density in that direction or two different kinematic components. The contrast of the velocity-integrated SO molecular emission at the various positions in the cloud is relatively low: the emission peaks towards IRAS16293 but otherwise it is widespread in the region between W1 and E2 (Fig. 2). Remarkably, there is not a much brighter SO $^2\text{S} \rightarrow ^1\text{S}$ emission towards the shocked regions with respect to the molecular cloud. The only two clear exceptions are represented by E1 and E2, where a high velocity component appears in the low energy SO transition (Fig. 3). In the following we will analyze separately the E2 low velocity component centered at 3.9 km s$^{-1}$ (hereinafter E2(LVC)), and the E2 high velocity component at 10 km s$^{-1}$ (hereinafter E2(HVC)), because the two components can be clearly disentangled. On the contrary, in E1 the situation is less clear and hence we didn’t pursue a separated analysis of
Fig. 2. Integrated intensity maps of SO $3_2 \rightarrow 2_1$(a), SO $6_5 \rightarrow 5_4$(b) and SO$_2$ $5_{1,5} \rightarrow 4_{0,4}$(c). (a) and (b) : first level is 0.5 K km s$^{-1}$ with level step of 1.0 K km s$^{-1}$. (c) : first level is 0.3 K km s$^{-1}$ with level step of 1.0 K km s$^{-1}$. In each map, the black points represent the observed positions. The two stars symbols show the position of the two protostellar sources. The arrows point to the eight “key” positions, whose spectra are displayed in Fig. 3.
the two components. We emphasize that the E2(HVC) component is detected at more than 3 RMS all along the red lobe of the outflow and it is also observed in the SiO transitions (CCLCL01). This high velocity component is not seen in SO 6\,→\,5\,1 probably because of unfavorable excitation conditions. Indeed, we will show in the next section that the gas density in E2(HVC) is lower than in the ambient gas (see Table 3). This fact, already recognized by CCLCL01, leads to the supposition that the E2(HVC) may represent the wind shock, whereas the lower velocity component, E2(LVC), may trace the so called cloud shock [Hollenbach 1993]. Finally, we also see hints of red and blue wings originating from the molecular outflows driven either by IRAS16293 or 16293E in the direction of W1, E1 and HE2 whereas no wing is seen in W2.

In the higher energy line SO 6\,→\,5\,4 the emission is peaked towards IRAS16293 and W1 (cf. Fig. 2) while the emission from the cloud is, as expected, weak. Relatively strong emission is also detected around E1. Moreover, the SO 6\,→\,5\,4 spectra in those positions have pronounced red and blue wings. The same happens in HE2 where the SO 6\,→\,5\,4 spectrum shows clearly the presence of a blue wing. The emitting region around IRAS16293 has a characteristic size of α\,×\,δ = 39\arcsec\,×\,16\arcsec namely it is not resolved in δ. Finally, the observed SO spectra towards 16293E are similar to those in the cloud: narrow, intense in the SO 3\,→\,2\,1 transition and weak in the SO 6\,→\,5\,4 transition, and no signs of wings are evident. Overall, 16293E does not seem to have any enhanced SO emission compared with the cloud.

3.2. SO2 and H2S emission

Unlike the SO 3\,→\,2\,1, the SO2 5\,1,5 \,→\,4\,0,4 emission is limited to a few spots (see Figs. 2 and 3), specifically toward IRAS16293, E1 and W2, probably because of the excitation conditions (the critical density of the SO2 5\,1,5 \,→\,4\,0,4 transition is about 20 times the SO 3\,→\,2\,1 critical density). Unfortunately, because of the lack of other observations around W2 we have no idea of its extent. Remarkably, no significant SO2 emission is detected towards E2. SO2 has also been detected at the cloud position. The linewidth (1.4 km s\(^{-1}\)) is equivalent to that of N2H\(^+\) 1 \,→\,0 – a good tracer of extended, cold and quiescent gas – observed at the same position (CCLCL01).

Probably because of similar critical densities, the SO2 5\,1,5 \,→\,4\,0,4 and SO 6\,→\,5\,4 emission shows up in the same regions. In addition, with the exception of E1, the SO2 5\,1,5 \,→\,4\,0,4 spectra show characteristics similar to the SO 6\,→\,5\,4 spectra, like for example the linewidth, in all “key” positions. On the contrary, in E1 the SO line profiles are characterized by a strong ambient component with blue- and redshifted wings of much lower brightness, whereas the high-velocity component appears as bright as the ambient component in the SO2 line, so that the whole SO2 5\,1,5 \,→\,4\,0,4 linewidth is approximately twice that of the SO 6\,→\,5\,4.

IRAS16293 is the only position where H2S 2\,2,0 \,→\,2\,1,1 has been detected. The line is relatively bright and rather broad (Δν = 5.0 km s\(^{-1}\)). There is no emission detected in shocks nor in the ambient cloud. Conversely, the lower H2S transition, observed only toward IRAS16293, 16293E and the cloud, has been detected in all these positions with a double-peaked profile towards the protostars and possibly the cloud position. The absorption dip is likely due to the optical depth of the line. In fact, [Minh et al. 1991] have observed the same H2S transition towards several star forming regions and found an opacity of ~10 for similar column densities.

3.3. Comparison with SiO

Contrary to the sulphur bearing species, the emission of SiO 2 \,→\,1 is stronger in the shocked regions than towards IRAS16293. The spectra in E1 and W1 show high velocity wings much more marked than for the SO and SO2 lines. The high velocity component of E2 seen in SO 3\,→\,2\,1 is very strong in SiO 2 \,→\,1 and have similar Δν (~6.5 km s\(^{-1}\)) and v\(_{LSR}\) (~10 km s\(^{-1}\)) for these two transitions.
|                  | SO          | SO          | ^3SO        | SO2         | H2S         | H2S         | SO         |
|------------------|-------------|-------------|-------------|-------------|-------------|-------------|------------|
|                  | 3_2 → 2_1  | 6_2 → 5_1  | 3_2 → 2_1  | 5_1,5 → 4_4 | 2_2,0 → 2_1 | 1_1,0 → 1_0 | 2 → 1      |
| IRAS 16293-2422  | T_{MB}      | Δv          | v_{LSR}     | T_{MB}δv    | T_{MB}δv    | T_{MB}δv    | T_{MB}δv   |
|                  | 2.9±0.1     | 3.7±0.1     | 2.8±0.5     | 4.2±0.2     | 0.5±0.0     | 6.2±0.6     | 0.35±0.05  |
|                  | 2.9±0.1     | 2.8±0.5     | 3.9±0.0     | 3.7±0.0     | 0.5±0.0     | 6.2±0.6     | 0.35±0.05  |
| 16293E           |            |             |             |             |            |             |            |
|                  | 3.4±0.1     | 1.2±0.2     | -           | -           | -           | -           | -          |
|                  | 3.4±0.1     | 1.2±0.2     | -           | -           | -           | -           | -          |
| E1               | T_{MB}      | Δv          | v_{LSR}     | T_{MB}δv    | T_{MB}δv    | T_{MB}δv    | T_{MB}δv   |
|                  | 2.9±0.1     | 2.4±0.2     | 0.5±0.1     | 0.7±0.1     | ≤ 0.2       | 1.1±0.1     | -          |
|                  | 1.8±0.2     | 1.6±0.3     | 1.2±0.3     | 3.1±0.1     | ≤ 0.2       | 1.1±0.1     | -          |
|                  | 4.0         | 3.8         | 3.7         | 4.0         | -           | 3.6         | -          |
|                  | 3.8±0.6     | 1.0±0.2     | -           | ≤ 0.1       | 0.6±0.1     | -           | -          |
| E2               | T_{MB}      | Δv          | v_{LSR}     | T_{MB}δv    | T_{MB}δv    | T_{MB}δv    | T_{MB}δv   |
|                  | 2.4±0.2     | 1.1±0.2     | 0.9±0.04    | ≤ 0.2       | ≤ 0.4       | 0.53±0.06   | -          |
|                  | 1.3±0.1     | 0.9±0.1     | 0.5±0.02    | -           | -           | 3.2±0.1     | -          |
|                  | 3.9         | 3.8         | 3.6         | -           | -           | 4.0         | -          |
|                  | 3.7±0.7     | 1.0±0.2     | 0.5±0.1     | ≤ 0.1       | ≤ 0.4       | 1.8±0.1     | -          |
| HVC              | T_{MB}      | Δv          | v_{LSR}     | T_{MB}δv    | T_{MB}δv    | T_{MB}δv    | T_{MB}δv   |
|                  | 0.5±0.15    | ≤ 0.6       | ≤ 0.1       | ≤ 0.2       | ≤ 0.4       | 0.83±0.06   | -          |
|                  | 6.6±0.6     | -           | -           | -           | -           | 6.3±0.2     | -          |
|                  | 10.4        | -           | -           | -           | -           | 11          | -          |
|                  | 3.6±0.7     | ≤ 0.5       | ≤ 0.2       | ≤ 0.3       | ≤ 0.8       | 5.6±0.2     | -          |
| W1               | T_{MB}      | Δv          | v_{LSR}     | T_{MB}δv    | T_{MB}δv    | T_{MB}δv    | T_{MB}δv   |
|                  | 2.6±0.1     | 3.3±0.2     | 0.2±0.4     | 0.3±0.1     | ≤ 0.2       | 0.3±0.1     | -          |
|                  | 1.8±0.2     | 1.3±0.03    | 2.2±0.2     | 1.9±0.3     | -           | 3.3±0.8     | -          |
|                  | 4.0         | 3.3         | 3.7         | 3.3         | -           | 4.6         | -          |
|                  | 5.8±1.0     | 9.0±1.5     | 0.5±0.1     | 0.7±0.2     | ≤ 0.4       | 1.1±0.2     | -          |
| W2               | T_{MB}      | Δv          | v_{LSR}     | T_{MB}δv    | T_{MB}δv    | T_{MB}δv    | T_{MB}δv   |
|                  | 2.4±0.2     | 1.6±0.2     | 0.3±0.04    | 0.7±0.1     | ≤ 0.2       | 0.5±0.1     | -          |
|                  | 1.4±0.1     | 1.6±0.1     | 1.1±0.1     | 1.2±0.1     | -           | 2.1±0.3     | -          |
|                  | 3.8         | 3.3         | 3.9         | 3.7         | -           | 3.5         | -          |
|                  | 3.8±0.7     | 2.7±0.5     | 0.3±0.1     | 0.9±0.2     | ≤ 0.3       | 1.2±0.1     | -          |
| HE2              | T_{MB}      | Δv          | v_{LSR}     | T_{MB}δv    | T_{MB}δv    | T_{MB}δv    | T_{MB}δv   |
|                  | 3.7±0.1     | 1.4±0.2     | 0.6±0.04    | 0.3±0.04    | ≤ 0.2       | -           | -          |
|                  | 0.9±0.1     | 0.9±0.1     | 0.9±0.1     | 1.8±0.02    | -           | -           | -          |
|                  | 3.7         | 3.5         | 3.5         | 3.6         | -           | -           | -          |
|                  | 5.3±0.8     | 2.7±0.5     | 0.6±0.1     | 0.6±0.1     | ≤ 0.3       | -           | -          |
| Cloud            | T_{MB}      | Δv          | v_{LSR}     | T_{MB}δv    | T_{MB}δv    | T_{MB}δv    | T_{MB}δv   |
|                  | 3.1±0.2     | 1.1±0.2     | 0.6±0.04    | 0.2±0.04    | ≤ 0.3       | 0.8±0.2     | -          |
|                  | 1.0±0.04    | 0.7±0.1     | 0.5±0.1     | 1.4±0.2     | -           | 1.1±0.4     | -          |
|                  | 3.8         | 3.8         | 3.8         | 3.9         | -           | 3.4         | -          |
|                  | 3.2±0.6     | 0.8±0.2     | 0.3±0.1     | 0.2±0.1     | ≤ 0.3       | 1.0±0.2     | -          |

Table 2. Line parameters (T_{MB} (K), Δv (km s^{-1}), v_{LSR}(km s^{-1}), ∫ T_{MB}δv(K km s^{-1})) for the various transitions observed at the “key” positions: the two protostars IRAS16293 and 16293E, the shocked regions E1, E2, W1, W2 and HE2, and the reference position in the cloud. The SO observations were previously published in CCLCL01. When no signal is detected, we give an upper limit for the intensity equal to 3 RMS of the relevant spectrum. The parameters are taken from the spectra not smoothed. The symbol “-” implies that the relevant transition has not been observed or detected.

4. Column densities

In this section we estimate the column densities of the observed species, namely SO, SO₂ and H₂S, as well of the SiO and H₂CO previously observed by CCLCL01, in the “key” positions. In order to do that, we first estimate the density and temperature of the gas in each position. To derive the gas temperature and density, as well as the column densities of the different species, we used the theoretical predictions from an LVG (Large Velocity Gradient) model described in detail in the next paragraph. The next three paragraphs describe the derivation of the gas temperature and densities as well as the column density of the observed species in the cloud, in the shocked regions, and in IRAS16293 respectively. Note that we did not carry out the analysis on 16293E, because the observed emission in that position seems to be dominated by the cloud emission.

4.1. LVG model description

To derive the gas temperature and density, as well as the column densities, we compared the observed line intensities with the theoretical predictions from a LVG model, which self-consistently accounts for the excitation conditions (density and temperature) as well as the line opacities. For the escape probability β we used the following function of the line optical depth: β = \frac{1 - \exp[-3\tau]}{3\tau}, valid
in the case of a homogeneous and isothermal semi-infinite slab. More details can be found in Ceccarelli et al. (2002). Note that the dust emission is neglected in the present computations.

The spectroscopic data of SO, SO$_2$, H$_2$S, SiO and H$_2$CO are all taken from the JPL catalogue (http://spec.jpl.nasa.gov/ftp/pub/catalog/catform.html; Pickett et al. 1998). The collisional coefficients are from Green (1994) for SO, Palma (1987) for SO$_2$, Turner et al. (1992) for SiO, and Green (1991) for H$_2$CO respectively. The collisional coefficients of H$_2$S are not available in literature, and we estimated them from the collisional coefficients of H$_2$O, multiplied by a factor 5 (following the discussion in Turner 1990). This is a very rough approximation, giving rise to unfortunately very rough estimates of the H$_2$S column density. Furthermore, the collisional coefficients used for the other molecules are not available in the full range of temperatures probed by our observations. In particular the low temperature regime is often missing. In this case we have extrapolated the coefficients at the lowest available temperature with a $\sqrt{T_{\text{kin}}}$ law. Finally, our code considers the first 50 rotational levels of each molecule, unless the relevant collisional coefficients are available for a lower number of levels.
Table 3. Gas temperature and density, and column densities of SO, SO$_2$, H$_2$S, SiO and H$_2$CO in six “key” positions. The column densities are beam-averaged in the shocked regions (on 27″ for SiO, 26″ for H$_2$CO, 24″ for SO, 18″ for SO$_2$ and 25″ for H$_2$S), whereas they are corrected from the beam dilution in IRAS16293. Errors on the estimates are around 15% if considering only the statistical uncertainties. However, a factor two of uncertainty has to be considered, when the uncertainty on the density and temperature of the emitting gas is considered.

| Cloud | Density (10$^5$cm$^{-3}$) | T (K) | N$_{SO}$ (10$^{13}$cm$^{-2}$) | N$_{SO_2}$ (10$^{13}$cm$^{-2}$) | N$_{H_2S}$ (10$^{13}$cm$^{-2}$) | N$_{SiO}$ (10$^{13}$cm$^{-2}$) | N$_{H_2CO}$ (10$^{13}$cm$^{-2}$) |
|-------|-----------------|-----|----------------|----------------|----------------|----------------|----------------|
| IRAS16293 | 250 | 100 | 13000 | 4100 | 4000 | 110 | 750 |
| E1     | 1.8  | 150 | 15  | 7.3  | ≤ 96 | 0.42 | 7.0  |
| E2(LVC) | 1.0 | 150 | 3.2  | ≤ 0.44 | ≤ 260 | 0.21 | ≤ 0.86 |
| E2(HVC) | 0.4 | 100 | 7.8  | ≤ 1.1 | ≤ 1200 | 1.0 | ≤ 1.8 |
| W1     | 2.6  | 150 | 24  | 2.4  | ≤ 72 | 0.15 | 3.4  |
| W2     | 1.8  | 80  | 8.7  | 2.9  | ≤ 76 | 0.15 | 3.6  |
| Cloud  | 0.3 | 26  | 30 - 80 | 2 | 1.5 | 0.02 | 2 |

4.2. Cloud

To estimate the gas density and temperature, and the SO column density in the cloud reference position we simultaneously best-fitted the $^{34}$SO and $^{32}$SO 3$\nu_2$ → 2$\nu_1$ observations (that give a line opacity for $^{32}$SO $\tau \sim 1.5$), and the $^{32}$SO 3$\nu_2$ → 2$\nu_1$ and 6$\nu_5$ → 5$\nu_4$ observations (whose ratio, together with the $^{32}$SO 3$\nu_2$ → 2$\nu_1$ intensity, gives pairs of gas temperature and density values). Note that we used the elemental ratio $^{34}$S/$^{32}$S = 22.5 (Wilson & Rood 1994; Chin et al. 1996; Lucas & Liszt 1998), and we assumed that the emission fills up the beam, when comparing observations obtained with different telescopes. The result of the modeling is shown in Fig. 4. We found that the ensemble of our observations constrains the SO column density in the cloud to be in the range 3 to 8 × 10$^{14}$ cm$^{-2}$. Adopting the gas temperature of 26 K, as found by Caux et al. (1994), we derive a density of $3 \times 10^4$ cm$^{-3}$.

The column densities of the other species, namely SO$_2$ and H$_2$S, have been derived assuming the same density and temperature. The SO$_2$ abundance was found to be $4 \times 10^{-9}$, a value equivalent to the ones obtained in other surveys. For this we assumed an excitation temperature of 5 K, as found by Swade (1989) and Hirahara et al. (1995) in similar molecular clouds (L134N and TMC-1) for several molecules whose fundamental transitions have A-coefficients similar to that for the H$_2$S 1$\nu_1$ → 0$\nu_1$ transition. In fact Minh et al. (1989) used an excitation temperature of 5 K for the H$_2$S 1$\nu_1$ → 0$\nu_1$ transition to compute the column density of H$_2$S in the molecular clouds L134N and TMC-1, which have temperatures and densities similar to L1689N. Note that increasing the excitation temperature by a factor two would decrease the H$_2$S column density by the same amount. We assumed a H$_2$S ortho-para ratio equal to 3. Finally the SiO and H$_2$CO column densities are taken from the modeling by Ceccarelli et al. (2000a) and Ceccarelli et al. (2001) respectively.

Although no SiO emission was detected towards the cloud position, Ceccarelli et al. (2000a) modeled the observed SiO

Fig. 4. Cloud reference position modeling. Theoretical predictions as function of the gas temperature and density for two different SO column densities. The curves refer the values of three observed quantities taking into account the uncertainties. Solid lines: observed integrated intensity ratio SO 3$\nu_2$ → 2$\nu_1$ over SO 6$\nu_5$ → 5$\nu_4$, between 3.2 and 5.2. Dashed lines: escape probability, derived from the $^{34}$SO and $^{32}$SO 3$\nu_2$ → 2$\nu_1$ line ratio, between 0.1 and 0.3. Dot-dashed line: the minimum integrated intensity of the SO 3$\nu_2$ → 2$\nu_1$ transition, 2.6 K km s$^{-1}$. Note that the intensity increases with increasing temperature, i.e. towards the upper part of the panel. Analogously, the lower limit of the escape probability (0.1) in the left panel is not shown because it lies outside the plot.

(from J$_{up}$ = 1 to 8) emission towards IRAS16293, taking into account the envelope physical structure, and found that the SiO abundance is $4.0 \times 10^{-12}$ in the outer envelope. In analogy with other molecules for which the abundances found in the outer envelope are equal to the (measured) abundances in the surrounding molecular clouds, we assumed $4.0 \times 10^{-12}$ for the SiO abundance in L1689N. In a similar way, although weak formaldehyde emission is detected at the cloud position, we used the abundance found in the IRAS16293 outer envelope for the cloud too.
example, Lis et al. (2002), using H2S. In practice, though, the error associated with the assumption. In principle each molecular species may originate in slightly different physical conditions and hence not take into account the possible structure of the shocked gas, but the results are indeed not much affected by this approximation that does not consider the possible structure of the shocked gas.

| Cloud  | x(SO) | x(SO2) | x(H2S) | x(SIO) | x(H2CO) |
|--------|-------|--------|--------|--------|---------|
| L1689N| 6 - 16 | 0.4    | 0.3    | 4      | 0.04    |
| L134N | 0.6 - 10 | 0.3 - 2.5 | 3      | ≤ 3.6  | 2       |
| TMC-1 | 0.3 - 4 | 2 - 6  | 0.7    | ≤ 2.4  | 7       |

Table 4. Abundances in molecular clouds. References: L1689N: SO, SO2 and H2S from this work, SiO from Ceccarelli et al. (2000b) and H2CO from Ceccarelli et al. (2001); L134N: SO and SO2 abundances from Swaddle (1989), H2S from Minh et al. (1989), SiO from Ziurys et al. (1989), H2CO from Ohishi et al. (1992); TMC-1: SO abundances from Hirahara et al. (1995) and Pratap et al. (1997), SO2 from Irvine et al. (1983), H2S from Minh et al. (1989), SiO from Ziurys et al. (1989), H2CO from Ohishi & Kaifu (1998).

column densities derived for all species are reported in Table 3 and the abundances in Table 4.

4.3. Shocked regions

We have used the gas temperature and density derived by CCLIClO1 in E1, E2(LVC), E2(HVC), W1, W2, i.e. in the shocked regions, by comparing the SiO observed lines (J from 2 to 5) with the relevant LVG model. The uncertainty in the derived densities and temperatures is around a factor two. We did not try to derive independently the gas temperature and density for each molecule, because of the lack of enough usable transitions. In fact, of the two SO transitions, the lowest lying transition is dominated by the cloud emission so it cannot be used to probe the shocked gas, and only one transition of SO2, H2S and H2CO respectively has been detected. We therefore derived the column densities of those last four species assuming the same density and temperature derived from the SiO observations. This is an approximation that does not take into account the possible structure of the shocked gas, but the results are indeed not much affected by this assumption. In principle each molecular species may originate in slightly different physical conditions and hence the computed column density may be consequently misinterpreted. In practice, though, the error associated with this approximation is lower than about a factor two. For example, Lis et al. (2002), using H2CO transitions, found different values for the temperature (45 K) and density (2 × 10^6 cm^-3) in E1. Even taking those values, the derived column density of the four molecules listed in Table 3 wouldn’t change by more than a factor two with respect to those quoted in the table. Finally, we also assumed that all the used lines are optically thin (e.g. Blake et al. 1994). The column densities, averaged on the relevant beam, derived for all species in each of the four shocked sites are reported in Table 3. Unfortunately, since we don’t have observations of the H2S lowest transitions in the shocks, the column density of this molecule is very poorly constrained.

4.4. IRAS16293

As mentioned in the Introduction, the envelope of IRAS16293 is formed by (at least) two components: an inner core characterized by a high temperature and an outer cold envelope with a temperature close to the cloud temperature. The hot core is a small region (∼ 2″ in diameter) whose temperature is about 100 K and the density 2.5 × 10^5 cm^-3 (Ceccarelli et al. 2000a; Schöier et al. 2002). At that temperature the grain mantles evaporate injecting into the gas phase their constituents (Ceccarelli et al. 2000a). The outer envelope is more extended (∼ 20″) and colder, with a temperature of 30 K (a little larger than the L1689N temperature) and a density of 2.5 × 10^3 cm^-3 (Ceccarelli et al. 2000a; Schöier et al. 2002). The molecular abundances in the outer envelope are similar to those in the molecular cloud, with the possible exception of the deuterated molecules. On the contrary, in the inner core, several molecules, those believed to be released from the grain mantles or formed from those evaporated molecules, undergo a jump in their abundances. In the following we focus on the abundance of the S-bearing molecules in the inner hot core. Since the temperature of the emitting gas is not known, we have used multifrequency observations, constructed the rotational diagrams of SO and SO2 and derived rotational temperatures relatively large (∼ 80 K). It is therefore very likely that the bulk of the emission for both molecules originates in the inner core. Furthermore, all linewidths are larger than 3 km s^-1 and increase with the upper level energy of the transition, once again arguing for an inner core origin. Pursuing this hypothesis we computed the column densities using these rotational diagrams, corrected for the beam dilution, reported in Table 4. In estimating the H2S column density we assumed that the 2_20 → 2_11 line emission originates entirely in the hot core, as it is suggested by its observed relatively large linewidth. Using then the estimates of the H2 column density in Ceccarelli et al. (2000a) (7.5 × 10^22 cm^-2) we derive the abundances reported in Table 3. Note that, provided that we use our volume density in the Schöier et al. (2002) model, our derived abundance compare extremely well with their abundances (which, as a result, is multiplied by a factor five), supporting the validity of our method. Actually Schöier et al. found abundances a factor 5 lower than ours, because they used a factor five larger density than us in the inner core. The two density estimates differ because of the different diagnostics used to derive them: Schöier et al. used the continuum spectral energy distribution, whereas Ceccarelli et al. used the water line spectrum. When CO lines are used instead, Schöier et al. found the same density in the inner region (Schöier private communication). We use therefore the estimate by Ceccarelli et al. (2000a), but keep in mind that we may be overestimating the abundances by a factor 5. Finally,
lies on the capacity to disentangle the contribution of the column densities into H\textsubscript{2}CO millimeter observations converting the measured CO usually the H\textsubscript{2}.

In the shocked regions, with the exception of E2, it is remarkable that the SO/H\textsubscript{2} abundance is lowest in the strongest SiO shock of the region, E2. Remarkably, SO is enhanced with respect to SO\textsubscript{2} in the shocked gas, because of the difficulty to disentangle the contribution of the cloud from the shocked gas in the CO emission. However, this is feasible when the shocked gas emits at relatively large velocities, i.e. when the two contributions can be separated based on their spectral properties (see for example Bachiller & Perez Gutierrez 1997). In the specific case of the outflows in L1689N, the projected velocity of the shocks is too small and the cloud and shocked gas cannot be disentangled, except in the E2 position, where a high velocity component is present. In order therefore to estimate the H\textsubscript{2} column density in the shocked regions we would need high spatial resolution observations, because single dish CO measurement are totally dominated by the cloud emission. For this practical reason, we computed only abundances ratios, as summarized in Table 5. Note that the quoted ratios have been obtained dividing column densities averaged on different beam sizes (18\arcsec for SO\textsubscript{2} observations and \sim 25\arcsec for the others), so that the SO\textsubscript{2} ratios may be off by a factor two (in the shocked regions). Fig. 5 shows a graphic representation of the derived abundances ratios in the shocked regions and in the cloud.

The first result to note is that, with the exception of the SO\textsubscript{2}/H\textsubscript{2}CO ratio, all other ratios in the shocked regions differ by more than a factor two when compared to the ratios in the cloud. In particular, the largest variations, by up a factor 100, are shown by the ratios with the SiO, confirming that SiO is the best molecule to trace shocks (Caselli et al. 1997; Schilke et al. 1997; Garay et al. 2002).

A second robust result is that SO\textsubscript{2} is enhanced with respect to SO in the E1, W1 and W2 shocks, when compared to the cloud (by up a factor 10). This also confirms a rather general theoretical prediction that SO\textsubscript{2} is over-produced with respect to SO in the shocked gas, because of endothermic reactions that lock most of the gaseous sulphur in SO\textsubscript{2} on timescales relatively small \sim 10\textsuperscript{3} yr (e.g. Pineau Des Forêts et al. 1993). Remarkably, SO\textsubscript{2}/SO is lowest in the strongest SiO shock of the region, E2.

### Table 5. Abundances of SO, SO\textsubscript{2}, H\textsubscript{2}S, SiO and H\textsubscript{2}CO with respect to H\textsubscript{2} in the hot core of IRAS16293.

| Region       | SO/H\textsubscript{2} | SO\textsubscript{2}/H\textsubscript{2} | H\textsubscript{2}S/H\textsubscript{2} | SiO/H\textsubscript{2} | H\textsubscript{2}CO/H\textsubscript{2} |
|--------------|------------------------|--------------------------------------|--------------------------------------|------------------------|----------------------------------------|
| IRAS16293    | 1.7 x 10\textsuperscript{-6} | 5.4 x 10\textsuperscript{-7} | 5.3 x 10\textsuperscript{-7} | 1.5 x 10\textsuperscript{-8} | 1.0 x 10\textsuperscript{-8} |
| L1157-mm     | 5.0 x 10\textsuperscript{-9} | 3.0 x 10\textsuperscript{-8} | 1.1 x 10\textsuperscript{-8} | - | 4 - 6 x 10\textsuperscript{-9} |
| Orion-KL     | 1.5 x 10\textsuperscript{-7} | 9.4 x 10\textsuperscript{-8} | 5.0 x 10\textsuperscript{-6} | 6.0 x 10\textsuperscript{-9} | 7.0 x 10\textsuperscript{-9} |
| G10.47       | 3.0 x 10\textsuperscript{-9} | 1.8 x 10\textsuperscript{-8} | 4.0 x 10\textsuperscript{-9} | - | - |
| G29.96       | \geq 5.0 x 10\textsuperscript{-9} | 2.0 x 10\textsuperscript{-8} | 1.5 x 10\textsuperscript{-9} | - | - |
| G75.78       | 3.0 x 10\textsuperscript{-9} | 2.0 x 10\textsuperscript{-9} | 1.0 x 10\textsuperscript{-9} | - | - |
| G9.62        | \geq 4.0 x 10\textsuperscript{-9} | 1.0 x 10\textsuperscript{-8} | 8.0 x 10\textsuperscript{-9} | - | - |
| G12.21       | \geq 8.0 x 10\textsuperscript{-10} | 5.0 x 10\textsuperscript{-10} | - | - | - |
| G31.41       | 4.0 x 10\textsuperscript{-9} | 1.2 x 10\textsuperscript{-8} | 3.0 x 10\textsuperscript{-9} | - | - |
| G34.26       | 6.0 x 10\textsuperscript{-9} | 1.5 x 10\textsuperscript{-8} | 2.0 x 10\textsuperscript{-9} | - | - |
| BF-Class 0   | 3.0 x 10\textsuperscript{-9} | 4.0 x 10\textsuperscript{-10} | 2.0 x 10\textsuperscript{-9} | - | - |

5. Discussion

The abundance ratios between the observed species are reported in Table 5. They show variations up to two orders of magnitude. In the following we analyze in detail the variations associated with the cloud, the shocked regions and the protostar IRAS16293 respectively.

5.1. The cloud

Adopting the H\textsubscript{2} column density derived by Ceccarelli et al. (2000) by means of atomic oxygen observations in L1689N, 5 x 10\textsuperscript{22} cm\textsuperscript{-2}, and using the column densities derived in the previous section (Tab. 4) we obtain the abundances reported in Tab. 5. In the table we also report, for comparison, the abundances measured in L134N and TMC-1, two among the best studied molecular clouds. With the possible exception of formaldehyde, which seems to be underabundant, L1689N has abundances typical of other cold molecular clouds and it is therefore interesting to study how those abundances change in the region either because of the presence of shocks or the presence of a protostar (IRAS16293).

5.2. Shocked regions

In the shocked regions, with the exception of E2, it is practically impossible to derive the absolute abundances of the observed molecules, because of the difficulty to derive reliable estimates of the H\textsubscript{2} column densities. In fact, usually the H\textsubscript{2} column densities are estimated from the CO millimeter observations converting the measured CO column densities into H\textsubscript{2} column densities. The method relies on the capacity to disentangle the contribution of the cloud from the shocked gas in the CO emission. However, this is feasible when the shocked gas emits at relatively large velocities, i.e. when the two contributions can be separated based on their spectral properties (see for example Bachiller & Perez Gutierrez 1997). In the specific case of the outflows in L1689N, the projected velocity of the shocks is too small and the cloud and shocked gas cannot be disentangled, except in the E2 position, where a high velocity component is present. In order therefore to estimate the H\textsubscript{2} column density in the shocked regions we would need high spatial resolution observations, because single dish CO measurement are totally dominated by the cloud emission. For this practical reason, we computed only abundances ratios, as summarized in Table 5. Note that the quoted ratios have been obtained dividing column densities averaged on different beam sizes (18\arcsec for SO\textsubscript{2} observations and \sim 25\arcsec for the others), so that the SO\textsubscript{2} ratios may be off by a factor two (in the shocked regions). Fig. 5 shows a graphic representation of the derived abundances ratios in the shocked regions and in the cloud.

The first result to note is that, with the exception of the SO\textsubscript{2}/H\textsubscript{2}CO ratio, all other ratios in the shocked regions differ by more than a factor two when compared to the ratios in the cloud. In particular, the largest variations, by up a factor 100, are shown by the ratios with the SiO, confirming that SiO is the best molecule to trace shocks (Caselli et al. 1997; Schilke et al. 1997; Garay et al. 2002).

A second robust result is that SO\textsubscript{2} is enhanced with respect to SO in the E1, W1 and W2 shocks, when compared to the cloud (by up a factor 10). This also confirms a rather general theoretical prediction that SO\textsubscript{2} is over-produced with respect to SO in the shocked gas, because of endothermic reactions that lock most of the gaseous sulphur in SO\textsubscript{2} on timescales relatively small \sim 10\textsuperscript{3} yr (e.g. Pineau Des Forêts et al. 1993). Remarkably, SO\textsubscript{2}/SO is lowest in the strongest SiO shock of the region, E2.
Table 6. Abundance ratios in the shocked regions and in the cloud, as derived from the column densities of Tab. 3. References for other outflows: L1157-B1 and L1157-B2: Bachiller & Perez Gutierrez (1997); CB3: Codella & Bachiller (1999); L1448, B1 and CepA: Martin-Pintado et al. (1992); NGC 2071: Chernin & Masson (1993).

CCLCL01 argued that E2 is an older shock based on 
H$_2$CO and SiO observations compared with models predictions and this would agree with the low SO$_2$/SO ratio, as SO$_2$ is expected to be converted into atomic sulphur at late stages $\geq 3 \times 10^4$ yr (e.g. Hatchell et al. 1998).

The third result, is the constant SO$_2$/H$_2$CO ratio, within a factor 2, in the shocked regions E1, W1 and W2, and in the cloud. Why SO$_2$/H$_2$CO has the same value in these shocked regions and in the cloud seems a remarkable coincidence for which we do not have an explanation. On the contrary, the constant SO$_2$/H$_2$CO ratio in these shocked regions may be due to the timescales involved in the formation and destruction of the two molecules, even though the mechanisms of SO$_2$ and H$_2$CO formation in shocks are expected to be different. On the one hand, formaldehyde is thought to be formed onto the grain mantles, released into the gas phase because of the mantle sputtering in the shock, and finally converted into more

| Region   | SO/H$_2$CO | SO$_2$/SO | SO$_2$/H$_2$CO | H$_2$S/SO | SiO/SO | SiO/SO$_2$ | SiO/H$_2$CO |
|----------|-------------|-----------|----------------|---------|--------|------------|-------------|
| Cloud    | 28          | $\sim 0.04$ | 1               | $\sim 0.03$ | $\sim 4 \times 10^{-3}$ | 0.01 | 0.01 |
| E1       | 2           | 0.5       | 1.1             | $\leq 6$ | 0.03   | 0.06       | 0.06        |
| E2(LVC)  | $\geq 4$    | $\leq 0.1$ | -               | $\leq 80$ | 0.06   | $\geq 0.5$ | $\geq 0.2$ |
| E2(HVC)  | $\geq 5$    | $< 0.1$   | -               | $\leq 150$ | 0.1    | $\geq 0.9$ | $\geq 0.5$ |
| W1       | 7           | 0.1       | 0.7             | $\leq 3$ | $6 \times 10^{-3}$ | 0.06 | 0.04 |
| W2       | 2.5         | 0.3       | 0.8             | $\leq 9$ | 0.02   | 0.05       | 0.04        |
| L1157-B1 | 0.6 - 1     | 0.6 - 1   | 0.4 - 1         | 0.8 - 1.3 | 0.2 - 0.3 | 0.3 | 0.1 - 0.3 |
| L1157-B2 | 1           | 1 - 3     | 1 - 3           | 0.7 - 2  | 0.1 - 0.4 | 0.1 | 0.1 - 0.4 |
| CB3      | -           | $\sim 1$  | -               | $\leq 1$ | $\ll 1$ | $\ll 1$ |
| L1448    | -           | -         | -               | -       | 0.3    | - | - |
| B1       | -           | -         | -               | -       | 0.1    | - | - |
| CepA     | -           | -         | -               | -       | 0.08   | - | - |
| NGC 2071 | -           | -         | -               | -       | 0.01 - 0.05 | - | - |

Fig. 5. The abundance ratios observed in the different shocked regions and in the molecular cloud and presented in Table 6: SO/H$_2$CO, SO$_2$/H$_2$CO and SiO/H$_2$CO on the lower panel and SO$_2$/SO, SiO/SO$_2$ and SiO/SO on the upper panel. The arrows represent upper and lower limits of the SO$_2$/SO, SiO/SO$_2$, SO/H$_2$CO and SiO/H$_2$CO ratios respectively.

The third result, is the constant SO$_2$/H$_2$CO ratio, within a factor 2, in the shocked regions E1, W1 and W2, and in the cloud. Why SO$_2$/H$_2$CO has the same value in these shocked regions and in the cloud seems a remarkable coincidence for which we do not have an explanation. On the contrary, the constant SO$_2$/H$_2$CO ratio in these shocked regions may be due to the timescales involved in the formation and destruction of the two molecules, even though the mechanisms of SO$_2$ and H$_2$CO formation in shocks are expected to be different. On the one hand, formaldehyde is thought to be formed onto the grain mantles, released into the gas phase because of the mantle sputtering in the shock, and finally converted into more
complex molecules by gas phase reactions on timescales larger than $\sim 3 \times 10^4$ yr (Charnley et al. 1992). SO$_2$ follows a totally different route: it has been proposed that sulphur is released into the gas phase mainly as H$_2$S, following also mantle sputtering, and then H$_2$S is transformed into SO and SO$_2$ via neutral-neutral reactions on timescales of $\sim 10^4$ yr (e.g. Charnley 1997). Later on $\sim 3 \times 10^4$ yr, gaseous sulphur is expected to be in atomic sulphur. Therefore, the constant SO$_2$/H$_2$CO ratio in E1, W1 and W2 may tell us that these three shocks have similar ages, around $10^4$ yr if models are correct, whereas E2 is a much older shock, $\geq 3 \times 10^4$ yr, and SO$_2$ and H$_2$CO both disappear because transformed into S and complex O-bearing molecules respectively.

The overall emerging picture is that the combination of the variations in the abundance of different molecules can in first instance give an estimate of the age of the shock. Table 7 summarizes the situation. The times noted in the Table 7 are really modeled dependent and are meant to represent a sequence. The simultaneous presence of SO, SO$_2$, H$_2$S, H$_2$CO, and SiO would mark relatively young shocks ($\leq 10^4$ yr), whereas the only presence of SiO emission would point towards relatively older shocks ($\geq 3 \times 10^4$ yr).

Finally, comparison with other molecular outflows can only be very approximate, but still somewhat illustrative (Tab. 6). The only molecular outflow at our knowledge in which SO, SO$_2$, SiO and H$_2$CO abundances have been measured is the L1157 outflow (Bachiller & Perez Gutierrez 1997). Looking at Table 6 L1157 B1 and B2 are rather similar to E2 with respect to the ratios involving SiO, i.e. they are relatively enriched in SiO with respect to the other shocks of L1689N and the molecular cloud. The likely interpretation is that E2, B1 and B2 are all relatively strong shocks. Yet, contrary to what happens in E2, H$_2$CO, SO and SO$_2$ are detected in L1157 B1 and B2, which would point towards relatively young shocks (Table 7). Note though that SO seems to be underabundant with respect to H$_2$CO and SiO in B1 and B2 when compared not only to E2, but also to E1, W1 and W2. At the same time, SO$_2$ is overabundant. Whether this is because of the stronger shock in B1 and B2 that converts SO into SO$_2$ more quickly, or because the shocks in L1157 have a different age of E1, W1 and W2, is impossible to say at this stage. A larger statistics on a larger number of outflow system is necessary to better understand this point.

5.3. IRAS16293

Table 6 quotes the absolute abundances of SO, SO$_2$, H$_2$S, H$_2$CO and SiO in the hot core of IRAS16293 and in the molecular cloud. As evident from the table, the sulphurated molecule abundances exhibit a strong enhancement with respect to the molecular cloud abundances. The abundance of SO increases by a factor 200, SO$_2$ by a factor 1300 and H$_2$S by a factor 1700 (see also Schöier et al. 2002).

As we mentioned in the Introduction, the sulphur species are expected to be useful to evaluate the age of hot cores. We could not resist the temptation to compare the measured abundance ratios with published theoretical predictions. In Fig. 6 we compare the H$_2$S/SO and SO$_2$/SO ratios obtained in the IRAS16293 hot core with the theoretical values predicted by chemical models. The observed H$_2$S/SO and SO$_2$/SO ratios are consistent with the theoretical predictions by Hatchell et al. (1998), but differ substantially with those by Charnley (1997). Both models use the sulphur chemistry described in Charnley (1997) and assume that the bulk of sulphur is stored in iced H$_2$S onto the grain mantles. When the dust temperature exceeds 100 K, the grain mantles evaporate releasing the H$_2$S into the gas phase, which is slowly converted into SO and subsequently into SO$_2$ by neutral-neutral reactions. The only difference between the two models is that Hatchell et al. use an updated rate for the reaction.

| Time (yr) | Formation | Destruction |
|-----------|-----------|-------------|
| $0^a$     | H$_2$S, H$_2$CO, SiH$_2$, SiH$_4$ |             |
| $10^3$    | SO, SO$_2$, H$_2$S, SiO        | SO$_2$, H$_2$CO |
| $3 \times 10^4$ |              | SiO          |

Table 7. Proposed schema of the formation and destruction of SO, SO$_2$, H$_2$S, SiO and H$_2$CO as function of time. The times are indicative and are meant to represent a sequence. $^a$ Injection in the gas phase of the molecules sputtered from the grain mantles.

![Fig. 6. Theoretical predictions of the evolution of SO$_2$/SO and H$_2$S/SO ratios as a function of time. The curves are adapted from the Hatchell et al. (1998) model, that assumes a gas temperature of 100 K and a density of $2 \times 10^6$ cm$^{-3}$. The grey squares represent the portion of the modelling curve in agreement with observations of the hot core of IRAS16293 (this work). Analogously, the stars mark the predicted values of the ratios in agreement with what observed towards L1157-mm (Bachiller & Perez Gutierrez 1997).](image-url)
of $\text{H}_2\text{S}$ with atomic hydrogen. This difference substantially 
changes the evolution of the abundances of $\text{H}_2\text{S}$, $\text{SO}$ and $\text{SO}_2$ at times larger than about $10^4$ yr. Our 
observations support the Hatchell et al. (1998) model, as 
shown in Fig. 1. The agreement between observations and 
model predictions for an age of $\sim 3 \times 10^4$ yr is remark-
able, as independent estimates of the age of IRAS16293 
converge towards the same value (Ceccarelli et al. 2000a). 

On the same figure we also report the values observed 
towards L1157-mm. Based on these observations and on 
the model predictions, L1157-mm has about the same age 
of IRAS16293. We caution that the error bars are indeed 
large enough to make the agreement between observed and 
predicted values just a coincidence. In this sense, this 
result may just mean an encouragement to pursue this kind 
of studies on a large sample of low mass protostars, where 
a statistical trend could be established. We have indeed 
started such a study on a sample of low mass protostars, 
whose we have derived the physical structure (i.e. density 
and temperature profiles) and formaldehyde abundance 
profiles (Maret et al. 2002).

A direct comparison between the measured abund-
dances in the hot cores quoted in Tab. 1 and that of 
IRAS16293 can only be done with respect to Orion-
KL, as in the other sources the abundances are not 
corrected for the beam dilution (Hatchell et al. 1998; 
Buckle & Fuller 2003). With respect to Orion-KL, the hot 
core of IRAS16293 is enriched in $\text{SO}$, $\text{SO}_2$ and $\text{H}_2\text{CO}$, 
whereas it is deficient in $\text{H}_2\text{S}$. The most plausible expla-
nation is that the different abundances reflect a differ-
en composition of the ices (from which $\text{H}_2\text{CO}$ and $\text{H}_2\text{S}$ 
evaporate), a fact now well documented by the study of 
deuterated molecules in high and low mass protostars (e.g. 
Ceccarelli 2002). However, the different gas temperature 
and density may also play a role. Finally, the $\text{SO}_2$/SO 
and $\text{H}_2\text{S}$/SO ratios of IRAS16293 differ by about a factor 
100 and 10 respectively with respect to the relevant ratios 
measured in the high mass protostars of the Hatchell et al. 
(1998) sample. Again, the difference may be attributed to 
both different evolutionary stages and different gas densi-
ties and temperatures.

Following the theoretical expectations that gaseous 
sulphur in the warm gas is mainly locked into $\text{SO}$, $\text{SO}_2$ 
and $\text{H}_2\text{S}$ (e.g. Pineau Des Forêts et al. 1992; Charnley 
1997), while silicon is mainly locked into $\text{SiO}$ (Herbst et al. 
1998), the $(\text{SO}+\text{SO}_2+\text{H}_2\text{S})/\text{SiO}$ ratio gives a measure 
of the gas phase elemental sulphur over silicon abun-
dance ratio in the IRAS16293 hot core. This value is 
about 300, to compare with the solar elemental sulphur 
over silicon abundance ratio of 0.5. It is unlikely that we 
overestimate the overall quantity of sulphur. Conversely, 
it could have been underestimated because of a possible 
optical thickness of the sulfuretted molecular lines 
and/or the presence of other important sulphur-bearing 
molecular species not considered here. Thus, the mea-
sured $(\text{SO}+\text{SO}_2+\text{H}_2\text{S})/\text{SiO}$ ratio suggests that there is 
an important deficiency of silicon in the warm gas of the 
IRAS16293 hot core. The likely explanation is that sil-
icon is mostly depleted into the non-volatile, refractory 
cores grains, whereas sulphur is depleted mostly onto the 
volatile grain mantles. This conclusion supports the thesis 
by Ruffio et al. 1999 that sulphur and silicon follow dif-
ferent routes of depletion, and specifically that sulphur is 
depleted at the time of mantle formation. Another possi-
bility to explain this deficiency of silicon is that sili-
con is mainly in another form than $\text{SiO}$ in the warm 
gas such as $\text{Si}$, $\text{Si}^+$ or $\text{SiO}_2$. The atomic silicon is dif-
cult to observe, since it has its ground transition at 
129 $\mu$m, i.e. a wavelength range obscured by the atmo-
sphere. Observations obtained with the Long Wavelength 
Spectrometer on board ISO did not detect any signal larger 
than about $5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ (Ceccarelli et al. 1998), 
corresponding to an upper limit for the Si column density 
of $6 \times 10^{17}$ cm$^{-2}$, and an abundance lower than $8 \times 10^{-6}$, 
i.e. about 500 times more than the SiO abundance found 
in IRAS16293. For $\text{Si}^+$, it is unlikely that the UV field in the 
observed regions is strong enough to ionize the silicon.

Finally, the total abundance of SO, $\text{SO}_2$ and $\text{H}_2\text{S}$ in 
the IRAS16293 hot core is $2.8 \times 10^{-6}$, namely more than 
ten times lower than the corresponding solar abundance 
$3.4 \times 10^{-5}$. Even adding up the OCS, whose abundance is 
about that of SO (Schöier et al. 2002), the overall sulphur 
abundance is still low. Unfortunately, Schöier et al. 2002 
could not estimate the CS abundance in the hot core of 
IRAS16293, but CS is unlikely to be the main reservoir of 
sulphur. The other possible reservoir of sulphur, the 
atomic sulphur (Charnley 1997), is extremely difficult to 
observe, because the ground state transition is at 25 $\mu$m, 
i.e. in a wavelength range obscured by the atmosphere.

6. Conclusion

We have presented a quantitative observational study of 
the most important S-bearing molecules, namely SO, $\text{SO}_2$ 
and $\text{H}_2\text{S}$, in the region of L1689N. We derived the column 
density of these molecules plus $\text{SiO}$ and $\text{H}_2\text{CO}$ molecules 
in six regions of L1689N: the cloud, the young protostar 
IRAS16293, and four shocked regions.

We found that $\text{SiO}$ is the molecule that shows the 
largest abundance variations in the shocked regions, 
whereas S-bearing molecules show more moderate vari-
atations. Remarkably, the region of the brightest $\text{SiO}$ emission 
in L1689N, namely E2, is undetected in $\text{SO}_2$, $\text{H}_2\text{S}$ and $\text{H}_2\text{CO}$ and only marginally detected in SO. We argued 
that this is possibly due to the relatively old age 
($\geq 3 \times 10^4$ yr) of this shock.

In the other weaker $\text{SiO}$ shocks, $\text{SO}_2$ is enhanced 
with respect to SO, in agreement with theoretical expectations 
that predict the conversion of the gaseous sulphur mostly 
into $\text{SO}_2$ on timescales of $\sim 10^3$ yr. In the same regions, 
the $\text{SO}_2$/H$_2$CO ratio is of order of unity. We argued that 
this may point to relatively young shocks ($\sim 10^4$ yr), 
where $\text{SO}_2$ has already formed and H$_2$CO has not yet 
destroyed.

Putting together the observed combinations of the SO, 
$\text{SO}_2$, H$_2$CO and $\text{SiO}$ ratios, we proposed a schema in which
the different molecular ratios correspond to different ages of the shocks.

Finally, we found that SO, SO$_2$ and H$_2$S have significant abundance jumps (200, 1300 and 1700 respectively) in the inner hot core of IRAS16293. We compared the measured abundances with theoretical models and discussed the derived protostar age. However, we cautioned that a more detailed study is necessary to draw reliable conclusions. The hot core of IRAS16293 seems to be enriched in SO, SO$_2$ and H$_2$CO with respect to Orion-KL, probably because of a different initial composition of the ices in the two sources. Comparing the SO+SO$_2$+H$_2$S/SiO ratio in the hot core of IRAS16293, we found that silicon is largely deficient in the warm gas (by a factor $\sim 600$), supporting the thesis that silicon is depleted into the grain refractory cores whereas sulphur is depleted into the grain volatile mantles. Nonetheless, sulphur in the IRAS16293 warm gas is also deficient.

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