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S-bearing molecules in Massive Dense Cores

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ABSTRACT

Context. High-mass stars, though few in number, play a major role in the interstellar energy budget and the shaping of the Galactic environment. However, despite this importance, the formation of high-mass stars is not well understood, due to their large distances, short time scales, and heavy extinction.

Aims. Chemical composition of the massive cores forming high-mass stars can put some constraints on the time scale of the massive star formation: sulphur chemistry is of specific interest due to its rapid evolution in warm gas and because the abundance of sulphur bearing species increases significantly with the temperature.

Methods. Two mid-infrared quiet and two brighter massive cores are observed in various transitions (E_{up} up to 289 K) of CS, OCS, H₂S, SO, SO₂ and of their ³⁴S isotopologues at mm wavelengths with the IRAM 30m and CSO telescopes. 1D modeling of the dust continuum is used to derive the density and temperature laws, which are then applied in the RATRAN code to model the observed line emission, and to derive the relative abundances of the molecules.

Results. All lines, except the highest energy SO₂ transition, are detected. Infall (up to 2.9 km s⁻¹) may be detected towards the core W43MM1. The inferred mass rate is 5.8-9.4 10⁻² M_⊙/yr. We propose an evolutionary sequence of our sources (W43MM1→IRAS18264–1152→IRAS05358+3543→IRAS18162–2048), based on the SED analysis. The analysis of the variations in abundance ratios from source to source reveals that the SO and SO₂ relative abundances increase with time, while CS and OCS decrease.

Conclusions. Molecular ratios, such as [OCS/H₂S], [CS/H₂S], [SO/OCS], [SO₂/OCS], [CS/SO] and [SO₂/SO] may be good indicators of evolution depending on layers probed by the observed molecular transitions. Observations of molecular emission from warmer layers, hence involving higher upper energy levels are mandatory to include.

Key words. ISM: individual objects: W43MM1, IRAS18264–1152, IRAS05358+3543, IRAS18162–2048 – ISM: abundances – Stars: formation – Line: profiles

1. Introduction

OB stars are the main contributors to the evolution and energy budget of galaxies. Their formation, however, is not understood yet and the "classical" scheme for low-mass star formation (see Andre et al. 2000, and references therein) cannot be applied as such to OB stars. Indeed, young OB stars and protostars strongly interact with the surrounding massive clouds and cores leading to a complex and still not clearly defined sequence of objects from pre-stellar cores which are often believed to be hosted in the so-called IR dark clouds (IRDCs), to High-Mass Protostellar Objects (HMPOs), to hot cores and Ultra Compact HII regions (e.g. Beuther et al. 2007a; Menten et al. 2005).

This tentative evolutionary scheme is however mostly based on observations of distant objects, for which, the physical scales are often at the order of 0.5 pc. In contrast, the well established protostellar evolution from Class 0 to Class III Young Stellar Objects (YSOs) for low-mass stars revealed that the envelopes of individual protostars have typical sizes ranging from 0.02 to 0.04 pc in clustered star-forming regions (see Motte & André 2001, and references therein). HMPOs are therefore more protoclusters than individual protostars. Recent interferometric observations

have confirmed that they are fragmented and that they actually form clusters of stars (e.g. Beuther & Schilke 2004; Shepherd et al. 2003). More recently, Motte et al. (2007) have obtained a complete view of high-mass protostellar phases at the scale of a giant molecular cloud which is not too distant (Cygnus X at 1.7 kpc). This complex is rich enough to provide a first reliable statistics (40 massive dense cores) at a physical scale of ~ 0.1 pc. From this unbiased survey of the earliest phases of the high-mass star formation, it was deduced that massive pre-stellar dense cores are extremely rare, and that of the order of 50 % of the massive dense cores are already forming high-mass stars while being still cold and not bright in the IR (IR-quiet dense cores). The remaining 50 % of dense massive cores can be referred as IR-bright dense cores. Referring to the typical sizes discussed in Williams et al. (2000), these 0.1 pc size objects are dense cores, in contrast to clumps which are more 1 pc size. On the other hand, these 0.1 pc dense cores are not necessary precursors of single stars and may form a group of stars, and would therefore be considered as clumps in the primary definition of Williams et al. (2000). We will here follow the scheme discussed in Motte & Hennebelle (2008) in which the study of massive dense cores at physical scales of ~ 0.1 pc or less is required to really address the question of evolutionary stages for high-mass star and clus-

ter formation. The interest of studying the evolution of massive dense cores is also supported by the most recent theoretical scenarios, which predict either a monolithic collapse of turbulent gas at the scale of massive dense cores (Tan & McKee 2002; Krumholz & McKee 2008), or a competitive accretion inside the gravitational potential of a cluster-forming massive dense core (Bonnell & Bate 2006). Finally, it is worth noting that some direct observational evidence for the so-called global collapse has usually been obtained for massive dense cores at the typical ~ 0.1 pc scale (e.g. Motte et al. 2005).

The chemical composition of the protostellar envelopes can be used to constrain the ages of low-mass protostars (Millar et al. 1997; Hatchell et al. 1998; Doty et al. 2002; Wakelam et al. 2004a). The sulphur chemistry is of specific interest because of its rapid evolution in warm gas and since the abundances of sulphur bearing species increase significantly with temperature, both by ice evaporation and by shock interaction. Sulphur could thus act as a clock on time scales relevant to the embedded phase of star formation (Charnley 1997; Wakelam et al. 2004a,b). A good sketch is now established for these objects allowing to date them within a “class” of objects. Here we propose some first constraints on the time of evolution of the targeted massive cores; detailed chemical modelling will be presented in a forthcoming paper (Wakelam et al., in preparation).

For high-mass protostars, the first studies using sulphur bearing molecules as evolutionary tracers are reported in Hatchell et al. (1998) and van der Tak et al. (2003). We present here a complementary study of sources, which are weaker at mid-infrared wavelengths. Also in contrast to van der Tak et al. (2003) who used chemical models without the inclusion of atomic oxygen (e.g., Charnley 1997), we prefer to use the recent results of Lis et al. (2001) and Vastel et al. (2002). Furthermore, Wakelam et al. (2004b) underlined that the sulphur may be mainly in the atomic form in hot cores.

To analyze these observations, we will apply a method similar to Wakelam et al. (2004a) who measured the age of the hot corinos of IRAS16293–2422 with reasonable success. Our observations of low- and high-energy transitions for each selected molecule enable us to probe the inner (> 100 K) and outer (< 100 K) regions of the objects studied. Using transitions at several energies, we first constrain, with a radiative transfer model (RATRAN, Hogerheijde & van der Tak 2000), the sulphur bearing abundance profiles within the envelopes (this paper). In a forthcoming paper, the derived abundance profiles will be compared to a grid of chemical models (NAHOON) adapted to the physical structure of each source in order to constrain the age of each source. To cover the complete range of energy of the massive envelopes (from 20 K to more than 100 K, Doty et al. 2002), transitions with upper energies between 10 and 110 cm^{-1} are required. Indeed, even if observing emission lines covering a large energy range is mandatory to derive the excitation conditions of the molecules, the only way to probe the inner warmer regions is to observe high energy transitions which levels are not populated in the cold outer gas. Actually, probing the inner region of massive dense cores is the only way to chemically date their evolution from the molecular cloud.

2. Description of the Source Sample

The selected sources are two IR-quiet dense cores (MSX Flux $_{21\mu\text{m}} < 10$ Jy at 1.7 kpc, following the definition of Motte et al. 2007) and two slightly brighter ones (IRAS05358+3543 and IRAS18162–2048), with bolometric luminosities $0.6\text{--}2.3\ 10^4 L_{\odot}$ at distances 1.8–5.5 kpc (see Table 1) and sizes of

Table 1. Source Sample. The F_{21} value is the MSX value for the $21\ \mu\text{m}$ flux, corrected for the distance of each source ($F_{21} \times (d/1.7)^2$).

Source	Source Coordinates ^a		V_{LSR} (km s^{-1})	Properties ^b		F_{21} (Jy)
	RA (J2000.0) (h m s)	Dec ($^{\circ}$ ' ")		L_{bol} (L_{\odot})	d (kpc)	
IRAS05358+3543	05 39 13.1	+35 45 50	−17.6	6.3×10^3	1.8	18.9
IRAS18162–2048	18 19 12.1	−20 47 31	+12.1	2.0×10^4	1.9	141.4
IRAS18264–1152	18 29 14.4	−11 50 23	+43.6	$1. \times 10^4$	3.5	4.9
W43MM1	18 47 47.0	−01 54 28	+98.8	2.3×10^4	5.5	4.8

^a Coordinates correspond to the peak of the mm continuum emission from Beuther et al. (2002a) and Motte et al. (2003), respectively for IRAS05358+3543, IRAS18264–1152 and W43MM1. For IRAS18162–2048, coordinates correspond to the CO emission peak from Benedettini et al. (2004).

^b Luminosity, distance and velocities are from Sridharan et al. (2002) (IRAS05358+3543 and IRAS18264–1152), Benedettini et al. (2004) (IRAS18162–2048) and Motte et al. (2003) (W43MM1).

$\sim 0.11\text{--}0.13$ pc (as seen in the beam of our observations, see Sect. 6.1). These massive dense cores are expected to be fragmented at small scales and are meant to represent the earliest phases of the formation of clusters. The expected multiplicity can however be neglected to first order, to follow the average chemical evolution of their surrounding dense cores. In fact, a small fraction of the total mass of the cores is in the individual fragments, and usually the large scale average density profile of the cores applies well down to the smallest observed structures. This suggests that the cores could be well represented to first order as spherically symmetric structures from a few 0.1 pc down to ~ 0.01 pc. IRAS05358+3543 has for instance been studied with millimeter interferometers (see Leurini et al. 2007). It appears that the ~ 0.3 pc size core of $613 M_{\odot}$ splits into two main objects (mm1a and mm1b) of 1 and $0.6 M_{\odot}$ inside regions of 0.006 pc diameter, separated only by ~ 0.008 pc. A mass of $1.6 M_{\odot}$ in a region ~ 0.01 pc comprising mm1a and mm1b, inside a 0.3 pc size core of $613 M_{\odot}$ corresponds to an average radial profile of the density of $r^{-1.25}$ which is actually close to the $r^{-1.4}$ profile derived from large scale by Beuther et al. (2002b) and which we use to describe the global 1D distribution of matter in the core. Two other millimeter condensations mm2 and mm3 are also detected with the interferometer. They could eventually confuse the results for molecular tracers which can trace such high density regions.

A large number of continuum and molecular line (CO, SiO, CH₃OH, H₂CO etc) data towards these sources have been published (e.g. Benedettini et al. 2004). The physical conditions have thus already been determined in some of the envelopes (e.g. Beuther et al. 2002b) and we use the published data together with our observations. We limit our study to massive dense cores to simplify this first step of the analysis for two reasons. First, different physical conditions have been observed in these objects, but they still have the same structure in the sense that there is no strong UV field or ultra-compact HII regions, which will change drastically the chemistry with time. The second reason is that these cores could be for massive dense cores the equivalent of the Class 0 YSOs in the general scenario of gas and dust evolution, for which sulphur chemistry (Wakelam et al. 2004a,b) has already been studied. Finally, the sources studied here are part of the sample that will be studied within the key program

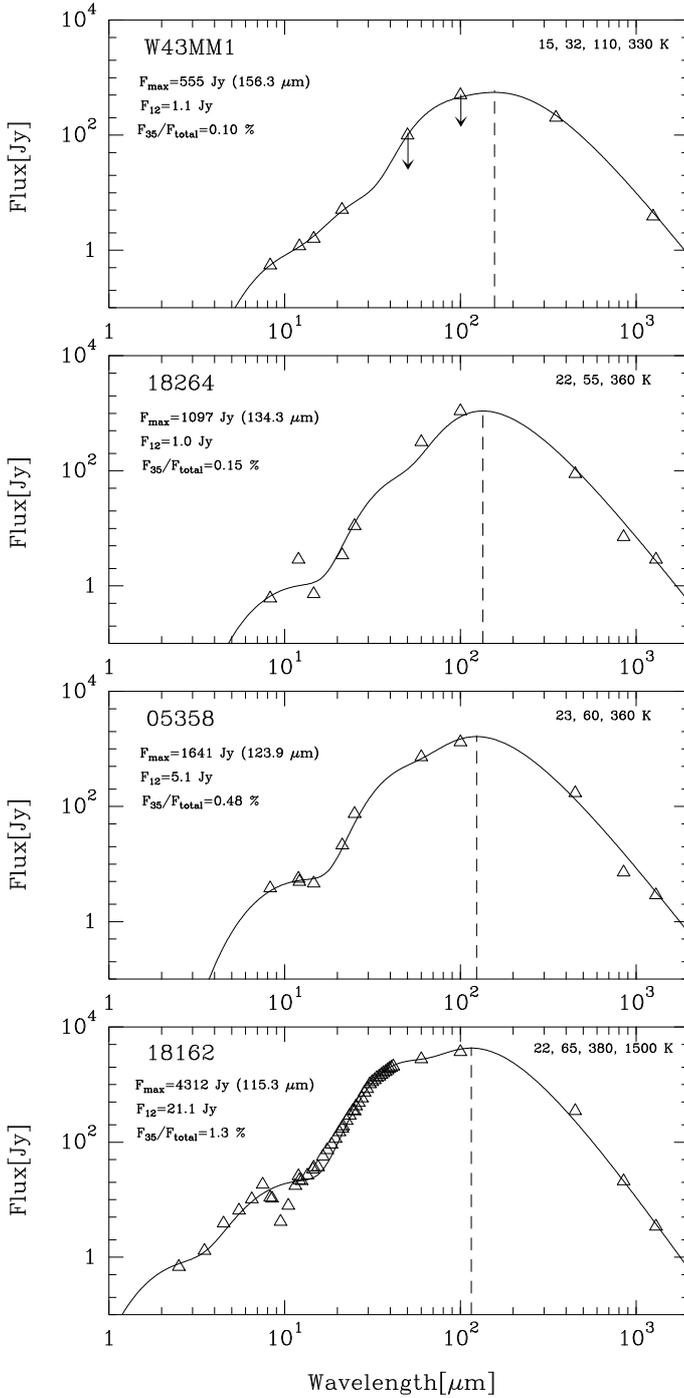


Fig. 1. Spectral energy distributions obtained from 1D model overlaid on observed fluxes of each source. Peak fluxes in the millimeter range have been adjusted to fit radial extension of the model. In each caption are given the temperatures of the black body components (top right), the maximum flux F_{\max} and the corresponding wavelength of the SED, the flux F_{12} at $12\ \mu\text{m}$, and the contribution of the hot part (F_{35} , integrated flux for $\lambda < 35\ \mu\text{m}$) to the total integrated flux F_{total} (top left).

*WISH*¹ with the HIFI instrument aboard the ESA Herschel Space Observatory.

Both IRAS05358+3543 and IRAS18264–1152 are part of the Sridharan et al. (2002) sample. IRAS05358+3543 is a rel-

atively low luminosity ($L \sim 6.3 \cdot 10^3 L_{\odot}$) and nearby (1.8 kpc) massive dense core, composed of three main sources (mm1, mm2 and mm3; total mass around $613 M_{\odot}$), all within $4'' \times 9''$ (Leurini et al. 2007), hence within the telescope beam. The source exhibits a hypercompact HII region which may evolve into an UC-HII region. Beuther et al. (2007b) show that the source actually splits into four individual continuum components, two of which are part of a proto-binary system, mm1 (dynamical age $\sim 3.6 \cdot 10^4$ yr). According to Longmore et al. (2006), the main mid-IR source coincides with mm1a of Beuther et al. (2007b), but the second mid-IR source does not coincide with the mm source mm1b, hence suggesting even more sub-structure. The source exhibits a class II methanol maser indicating that it is a very young object. The source mm3 is the coldest and youngest ($T_{\text{dust}} \leq 20$ K). Several molecular outflows are observed (two from mm1, outflow rate of $6 \times 10^4 M_{\odot}$; Beuther et al. 2002a). Strong line emission asymmetries in HCO^+ have been observed by Fuller et al. (2005).

IRAS18264–1152 is a massive dense core at a distance of 3.5 kpc. Its luminosity is estimated to be up to $10^4 L_{\odot}$. A massive molecular outflow is centered on the mm dust peak (Beuther et al. 2002a). Continuum observations with Plateau de Bure (Qiu et al. 2007) reveal that the source is double; the mass of the dust-gas core is estimated to be $570 M_{\odot}$, while the outflow mass is $20.2 M_{\odot}$ (dynamical age of $0.5 \cdot 10^4$ yr).

Benedettini et al. (2004) performed multi-line observations of IRAS18162–2048, a luminous infrared source ($L = 2 \cdot 10^4 L_{\odot}$; Yamashita et al. 1989) at a kinematic distance of 1.9 kpc (Kurtz et al. 1994). This object is associated with the IRAS source and is actually an IR-bright dense core. A very powerful outflow ($M \sim 570 M_{\odot}$), one of the most massive known, was observed (dynamical age $\sim 10^6$ yr). The source has been resolved into a cluster of several objects (Stecklum et al. 1997).

W43 is a massive star-forming region, located at 5.5 kpc, which harbors a giant HII region and was studied in detail by Motte et al. (2003). W43MM1 is the most massive dense core of the region and does not coincide with any known IR source. The dust temperature is estimated to be 19 K and its luminosity $2.3 \cdot 10^4 L_{\odot}$. W43MM1 harbors a methanol and a water maser, but does not show any infrared or centimeter emission. An infall has been detected by Motte et al. (private communication).

Continuum emission from our sources is quite well determined with well sampled observations from IRAS, MSX, SCUBA/JCMT or SHARC/CSO (Hunter et al. 2000; Jenness et al. 1995; Minier et al. 2005), SMA (Beuther et al. 2007b; Su et al. 2004) and MAMBO/IRAM30m (Beuther et al. 2002b). The SED for IRAS18162–2048 is particularly well constrained, thanks to a complete ISO-SWS observation. Fewer continuum observations are available for the source W43MM1.

From the fitted SEDs (see Sect. 6.1), shown in Fig. 1, we make a rough evolutionary classification of our 4 objects, using the following parameters:

- wavelength and flux of the maximum continuum emission,
- flux at $12\ \mu\text{m}$,
- contribution of the hot part ($\lambda < 35\ \mu\text{m}$) to the total integrated flux,
- temperature of the black-body components.

We assume that the less evolved the source is, the coldest it is, hence the SED peaks at longer wavelength with weaker flux. As the massive core evolves, it becomes warmer hence heating the dust wherein it is embedded: as a consequence the contribution of the flux at shorter wavelength (F_{35} , the integrated flux for $\lambda < 35\ \mu\text{m}$) increases.

¹ <http://www.strw.leidenuniv.nl/WISH/>, PI: E. van Dishoeck

Applying these criteria, W43MM1 appears to be the youngest object. A sequence of evolution W43MM1 \rightarrow IRAS18264–1152 \rightarrow IRAS05358+3543 \rightarrow IRAS18162–2048 is proposed and adopted for the following discussion. This evolutionary sequence is also suggested by the dynamical ages derived by the authors cited above.

3. Observations

The observations presented here were performed during two sessions. The first one in September 2005, using the IRAM-30m antenna². The second one in May 2006, using the Caltech Submillimeter Observatory³, on the summit of Mauna Kea (Hawaii).

With the 30m telescope, all sources were observed in the rotational transitions lines of CS $J=5-4$, SO $J=3_4-2_3$, $J=5_6-4_5$, $J=6_5-5_4$, SO₂ $J=5_{1,5}-4_{0,4}$, $J=10_{0,10}-9_{1,9}$, $J=11_{1,11}-10_{0,10}$, $J=14_{0,14}-13_{1,13}$, OCS $J=8-7$, $J=13-12$, $J=19-18$, H₂S $J=1_{1,0}-1_{0,1}$, $J=2_{2,0}-2_{1,1}$, and in the isotopic lines of ³⁴SO $J=3_4-2_3$, SO₂ $J=5_{1,5}-4_{0,4}$, OC³⁴S $J=8-7$, H³⁴S $J=1_{1,0}-1_{0,1}$ (see Table 2). Only IRAS05358+3543, IRAS18264–1152 and W43MM1 were observed in the CS and C³⁴S $J=3-2$ lines. Observations were made using multiple receivers (either simultaneously A100, B100, A230, B230 or C150, D150, C270, D270) coupled to the high-resolution VESPA backend (resolution of 80 kHz) in frequency switching model (frequency throw of 7.9 MHz). The sky conditions were reasonable ($\tau_0^{atm} \sim 0.1-0.5$ at 225 GHz, see Table 2 for the T_{sys}). The telescope pointing (better than 2'') and focus have been set on suitable planets (*i.e.* Jupiter) or standard calibration sources.

Complementary observations have been performed with the CSO telescope for lines with frequencies higher than 300 GHz (in order to better cover the energy ladder). As IRAS05358+3543 was not visible at the CSO during our run, only the other three sources were observed in lines of CS $J=7-6$, SO $J=8_8-7_7$, SO₂ $J=18_{0,18}-17_{1,17}$, and in corresponding isotopic lines of C³⁴S, ³⁴SO, ³⁴SO₂. The receiver is a helium-cooled SIS mixer operating in double-sideband mode designed to fully cover the 280-420 GHz window. The backend consists of a 1024 channel acousto-optical spectrometer covering a bandwidth of 50 MHz, providing a velocity resolution of $\Delta v \simeq 0.086$ km s⁻¹ at 345 GHz. Observations were performed under good but unstable weather conditions ($\tau_0^{atm} \sim 0.06-0.15$ at 225 GHz, see Table 2 for the T_{sys}). The pointing accuracy was of the order of 4-5''. The CS $J=7-6$ line was blended with an H₂CO line from the image sideband, therefore we applied a frequency shift to the local oscillator frequency to separate the two lines, but the procedure did not work well for IRAS18264–1152 and W43MM1 (hence the CS spectra are contaminated).

Data reduction was performed using the CLASS software from the GILDAS suite (Guilloteau & Lucas 2000). We found and eliminated unusable data, subtracted a baseline, then spectra at the same position were summed and finally antenna temperature T_a^* was converted into T_{mb} (using the η_{mb} values from Tab. 2). Special attention was paid to the frequency switching observing method.

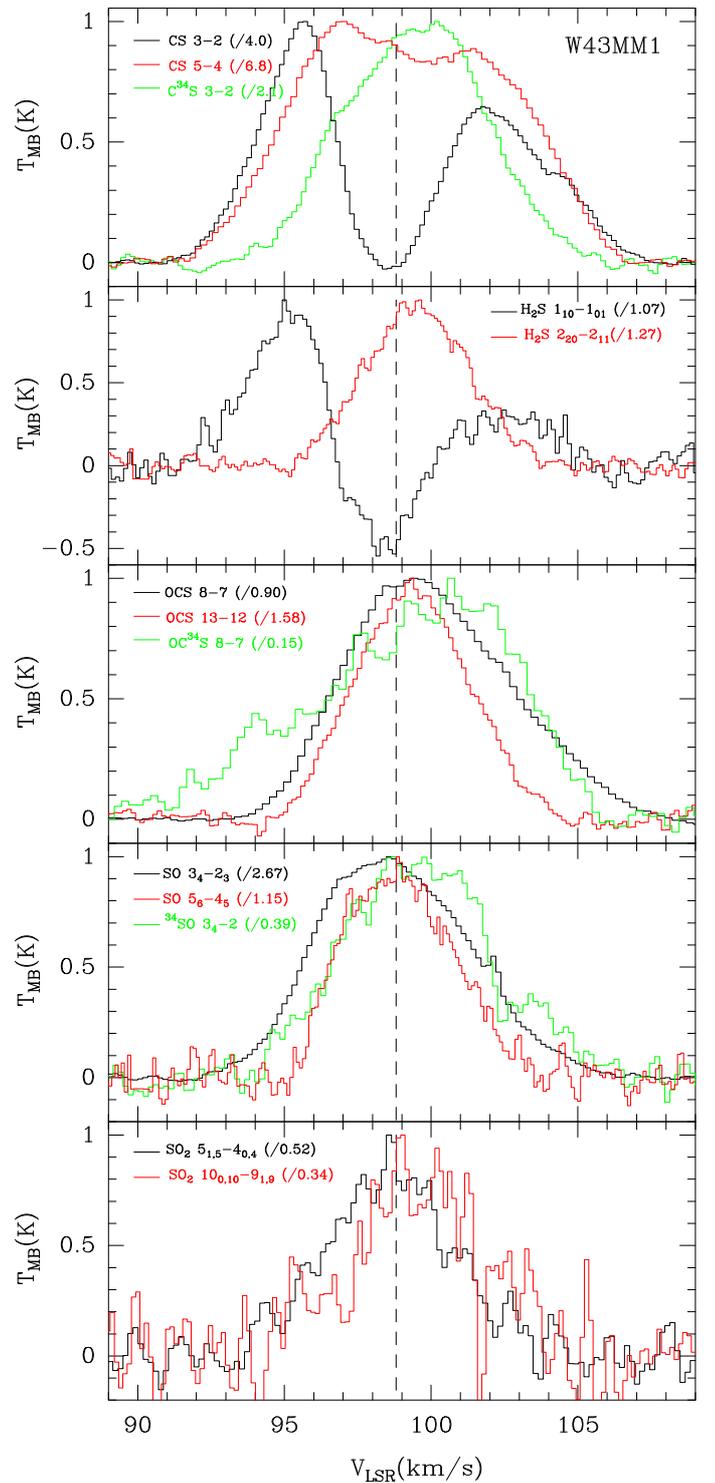


Fig. 2. Normalized emission of CS, H₂S, OCS, SO, SO₂ (and isotopic species) lines from W43MM1. Spectra velocity resolutions are 0.10-0.19 km s⁻¹. The dashed line shows the source LSR velocity.

4. Results

We present here the result of the observations for each source. Some spectra of the detected lines are displayed in Fig. 2–5 (the remaining spectra are available as online material). Some transitions (³⁴SO 8₈ – 7₇, SO₂ 28_{4,24} – 28_{3,25} and ³⁴SO₂ 5_{1,5} – 4_{0,4}) are not detected in any of our sources. The line parameters are

² <http://iram.fr/IRAMES/index.htm>

³ <http://www.cso.caltech.edu>. The Caltech Submillimeter Observatory is supported by the National Science Foundation under award AST-0540882.

Table 2. List of observational parameters for the IRAM 30m and CSO telescopes (observed species, energy level transitions, upper energy, line emission frequencies, half power beam width, instrument, main beam efficiency η_{mb} , receiver name, velocity resolution δv and system temperature T_{sys}).

Species	Transition	E_{up} [cm ⁻¹]	Frequency [GHz]	HPBW [$''$]	Instrument ^a	η_{mb}	Receiver	δv [m·s ⁻¹]	T_{sys} [K]
CS	3 – 2	10	146.969	17	30m	0.69	D150	160	315-350
	5 – 4	24	244.936	10	30m	0.48	A230	96	530-860
	7 – 6	46	342.883	24	CSO	0.75	345	43	1210-1340
C ³⁴ S	3 – 2	10	144.617	17	30m	0.69	D150	162	270-390
	7 – 6	46	337.396	25	CSO	0.75	345	43	1260-1760
SO	3 ₄ – 2 ₃	11	138.178	18	30m	0.70	D150	170	300-330
	5 ₆ – 4 ₅	24	219.949	11	30m	0.55	B230	110	590-930
	6 ₅ – 5 ₄	35	251.825	10	30m	0.48	D270	190	750-830
	8 ₈ – 7 ₇	61	344.308	24	CSO	0.75	345	43	1020-1050
³⁴ SO	3 ₄ – 2 ₃	11	135.775	18	30m	0.70	D150	170	290-350
	8 ₈ – 7 ₇	61	337.582	25	CSO	0.75	345	43	1020-1060
SO ₂	5 _{1,5} – 4 _{0,4}	11	135.696	18	30m	0.70	D150	170	270-400
	10 _{0,10} – 9 _{1,9}	34	160.827	15	30m	0.66	C150	150	350-520
	11 _{1,11} – 10 _{0,10}	42	221.965	11	30m	0.55	B230	100	530-550
	14 _{0,14} – 13 _{1,13}	65	244.254	10	30m	0.48	A230	190	830-1430
	18 _{0,18} – 17 _{1,17}	105	321.330	26	CSO	0.75	345	45	770-820
	28 _{4,24} – 28 _{3,25}	289	267.719	9	30m	0.46	D270	170	470-510
³⁴ SO ₂	5 _{1,5} – 4 _{0,4}	11	133.471	18	30m	0.70	D150	170	200-220
OCS	8 – 7	14	97.301	25	30m	0.77	A100	240	140-160
	13 – 12	37	158.107	15	30m	0.66	C150	150	340-360
	19 – 18	77	231.060	11	30m	0.52	A230	100	450-580
OC ³⁴ S	8 – 7	14	94.922	25	30m	0.77	B100	240	140-160
H ₂ S	1 _{1,0} – 1 _{0,1}	19	168.762	14	30m	0.70	D150	140	610-800
	2 _{2,0} – 2 _{1,1}	58	216.710	11	30m	0.57	B230	110	410-600
H ₂ ³⁴ S	1 _{1,0} – 1 _{0,1}	19	167.910	14	30m	0.70	D150	140	630-670

^a Conversional factor is $S/T_{mb} = 4.95$ Jy/K for IRAM 30m telescope and $S/T_{mb} = 74$ Jy/K for CSO telescope.

given in Table 6–9 (only available in electronic form). For all observations, contamination from lines in the image sideband of the receiver has been checked.

4.1. W43MM1

The CS line emission from this source is characterized by what looks like a strong self-absorption (at ~ -0.2 km s⁻¹ from the source velocity) with a stronger blue component compared to the red one. Indeed the self-absorption in the 3 – 2 line goes below zero kelvins, splitting the line profile into two well separated components. The 2mm continuum flux is actually high (0.8 Jy), which converts into a brightness temperature of 5.5 K, and can therefore explain the observed dip. Similar, but weaker, self-absorption is observed in the 5 – 4 and 7 – 6 transitions. However, the isotopic lines are only weakly asymmetric, redshifted with respect to the systemic velocity. The derived opacities (from our model, see Sect. 6.2) are respectively 0.4 and 0.6 for the C³⁴S 3 – 2 and 7 – 6 line emissions, indicating optically thick lines. All lines are very broad, up to 15 km s⁻¹. Note that HCO⁺ and H¹³CO⁺ 3 – 2 emission lines observed by Motte et al. (2003) have exactly the same profiles as the CS and C³⁴S emission lines, respectively. The self-absorption is present in the H₂S line emissions too (the isotopic line is not detected), even producing for the 1_{1,0} – 1_{0,1} line a negative dip, below the continuum level, at the same velocity as CS. The 2_{2,0} – 2_{1,1} line emission has a different profile with more redshifted emission.

The SO 3₄ – 2₃, 5₆ – 4₅ and the isotopic 3₄ – 2₃ line profiles are also weakly asymmetric, with a more pronounced blueshifted

emission. The 6₅ – 5₄ and 8₈ – 7₇ lines exhibit, on the contrary, a stronger redshifted component. The SO₂ 5_{1,5} – 4_{0,4} line is also blue-asymmetric, but all other SO₂ lines are more or less symmetrical and gaussian.

All OCS lines exhibit a gaussian profile, slightly red-shifted by ~ 0.5 km s⁻¹ from the source velocity, with a red wing. The isotopic OC³⁴S line profile is complicated with several components in emission at 91.8, 94.0 and 95.5 km s⁻¹ (see Fig. 2). No identification with known species was possible (we also checked the frequencies in the image band) and instrumental effects have been ruled out. This weak component is not seen in the corresponding OCS line profile. Since W43MM1 is a very rich molecular source (see Sect. 7.1), this could well be real lines.

4.2. IRAS18264–1152

All line emission profiles are well peaked on the source velocity and have more or less the same shape, with a blue wing. Nonetheless, a distinct weak emission at 48–50 km s⁻¹ is observed for all transitions of all species. These emissions cannot be due to a contamination from any OFF position as observations have been performed in frequency-switch mode. None of these features correspond to a known molecular line. We propose that this secondary emission comes from a different location than the main one, either from another source within the beam, or from a knot in the outflow. Actually, an SiO outflow component at 48 km s⁻¹, offset by 20 $''$ has been observed by Qiu et al. (2007).

All CS lines are detected, except the 7 – 6 transition that is blended with an H₂CO line from the image band, hence com-

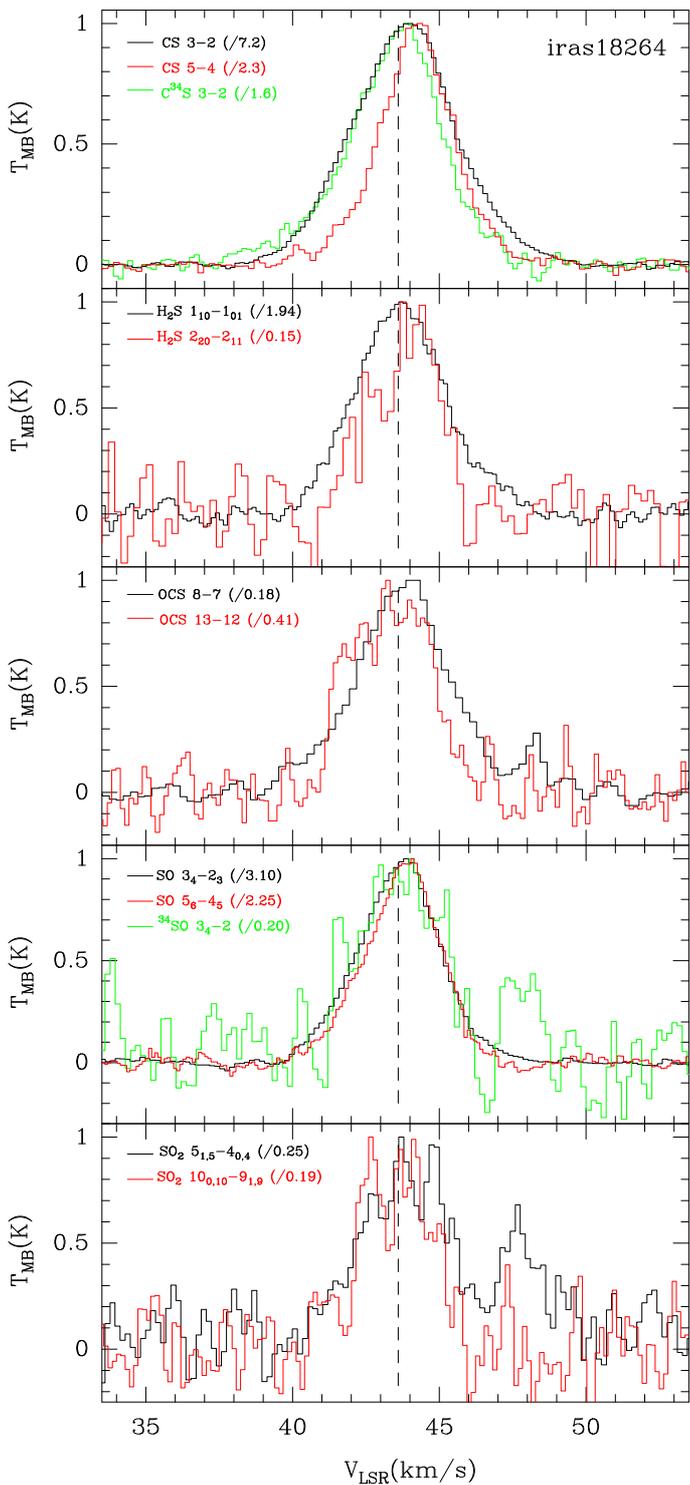


Fig. 3. Normalized emission of CS, H₂S, OCS, SO, SO₂ (and isotopic species) lines from IRAS18264–1152. Spectra velocity resolutions are 0.10–0.19 km s⁻¹. The dashed line shows the source LSR velocity.

pletely contaminating the profile. The C³⁴S 7 – 6 line is tentatively detected. The H₂S lines exhibit a less peaked profile with a blue wing too. All the SO lines are detected too, but the 6₅ – 5₄ line emission exhibits a strong and very broad red wing which looks suspicious. We do not consider this line for further analysis. The SO₂ line profiles are more flattened. Actually, an unidentified line at 47.8 km s⁻¹ is observed in the SO₂ 5_{1,5} – 4_{0,4} spectra,

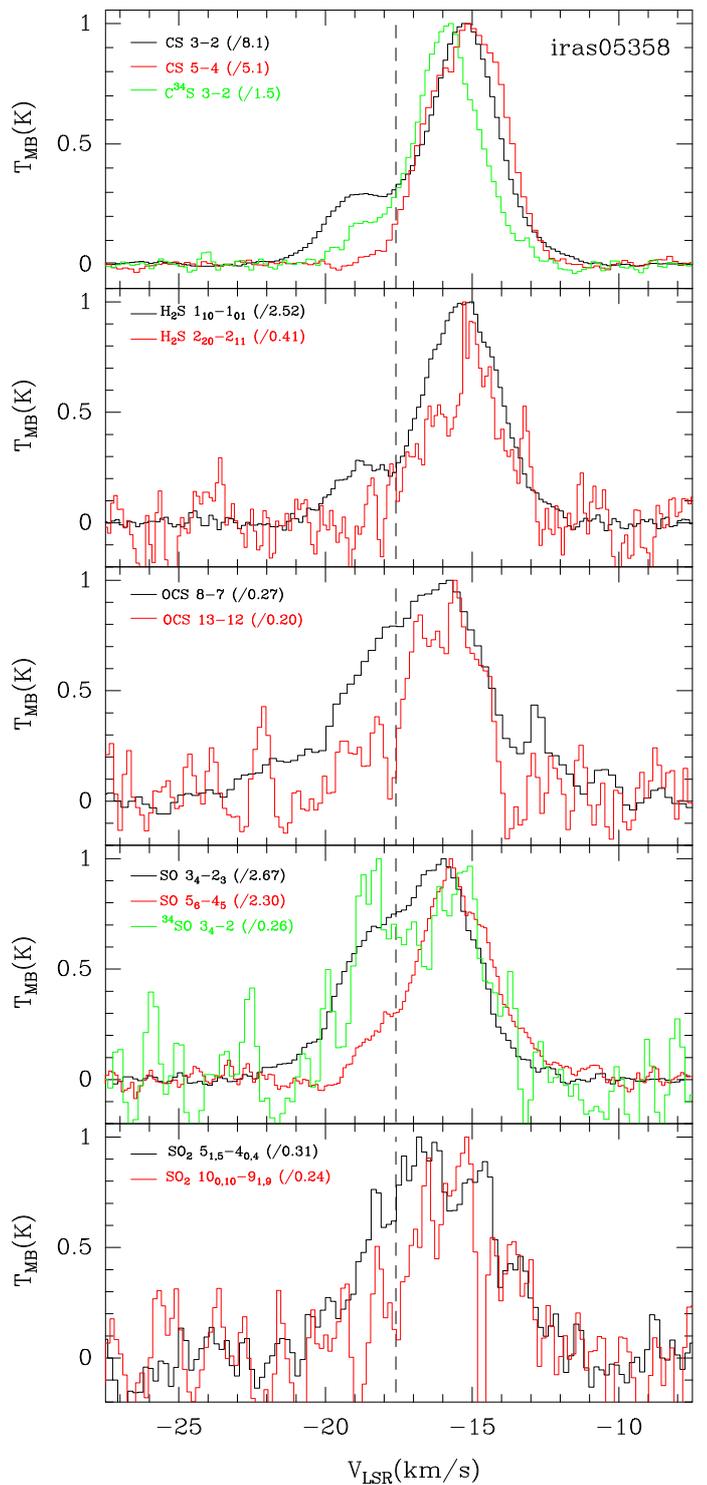


Fig. 4. Normalized emission of CS, H₂S, OCS, SO, SO₂ (and isotopic species) lines from IRAS05358+3543. Spectra velocity resolutions are 0.10–0.19 km s⁻¹. The dashed line shows the source LSR velocity.

and could come from the reference OFF spectra, just as the suspicious 6₅ – 5₄ wing. The OCS lines exhibit similar profiles, with a blue asymmetry.

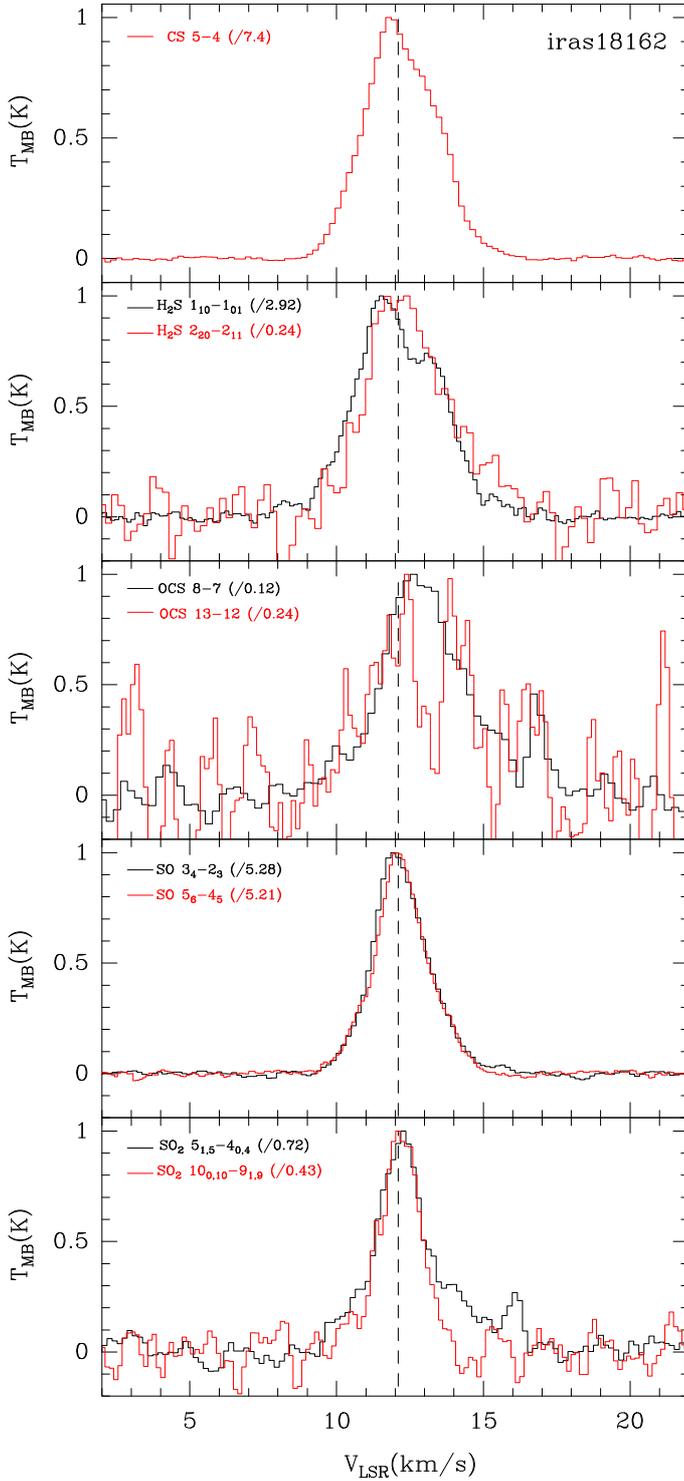


Fig. 5. Normalized emission of CS, H₂S, OCS, SO, SO₂ (and isotopic species) lines from IRAS18162–2048. Spectra velocity resolutions are 0.10–0.19 km s^{−1}. The dashed line shows the source LSR velocity.

4.3. IRAS05358+3543

The CS line emission is strong in both observed transitions (the 3 – 2 line emission being the strongest and broadest one) with a strong dip at the source velocity, even for the isotopic line. The isotopic line emission here is optically thin (around 0.1 according to our model), therefore this dip is likely owing to two

velocity components rather than to self-absorption. All profiles are asymmetrical with a stronger red component, the blue one being almost completely extinguished (nearly in absorption) for the CS 5 – 4 line emission. The peak-to-peak velocity separation is 3.0, 3.5 and 4.3 km s^{−1}, respectively for the C³⁴S 3 – 2, CS 3 – 2 and 5 – 4 lines.

The H₂S 1_{1,0} – 1_{0,1} line emission also exhibits a strong dip at the source velocity. The separation between the two emission peaks is 3.6 km s^{−1}. The same shape is also seen for the 2_{2,0} – 2_{1,1} line, where no blue peak is seen, the red component being split in two peaks. The isotopic line might be tentatively detected, with a very strong asymmetry.

Profiles of the SO lines generally exhibit a dip at the source velocity. The peak-to-peak separation is 3 km s^{−1} for the 3₄ – 2₃ line. The isotopic 3₄ – 2₃ line shows a red-shifted (by more than 1 km s^{−1}) double-horn profile. ³⁴SO 3₄ – 2₃ line emission is marginally detected, suffering from obvious baseline problems. We checked, without success, if the double-peak profile could be due to other species.

The SO₂ emission is detected in all transitions (except the 11_{1,11} – 10_{0,10}), but the *S/N* is quite low (5–9). All the lines are asymmetric, nearly without any red component. The 14_{0,14} – 13_{1,13} emission is the strongest.

A dip is seen in all OCS lines too, most prominently in the 13 – 12 transition. The 19 – 18 line is the strongest. The OCS 13–12 line is only tentatively detected with a complex profile.

A second emission component is seen in the C³⁴S 3–2, OCS 8–7, SO 3₄ – 2₃, SO₂ 5_{1,5} – 4_{0,4} spectra at −13 km s^{−1}. As this emission is also present in the wing of the CS 3–2 and H₂S 1–1 line emission (observed with a smaller telescope beam), we believe that this emission originates from the source mm1b as observed in the C³⁴S 5–4 line emission by Leurini et al. (2007) at the same velocity.

4.4. IRAS18162–2048

The CS line shapes are similar for the different transitions observed, with the 5 – 4 line being substantially stronger and broader, exhibiting a red wing.

The H₂S emission is slightly broader than CS, with more complex profiles: the 1_{1,0} – 1_{0,1} emission profile is made of two peaks, possibly revealing self-absorption at a redshifted velocity (by 0.5 km s^{−1} with respect to the source systemic velocity). The 2_{2,0} – 2_{1,1} line profile is slightly asymmetrical, with a red wing. The optically thin isotopic line emission exhibits a symmetrical profile centered on the source velocity, with a narrower profile than for the H₂S emission.

The SO lines are strong and easily detected, but the isotopic line is not detected. The SO₂ lines are well detected, even the 18_{0,18} – 17_{1,17} transition, the 11_{1,11} – 10_{0,10} being the strongest one. The line profiles show a red wing.

All the OCS lines are completely asymmetrical with a very weak blue component, indicating a self-absorption at the source velocity.

For that source too, emission a few km s^{−1} away from the main emission is detected (at 16–17 km s^{−1}) for the lines observed with a beam larger than 18″, likely revealing the presence of a second source within the beam.

Table 3. Asymmetry parameter (Mardones et al. 1997) calculated for the detected line emissions. Negative values of δv correspond to blueshifted emission while positive values are redshifted.

Species	Line ^a	Source			
		W43MM1	18264	05358	18162
CS	3-2	-0.69	0.05	0.37	
	5-4	-0.41	0.16	0.42	0.03
	7-6	-0.40	^b		-0.01
C ³⁴ S	3-2	0.05	-0.02	0.27	
	7-6	0.18	0.20		0.13
SO	3 ₄ – 2 ₃	-0.10	0.00	0.22	0.03
	5 ₆ – 4 ₅	-0.06	0.05	0.29	0.06
	6 ₅ – 5 ₄	0.11	^c	0.28	-0.08
	8 ₈ – 7 ₇	0.11	0.04		0.12
SO ₂	5 _{1,5} – 4 _{0,4}	-0.11	0.08	0.17	0.03
	10 _{0,10} – 9 _{1,9}	0.05	-0.02	0.27	0.05
	11 _{1,11} – 10 _{0,10}		-0.03		0.44
	14 _{0,14} – 13 _{1,13}		-0.12	0.38	0.00
	18 _{0,18} – 17 _{1,17}	0.10			0.19
OCS	8 – 7	0.11	0.06	0.26	0.53
	13 – 12	0.03	-0.06	0.24	0.52
	19 – 18	0.10	0.09	0.17	1.08
H ₂ S	1 _{1,0} – 1 _{0,1}	-0.76	0.02	0.39	-0.37
	2 _{2,0} – 2 _{1,1}	0.06	0.08	0.42	0.16

^a Reference lines are optically thin ³⁴SO and H₂³⁴S line emissions

^b doubtful line

^c doubtful line

5. Analysis

5.1. Line Asymmetries

Analysis of the line profiles can reveal the presence of outflows, infall or even rotation because of their known signatures (see Fuller et al. 2005, and references therein): outflow or rotation give rise to both red and blue asymmetric lines, while infall produces only blue ones. Indeed, the profiles of optically thick lines from infalling material have stronger blueshifted emission than redshifted one. However, it is important to stress that outflow or rotation could also produce a blue asymmetric line profile along a particular line of sight to a source.

To quantify the asymmetry of a line, we use Mardones et al. (1997) criteria: we calculate the asymmetry parameter

$$\delta v = \frac{v_{\text{thick}} - v_{\text{thin}}}{\Delta v_{1/2}} \quad (1)$$

where v_{thick} and v_{thin} are the line peak velocity respectively of an optically thick and thin tracer, and $\Delta v_{1/2}$ the line width (FWHM) of the optically thin line.

Because not all the same lines are detected or observed in all sources, the difficulty is to find a common strong optically thin line, generally from isotopic species. We use ³⁴SO 3₄ – 2₃ for IRAS05358+3543 ($v_{\text{thin}} = -17.0$ km s⁻¹, $\Delta v_{1/2} = 4.4$ km s⁻¹), IRAS18264–1152 ($v_{\text{thin}} = 43.6$ km s⁻¹, $\Delta v_{1/2} = 4.0$ km s⁻¹), and W43MM1 ($v_{\text{thin}} = 99.2$ km s⁻¹, $\Delta v_{1/2} = 5.5$ km s⁻¹), and H₂³⁴S 1_{1,0} – 1_{0,1} for IRAS18162–2048 ($v_{\text{thin}} = 12.1$ km s⁻¹, $\Delta v_{1/2} = 1.5$ km s⁻¹). Results are given in Table 3.

Negative values of δv correspond to blueshifted emission while positive values to redshifted one. Following Mardones et al. (1997) and Fuller et al. (2005), we adopt a criteria of $|\delta v| > 0.25$ to indicate that a line profile is asymmetric. Main conclusions are that the source IRAS18264–1152 has quite symmetric

lines, except for the C³⁴S 7 – 6 line (close to the 0.25 value), while for IRAS18162–2048 asymmetric lines are observed in OCS, in the H₂S 1_{1,0} – 1_{0,1} (redshifted) and in the SO₂ 11-10 transitions (blueshifted). Very strong asymmetries are observed for the two other sources: most of the lines from IRAS05358+3543 are strongly redshifted (δv up to 0.42); W43MM1 shows clearly blueshifted lines in CS (up to -0.69) and H₂S (up to -0.76), probably indicating the presence of infall towards this source. Nevertheless, we stress again that such an emission profile can be sometimes produced by an outflow too, *e.g.* CO 1 – 0 line profile towards IRAS18162–2048 by Benedettini et al. (2004). Hence, this option cannot be eliminated without further investigations.

5.2. Possible Infall in W43MM1

Assuming the observed CS profile towards W43MM1 is due to infall, we estimate the infall velocity using the approximate method described in Myers et al. (1996) for the optically thick lines with a strong blue asymmetry:

$$v_{\text{in}} \approx \frac{\sigma^2}{v_{\text{red}} - v_{\text{blue}}} \ln \left(\frac{1 + eT_{\text{BD}}/T_{\text{D}}}{1 + eT_{\text{RD}}/T_{\text{D}}} \right) \quad (2)$$

where T_{D} is the brightness temperature of the dip (assumed optically thick), T_{BD} and T_{RD} the height of respectively the blue and red peak above the dip, and v_{blue} and v_{red} respectively the velocity of the blue and red peak. The velocity dispersion σ is obtained from the FWHM of an optically thin line.

Adopting the ³⁴SO 3₄ – 2₃ line as an optically thin tracer, the velocity dispersion in the circumstellar material is estimated to be 5.5 km s⁻¹ and the source velocity to be 99.2 km s⁻¹. The derived infall velocities v_{in} are 2.1, 1.8 and 2.9 km s⁻¹, calculated respectively for the CS 3 – 2, 5 – 4 and H₂S 1_{1,0} – 1_{0,1} line emissions. Using the following formula (where m is the mean mass of the molecule and r_{out} the inner radius of the most outer layer):

$$\frac{dM}{dt} = 4\pi r_{\text{out}}^2 m n v_{\text{in}} \quad (3)$$

the inferred *kinematic* mass infall rate (for a size r_{out} of 3.4 10¹⁷ cm and a density n of 2.5 10⁶ cm⁻³, cf. Table 4) is 5.8–9.4 10⁻² M_⊙/yr.

5.3. Outflows in the other sources or multiplicity effect ?

The SO 3₄ – 2₃ lines towards IRAS18162–2048 can be fitted with two Gaussians of FWHM line widths of 1.2 and 2.6 km s⁻¹ (see Fig. 6). The CS 7 – 6 line emission can be fitted by two Gaussians too: one of 1 km s⁻¹ broad, the other one of 2.8 km s⁻¹. The optically thin H₂³⁴S line can be fitted by two Gaussians of FWHM 1.2 and 3.2 km s⁻¹, comparable to the components derived from the other lines. Moreover, it is interesting to note that the two gaussian components are centered at velocities (11.9 and 12.3 km s⁻¹) comparable to the velocities (11.9 and 12.8 km s⁻¹) of the two major outflow components seen in CO, ¹³CO and C¹⁸O 1 – 0 line emissions by Benedettini et al. (2004). For IRAS181264, the CS 3 – 2 and SO 3₄ – 2₃ line emissions can be fitted with two Gaussians of two different FWHM: 1.7 and 3.7 km s⁻¹. These two-components reveal the presence of gas flows, possibly an outflow towards objects IRAS18162–2048 and IRAS18264–1152.

Line emission profiles seen in the source IRAS05358+3543 exhibit a strong dip (especially for CS), even for the optically thin isotopic species, which is hence not a self-absorption but

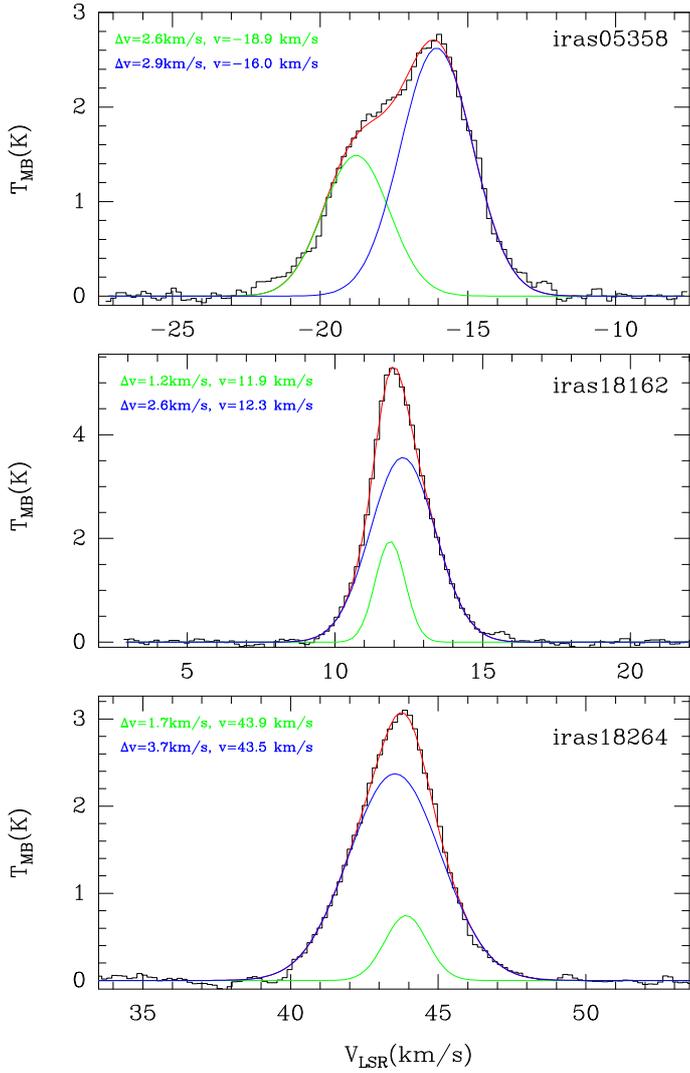


Fig. 6. Gaussian fit of the $\text{SO } 3_4 - 2_3$ line emission from IRAS05358+3543, IRAS18162–2048 and IRAS18264–1152. The observed spectra are in black, total fit in red, individual components in blue and green.

rather a the signature of two well separated velocity components with FWHM around 2.6 and 2.9 km s^{-1} (derived from $\text{CS } 3 - 2$ and $\text{SO } 3_4 - 2_3$ lines emission fitting, see Fig. 6). This could be due to the outflow detected by Beuther et al. (2002a) and Beuther et al. (2002c) or to the multiplicity of the source itself. IRAS05358+3543 is indeed composed of three mm sources (Leurini et al. 2007), all within our beam, mm1 being the most massive, the other two being less evolved (mm3 is probably a starless massive core). Actually, the component at -16 km s^{-1} is at the same velocity as the source mm2 (Leurini et al. 2007). Hence the profile may result from the source multiplicity.

6. Modelling the continuum and the molecular emission of the sources

We use the modeling method described in Marseille et al. (2008) and originally developed by Hogerheijde & van der Tak (2000). It consists, in a first step, of constraining the physical structure of the source using a modeling of the SED, and in a second step of applying the obtained physical model to derive abundances of the observed species. In order to reduce the number of free

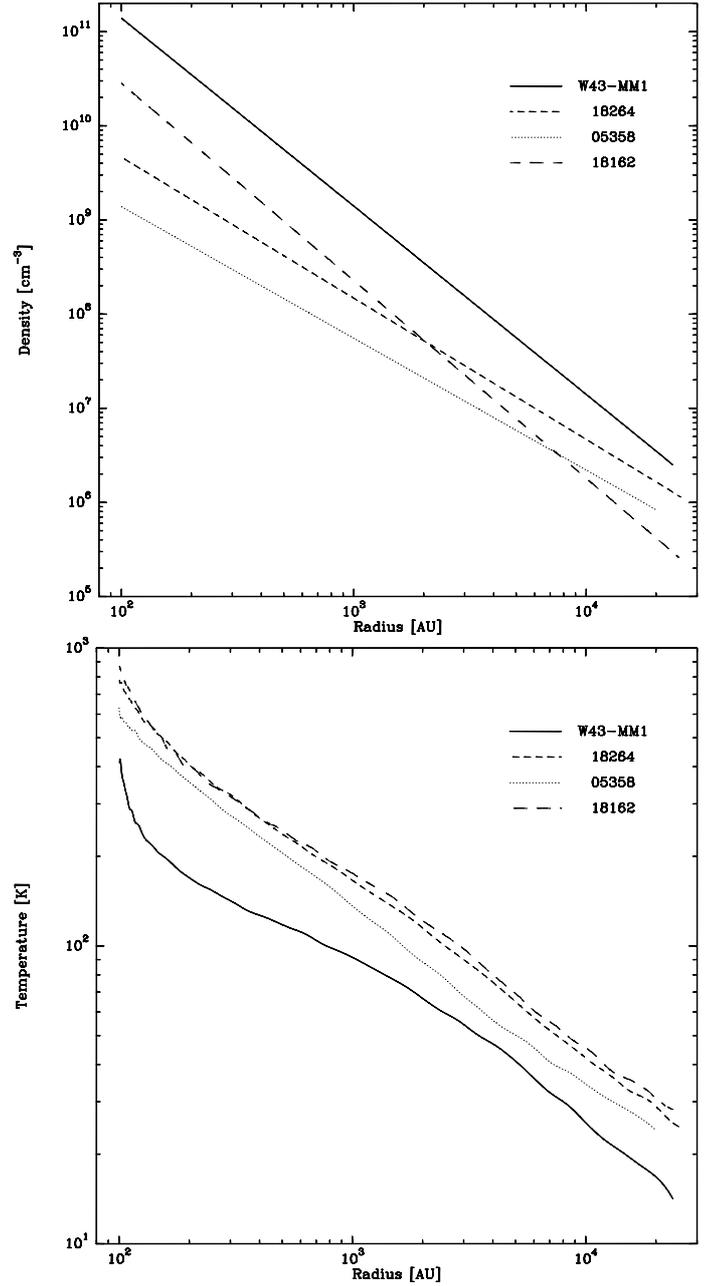


Fig. 7. Plot of the density (top) and temperature (bottom) versus the distance to the center for the 4 objects.

parameters, we restrict our modeling to a simple 1D, radial description of the sources. The assumed spherical symmetry of the sources is acceptable if we restrict our study to the molecular line emission modeling coming from cold gas ($T < 100 \text{ K}$) as Marseille et al. (2008) showed it for the massive dense core case.

6.1. SED distribution

We use the radiative transfer code MC3D (Wolf et al. 1999) in its 1D version to model the SED. The model parameters are taken from literature (distance, d , power law index, p , for density distribution, heating source temperature, T_* , and source sizes, r_{out} , the total luminosity, L). The parameter, p , which defines the density distribution through a power law in the form $\rho(r) \propto r^p$, was derived by Beuther et al. (2002c) and Motte et al. (2003) from

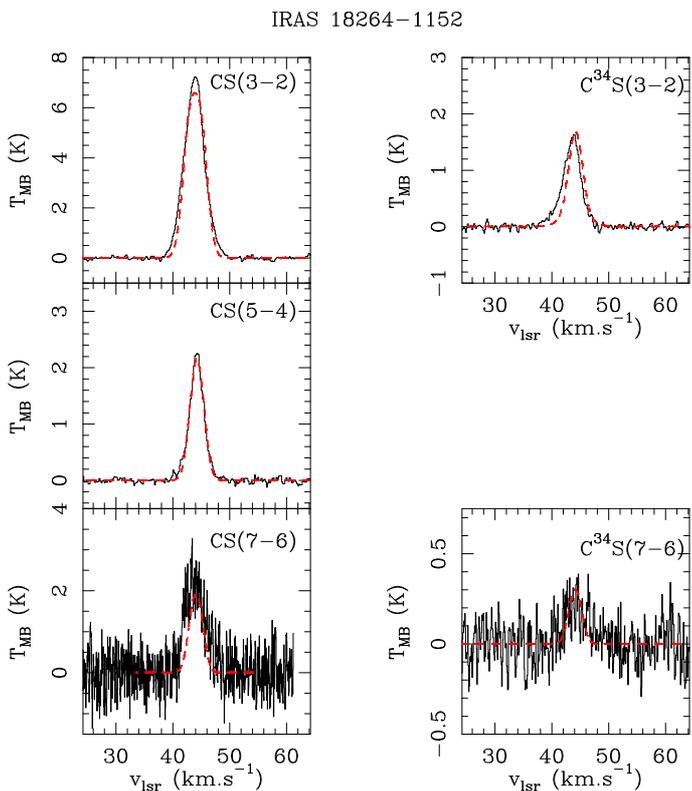


Fig. 8. Fit of the CS lines emission from IRAS18264–1152. The observed spectra are in black, fit in red.

fits to the millimeter continuum emission maps. Concerning the source size, we adopt systematically the size of the continuum mm-wave emission, deconvolved by the beam. These values are summarized in Table 4. The actual value used for the inner radius of the physical structure has virtually no observable effect on the results, we therefore adopt for the inner radius (r_{sub}) the radius of dust sublimation taken at 1500 K.

The fit of the millimeter and submillimeter SED of each source allows deriving the best temperature and distributions by iterating on the total mass which is controlled by the value of the density n_0 at reference radius r_0 taken equal to 100 AU, and on the average temperature. The values obtained, with mean densities and temperatures of the sources, are reported in Table 4 and shown in Fig. 7.

6.2. Modeling of the molecular emission

The physical description of the sources obtained from the SED modelling is then used to model the molecular emission. We use the RATRAN radiative transfer code developed by Hogerheijde & van der Tak (2000). We build data cubes with a velocity resolution equivalent to the observations, and with a high spatial resolution ($0.5''$) which are convolved with the beam sizes of the observations for a direct comparison with the observed spectra. We adopt constant abundances for the RATRAN modeling. The abundances of all species are derived independently for each observed transitions of each species. Then the different abundances obtained for each particular species are interpreted as due to change in abundance as a function of the excitation temperature and therefore as a function of depth into the sources.

The line profiles observed are also affected by gas motions, particularly through the turbulence which is mainly responsible

Table 4. Summary of results from dust continuum emission modeling (above mid-line) and from molecular line emission modeling (below mid-line). Different turbulent (v_T) or infall (v_{infall}) velocities are used to reproduce the different line emissions from each source.

Source	W43MM1 ^a	18264	05358	18162
d (kpc)	5.5	3.5	1.8	1.9
L ($10^4 L_\odot$)	2.3	1.4	0.7	2.9
T_* (10^4 K)	3.0	2.9	2.6	3.0
r_{out} (10^4 AU)	2.5	2.7	2.1	2.6
p^b	-2.0	-1.5	-1.4	-2.1
n_0^c (10^4)	40	1.0	0.3	6.1
r_{sub} (AU)	4.9	26.5	20.1	27.2
α^d	-0.54	-0.61	-0.62	-0.60
β	3.55	4.05	3.99	4.04
$\langle T \rangle$ (K)	20.0	32.6	31.1	35.6
T_{out} (K)	14.2	24.6	24.1	27.2
$\langle n \rangle$ (10^6 cm^{-3})	11.8	2.6	0.2	1
M (M_\odot)	4100	1200	400	570
v_t (km/s)	0.8-1.5	0.7-1.3	0.7-2.6	0.5-1.8
v_{infall} (km/s)	-(3.5-0.5)			

^a source description from Motte et al. 2003

^b from Beuther et al. 2002, excepted for W43MM1

^c density at 100 AU

^d $\text{Log}(T) = \alpha \text{Log}(r) + \beta$

for the line emission widths seen in massive protostars. Thus we add a turbulent velocity field characterized by a rms velocity v_T , for each transition of each molecular species (actually OCS lines are the most sensitive to the gas components in our model). In the case of W43MM1, where asymmetric profiles possibly due to infall are detected, we introduce a radial velocity field that follows a law in the form $v_{\text{inf}} = v_0 / \sqrt{r/r_{\text{out}}}$, and fit the asymmetry parameter with different values of v_0 for each transition and molecular species. Concerning the other sources, when the line emission profiles are clearly asymmetric, we are not able to reproduce those line profiles because:

- the modelling does not take into account the sub-structure (i.e. multiplicity of the massive dense cores, as for IRAS05358+3543) which is hence not reproduced correctly in the derived source model,
- outflows are not included in the model while they strongly influence the line profiles.

Some results for CS in the source IRAS18264–1152 are shown in Fig. 8.

6.3. Uncertainties

An overview of uncertainties in the modeling process that we used shows that precision on our abundance results are influenced by four main points: the signal-to-noise ratio, the total mass of the source in the model, its temperature and the populations of energy levels of the molecule studied. Furthermore, an absolute error comes from the uncertainty on the dust opacity at millimeter wavelengths, but it disappears in the context of our work where the use of the same radiative transfer code and the same modeling process keep the comparison between each sources relevant. While signal-to-noise ratio is directly known from observations, the other uncertainties have to be detailed and derived to determine how important they are.

Table 5. Molecular abundances derived for all species within the 4 sources. The temperature of the layer where most of the emission comes from is given. The column 4 gives the line whose emission is the strongest at this distance. Abundances for other sources (from the literature) are given in the columns 9, 10 and 11 for comparison. AFGL2591 is a mid-IR bright HMPO, G31.41+0.31 a hot core, and IRAS16293 a low-mass protostar.

Source		W43MM1	18264	05358	18162	AFGL2591 ^a	G31.41 ^b	16293 ^c		
Abundance ($\times 10^{-10}$)	T (K)	d^d (10^3 AU)	Line							
$\chi(\text{CS})$	60	5.9	3 – 2	36	4.0	2.3	–	100	70	5100
	75	4.9	5 – 4	30	0.26	1.3	1.0			
	96	3.3	7 – 6	160	1.1	–	4.6			
$\chi(\text{C}^{34}\text{S})$	60	5.9	3 – 2	1.8	0.32	0.27	–			
	96	3.3	7 – 6	8.0	0.50	–	0.27			
$\chi(\text{OCS})$	72	5.2	8 – 7	92	2.5	2.4	1.4	100	40	10000
	76	4.8	13 – 12	37	2.4	0.92	1.2			
	96	3.3	19 – 18	130	1.1	3.7	3.3			
$\chi(\text{OC}^{34}\text{S})$	72	5.2	8 – 7	4.6	<0.07	<0.35	<0.25			
$\chi(\text{H}_2\text{S})$	60	5.5	$1_{10} - 1_{01}$	3.0	1.3	1.2	3.1	80	≥ 30	5300
	96	3.3	$2_{20} - 2_{11}$	4.0	0.15	0.51	0.30			
$\chi(\text{H}_2^{34}\text{S})$	60	5.5	$1_{10} - 1_{01}$	<0.19	0.11	<0.13	0.21			
$\chi(\text{SO})$	51	8.7	$3_4 - 2_3$	16	1.7	3.8	4.4	100	40	17000
	62	6.4	$5_6 - 4_5$	0.90	0.48	1.1	2.4			
	75	4.8	$6_5 - 5_4$	0.70	0.57	0.8	1.8			
	96	3.3	$8_8 - 7_7$	24	0.64	–	3.6			
$\chi(^{34}\text{SO})$	51	8.7	$3_4 - 2_3$	0.80	0.11	0.33	<0.06			
	96	3.3	$8_8 - 7_7$	<4.0	<1.0	–	<0.5			
$\chi(\text{SO}_2)$	57	7.2	$5_{1,5} - 4_{0,4}$	2.0	0.42	0.62	1.7	20	120	5400
	71	5.3	$10_{0,10} - 9_{1,9}$	1.8	0.36	0.52	0.70			
	76	4.8	$11_{1,11} - 10_{0,10}$	–	0.38	–	1.76			
	112	2.7	$14_{0,14} - 13_{1,13}$	–	2.0	6.4	7.6			
	112	2.7	$18_{0,18} - 17_{1,17}$	160	<6	–	10.6			
$\chi(^{34}\text{SO}_2)$	57	7.2	$5_{1,5} - 4_{0,4}$	<0.33	<0.44	<16	<0.22			

^a Mean abundances from van der Tak et al. 2003

^b Mean abundances from Hatchell et al. 1998

^c Mean abundances from Wakelam et al. 2004a

^d indicative corresponding distance to the center for the source IRAS18162–2048

At first, mass uncertainty comes from measurements of the flux at millimeter wavelengths. Considering calibration errors, we can assume that this value is known with a 20 % accuracy. Error on temperature is directly linked to this first error, in addition with the little variation of the bolometric luminosity induced. Nevertheless, results of the radiative transfer models show that extreme cases make the temperature varying by 3 % at the maximum, and tend to compensate first error in the total mass. Even if temperature does not change a lot, its influence on energy level populations, combined with total mass (hence density) uncertainty, can be strong enough to be significant. These uncertainties are dependent on the molecule studied and the transition observed. As we noted previously, the errors can compensate themselves, especially when variation of the level energy populations of a transition are going the same way.

Finally, we derived rough values of uncertainties by testing temperature and energy level population variations induced by flux errors at millimeter range. Results show that our modeling process has a relative precision between 25 % and 30 %, depending on the considered molecular line emission. This range of values does not take into account the signal-to-noise ratio of the observations. Concerning SO_2 transitions, populations of the energy levels are varying widely, making the uncertainty increase up to 40 %, even 70 % for the $5_{1,5} - 4_{0,4}$ where populations have an opposite behaviour against temperature variations in our

models. Furthermore, we note that optically thin emission was assumed, whereas some of them are clearly thick (see Table 10). That is why abundances derived in this case must be treated as order of magnitude indicative values.

6.4. Molecular abundances: results

The derived abundances for each molecule and each source are given in Table 5 for different layers. Each layer is characterized by a temperature (and of course by a density, but the population of high-energy levels is sensitive to the temperature for dense gas tracers). We also give the strongest line emission in that layer (but of course lines are excited over several layers). Results are plotted in Fig. 9 versus the energy of the upper level of the transition. Obviously emission lines coming from warmer regions (more than 120 K), *e.g.* involving higher upper energy levels, are missing to probe the most inner regions.

The H_2S abundance is roughly the same in the 4 objects studied ($1.6 - 3.6 \cdot 10^{-10}$) in the outer region ($T \sim 60$ K), showing more variation ($0.16 - 4 \cdot 10^{-10}$) in the warmer inner parts ($T \sim 100$ K): in IRAS18264–1152, IRAS05358+3543 and IRAS18162–2048, the abundance is one order of magnitude lower while it remains constant in W43MM1.

An obvious trend is seen for SO_2 , likely because the energy ladder of this molecule is best sampled. Its abundance is roughly

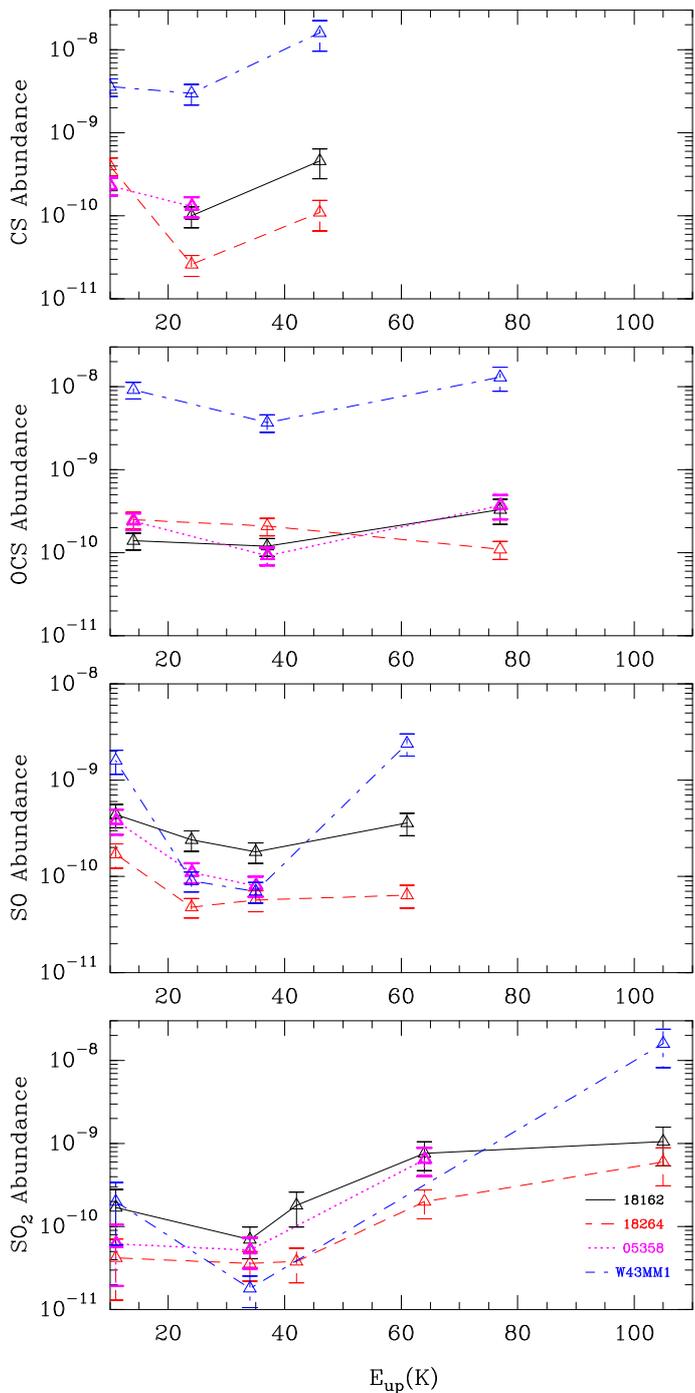


Fig. 9. Abundances of CS, OCS, SO and SO₂ (relative to H₂) versus the energy of the upper level of the transition given in Table 5 for the 4 sources.

constant (or decreases for W43MM1) in colder layers ($T < 80$ K, e.g. $> 5 \cdot 10^3$ AU for the source IRAS18162–2048, and $E_{\text{up}} < 35$ K), then increases by one order of magnitude in warmer layers (hence outer to more inner parts), e.g. $\sim 3 \cdot 10^3$ AU for the same source. Concerning all the other molecules, as fewer transitions have been observed, i.e. the energy ladder is not completely covered, no obvious trends are seen. In spite of an insufficient energy coverage, the derived OCS abundance might weakly follow the same trend as seen for CS, except in the source IRAS18264–1152. We note that the sources IRAS18264–1152

and IRAS05358+3543 exhibit the same abundance variations for SO and SO₂.

In the three less evolved objects, CS and OCS are the most abundant species in the colder outer region while it is SO for IRAS18162–2048 (for that source OCS is less abundant than SO and no CS 3–2 has been observed), SO₂ being the least abundant.

Reproducing the whole CS and C³⁴S emission is impossible with the same isotopic ratio for all the sources. The derived isotopic ratio [³²S/³⁴S] is 9 – 12, 10 – 15, 15 – 20 and 20 respectively for IRAS05358+3543, IRAS18264–1152, IRAS18162–2048 and W43MM1. The Solar system abundance ratio is 22.5 (Kahane et al. 1988), but Chin et al. (1996) found ratios increasing from 14 to 35 with the distance to the Galactic center, but this is in contradiction with Nilsson et al. (2000) who derived a ratio of 11 towards the very distant source W49N.

7. Discussion

7.1. W43MM1: a special case

W43MM1 is clearly different from the other sources, with the highest abundances (relative to H₂) of CS, OCS, SO (except in the flattening region); the SO₂ abundance in W43MM1 is the highest in the warmer inner part. Moreover the plots (see Fig. 10 and 11) of the CS and OCS molecular ratios relative to H₂S underline this difference, showing high ratios for that source compared to the others.

The reason might be that W43MM1 though being a very young source has already developed a hot core with temperatures larger than 200 K (e.g. CH₃CN lines observed by Motte et al. 2003). This hot core region might also be at the origin of the unidentified lines described in Sect. 4.1. The presence of this hot core might also explain the high abundance of H₂S and OCS molecules which evaporation from grain surface could be important (Wakelam et al. 2004a), and consequently the high abundance of SO. The CS case is different because this molecule is already present in the gas before the evaporation. Actually the CS chemistry is closely linked to the atomic carbon abundance which might be higher in W43MM1 than in the other sources.

The very high SO₂ abundance close to the center of W43MM1 may be due to strong shocks occurring in the inner part of the envelope. The fact that W43MM1 is a very young source (as indicated by the possibly detected infall, see Sect. 5.2) suggests that this massive dense core harbors one or several high-mass protostars with powerful outflows, which might induce shocked regions. Strong shocks can convert SO into SO₂ (see Hatchell et al. 1998), leading then to a ratio of unity, as observed in the other sources where the process has already taken place, transforming the ratio all across the envelope. Hence shock chemistry might contribute to the SO₂ formation process.

Actually, IRAS05358+3543 harbors a hot core too (Leurini et al. 2007), but very likely more compact than the one of W43MM1 (Motte et al. 2003), hence more diluted in the beam of our observations. Moreover, Leurini et al. (2007) suggested that the IRAS05358+3543 hot core might not produce a very rich chemistry (indeed, these authors underlined differences between its molecular spectrum and the one of typical massive hot cores).

7.2. Molecular ratios as a diagnostic tool of evolution ?

Sulphur is released into the gas phase in the form of H₂S, which is subsequently transformed into SO and later into SO₂ via neutral-neutral reaction at 100 K on time scales of $\sim 10^3$ yr

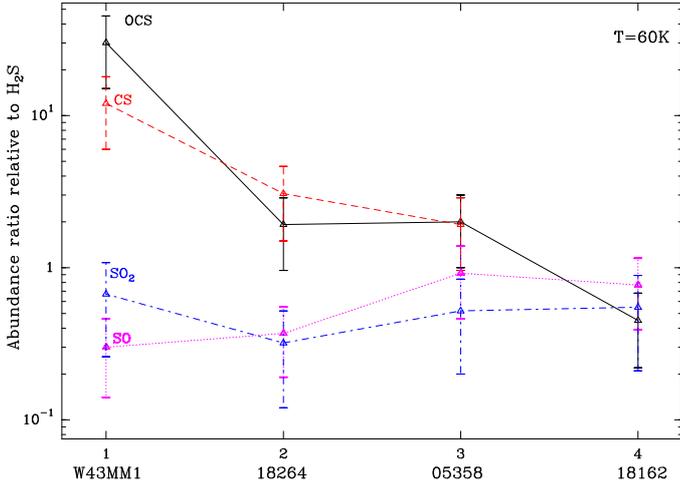


Fig. 10. Abundance ratio of OCS, CS, SO and SO_2 relative to H_2S for each source in the layer at $T = 60$ K. The sources are ordered according to the SED classification.

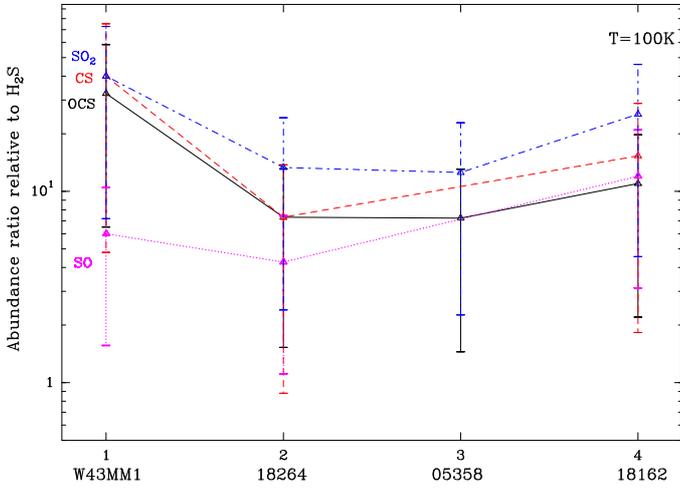


Fig. 11. Abundance ratio of OCS, CS, SO and SO_2 relative to H_2S for each source in the layer at $T = 100$ K. The sources are ordered according to the SED classification.

(Wakelam et al. 2004a). The initial destruction of H_2S by H_3O^+ is even more efficient in the high-mass objects than in low-mass protostars, as water is more abundant here (see van der Tak et al. 2006). At higher temperature ($T \geq 300$ K), H_2S can be produced again. Once in the gas phase, OCS is destroyed later than H_2S (by S^+ and cosmic rays). CS destruction at low temperature produces SO and SO_2 too, while CS is produced again at higher temperature from OCS. The time dependence of these process might allow us to see an evolution of the abundance along the protostar evolutionary track.

Actually no evolution is obviously seen for the abundances relative to H_2 , even if they differ significantly from source to source. Nevertheless, W43MM1 shows larger abundances of CS, OCS and SO compared to IRAS18264–1152 and IRAS05358+3543 (see Sect. 6.4).

We have investigated possible correlations of the molecular abundance ratios with the order of evolution of our 4 objects for two different layers: one around $T = 60 - 70$ K and a more inner one around $T = 100$ K. To be coherent, we only consider values derived for the same layer, i.e. same temperature (*e.g.* transitions CS 5 – 4 and OCS 13 – 12 with $E_{\text{up}} = 24 - 37$ K, hence mostly

excited in the 75 K layer). Figures 10, 11, 12 and 13 show that some global trend appears, either a decrease or an increase with the evolution, but depending on the layer.

We first compare the molecular abundances relative to H_2S whose abundance is assumed to remain globally constant during the studied evolutionary period and hence comparable from source to source. In the colder region ($T = 60$ K, Fig. 10), the $[\text{OCS}/\text{H}_2\text{S}]$ ratio is clearly decreasing from W43MM1 to IRAS18162–2048 by a factor 10. This trend is also visible for CS. The $[\text{SO}/\text{H}_2\text{S}]$ and $[\text{SO}_2/\text{H}_2\text{S}]$ ratios remain roughly constant; a small increase might actually be present for SO. In the inner, hence warmer, part of the envelope ($T = 100$ K, Fig. 11), drawing conclusions is more difficult, because not all 4 sources were observed in the same transitions. Moreover, again, W43MM1 stands out as it shows the highest ratio (except for SO), independently of the trend seen for the three other objects. Actually, according to the temperature and density distributions derived by our model (see Fig. 7), the 100 K layer for W43MM1 is closer to the center of the massive core than in the other sources, and moreover corresponds to a higher density. But the other reason could be that the hot core is dominating. Hence, considering the three other sources, an increase of the different ratios relative to H_2S from IRAS181264 to IRAS18162–2048 is seen. Comparing the 60 and 100 K regions, the main difference is for OCS and CS: ratios are decreasing at $T = 60$ K, but increasing at higher temperature.

Relative to OCS (Fig. 12), the abundance of CS does not show any trend, neither at 76 K nor at 96 K. At 70 – 75 K, the $[\text{SO}/\text{OCS}]$ and $[\text{SO}_2/\text{OCS}]$ ratios increase by at least one order of magnitude along the derived evolutionary track. At higher temperature, hence in the inner regions, the same trend is observed for the $[\text{SO}/\text{OCS}]$ ratio, while $[\text{SO}_2/\text{OCS}]$ remains approximately constant.

For both probed layers, the $[\text{CS}/\text{SO}]$ and $[\text{SO}_2/\text{SO}]$ ratios decrease (Fig. 13), the variation being more important at 60 K.

Cross-comparison of the plots for outer regions reveals that the OCS (and maybe CS) abundance (relative to H_2S) decreases while the SO and SO_2 relative abundance (compared to other molecules) increase along the object evolution. This trend is less obvious at higher temperature, maybe because in these regions the H_2S transformation process into SO and SO_2 (Wakelam et al. 2004a,b) is becoming less efficient, as it gets close to the completion: the *new* SO and SO_2 molecules have already been produced in the inner parts. This hypothesis is strengthened by the larger SO_2 abundance measured in all the objects for the larger temperatures, *i.e.* in warmer environments. Nevertheless, any conclusions for inner parts are tricky, because of the incomplete energy ladder coverage of our observations and so the lack of very high energy transitions.

7.3. Comparison with previous studies

A comparison between abundances derived for low- and high-mass protostars is not straightforward, because of the different composition of the ices (from which H_2S evaporates) and of the different physical conditions (density and temperature; *e.g.* density can be two orders of magnitude higher for the same temperature) as stressed by Wakelam et al. (2004a). Nevertheless, Table 5 also gives abundances for AFGL2591 (van der Tak et al. 2003), a *mid-IR bright* HMPO (L_{bol} 2 – 10 times larger, warmer SED with higher F_{12} and F_{35}/F_{total}), hence more evolved object, and G31.41+0.31 (Hatchell et al. 1998), a massive hot core and IRAS16293 (Wakelam et al. 2004a). We stress that those values are mean abundances across the whole envelope. Values

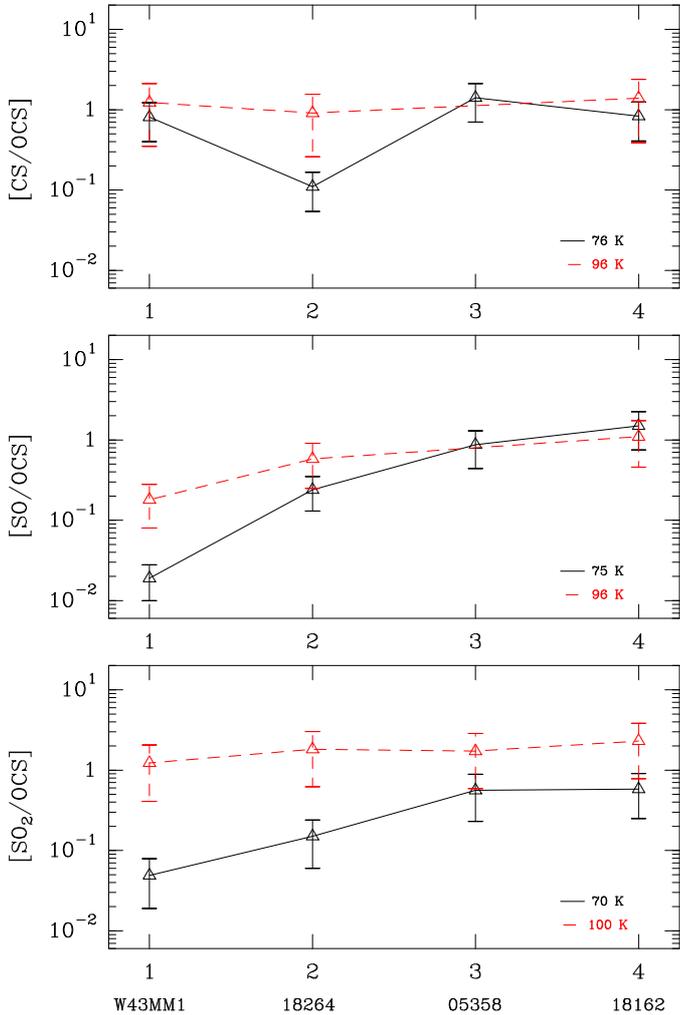


Fig. 12. Abundance ratio of CS, SO and SO₂ relative to OCS for each source in two different layers. The sources are ordered according to the sED classification.

for AFGL2591 and G31.41 differ a lot for H₂S and SO₂ (by at least a factor 10) but are comparable for CS, OCS, and SO to the abundances found in W43MM1. The other sources from our sample exhibit abundances one or two order of magnitude lower. Abundances in low-mass protostar are 100 – 1000 times larger. Clearly the same set of lines has to be observed towards these sources and the same modelling applied in order to be able to be compared with our sample.

The sulphur chemistry was studied by van der Tak et al. (2003) in the envelopes of more evolved massive protostellar object, *mid-IR bright* HMPOs. The abundances they derived are 10 – 100 times higher than ours (see Table 5). They concluded that shock chemistry is unlikely to contribute and that OCS is a major sulphur carrier in the ices. The molecular ratios computed from their work do not show significant variations from source to source.

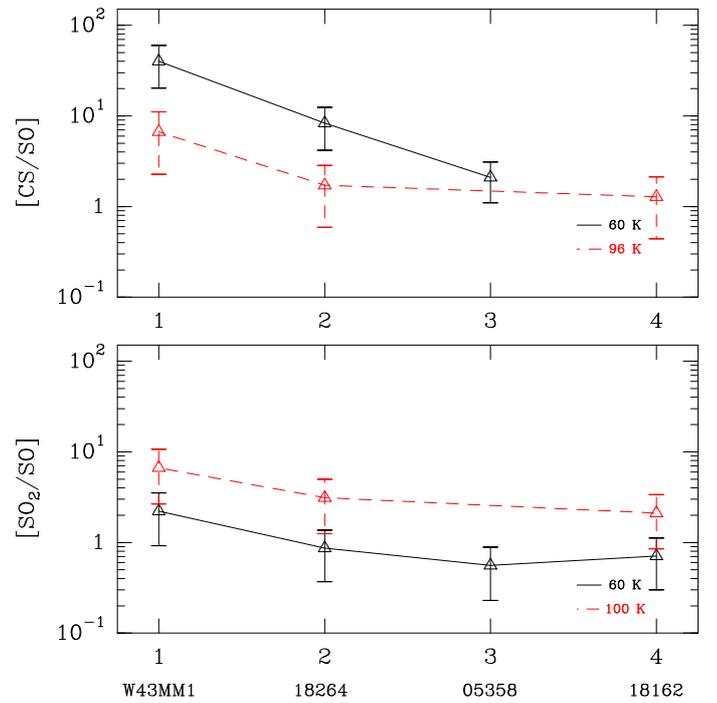


Fig. 13. Abundance ratio of CS and SO₂ relative to SO for each source in two different layers. The sources are ordered according to the sED classification.

From our work, the total abundance of sulphur (CS+SO+SO₂+H₂S+OCS) can be estimated to be $2 \cdot 10^{-9} - 5 \cdot 10^{-8}$, several orders of magnitude lower than the corresponding solar abundance ($3.4 \cdot 10^{-5}$) and the value derived in the low-mass hot core IRAS16293 by Wakelam et al. (2004a) ($2.8 \cdot 10^{-6}$). It is likely that we do not probe the very inner parts of the protostars where the S-bearing molecules are fully evaporated from the grain mantles. Hypothesis to explain such depletion of sulphur (including the one previously mentioned) will be explored in another paper on the chemistry.

8. Conclusion

We have presented here new observations of sulfur-bearing species toward 4 massive dense cores. Different gas components, revealing outflows or multiplicity, are detected in IRAS05358+3543, IRAS18264–1152 and IRAS18162–2048. A strong infall of more than 2 km s^{-1} towards W43MM1 might be observed, leading to an impressive kinematic mass infall rate. W43MM1 study shows that hot core may appear earlier than expected in the evolution.

An evolutionary classification derived from the calculated SEDs is proposed, from W43MM1 to IRAS18162–2048, and is likely to be observed in the molecular abundances too. More precisely, molecular ratios like [OCS/H₂S], [CS/H₂S], [SO/OCS], [SO₂/OCS], [CS/SO] and [SO₂/SO], using low energy transitions, might be good indicators of evolution depending on layers probed by the observed molecular transitions: obvious trends along the massive core evolution are seen for colder outer regions at 60 K, but drawing definitive conclusions is more difficult for the inner regions. Observations of molecular emission from warmer layers, hence implying higher upper energy levels are mandatory to include. A follow-up with APEX telescope should be made to have access to these higher frequencies. Of

course, the source multiplicity due the distance is problematic and only ALMA will provide a definitive answer.

Nevertheless, a specific chemical modelling will be done for these sources in a forthcoming paper (Wakelam et al., in preparation) in order to explain the observed molecular ratios and to try to date the studied objects.

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Online Material

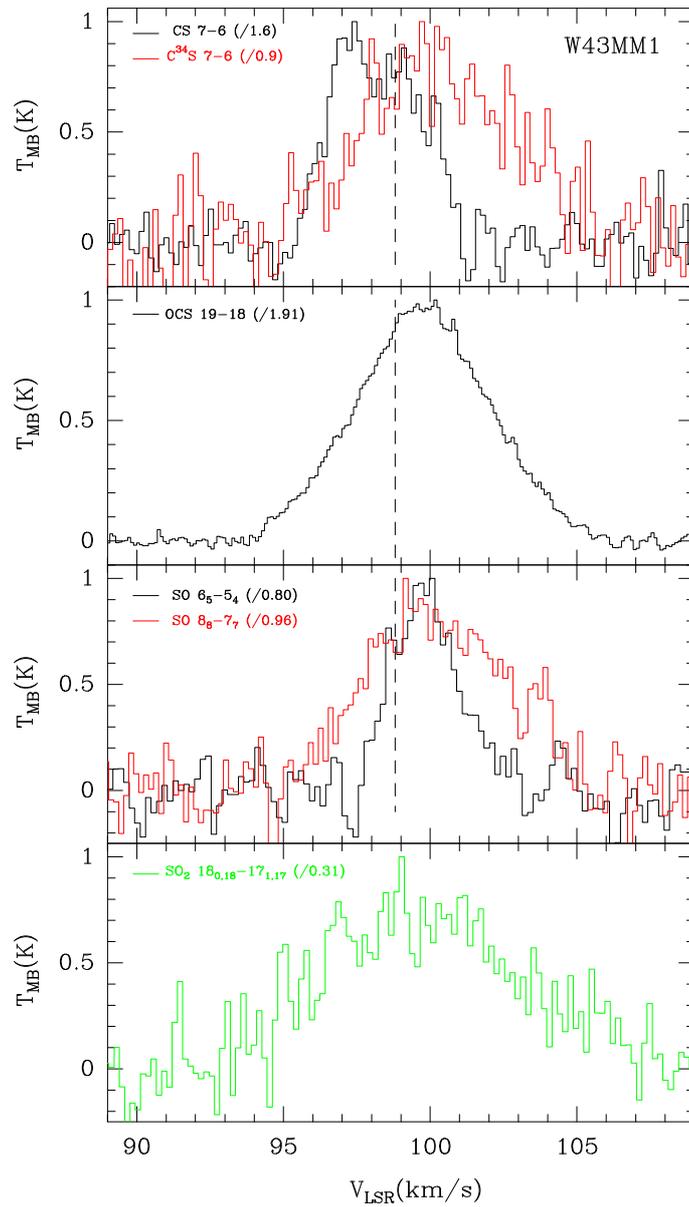


Fig. 14. Normalized emission of CS, H_2S , OCS, SO, SO_2 (and isotopic species) lines from W43MM1. Spectra velocity resolutions are $0.10\text{-}0.19 \text{ km s}^{-1}$. The dashed line shows the source LSR velocity.

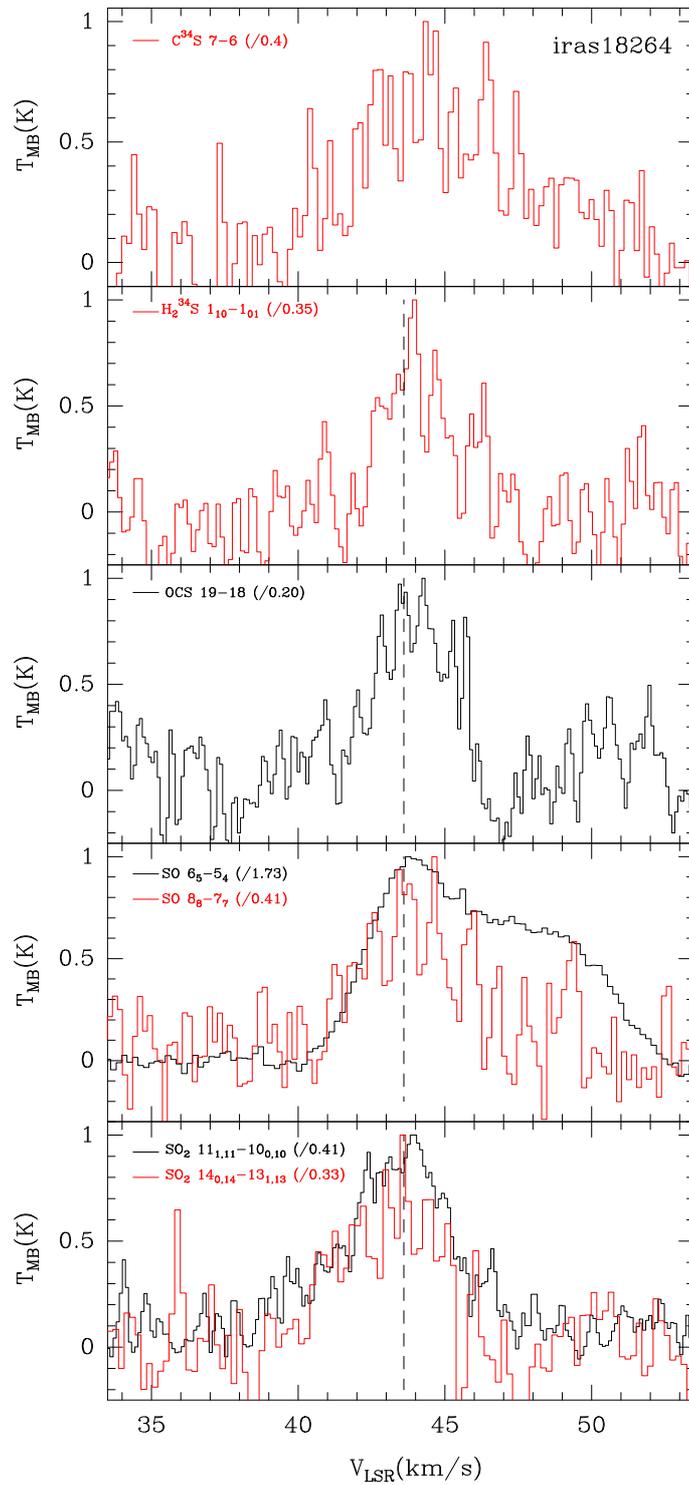


Fig. 15. Normalized emission of CS, H₂S, OCS, SO, SO₂ (and isotopic species) lines from IRAS18264–1152. Spectra velocity resolutions are 0.10-0.19 km s⁻¹. The dashed line shows the source LSR velocity.

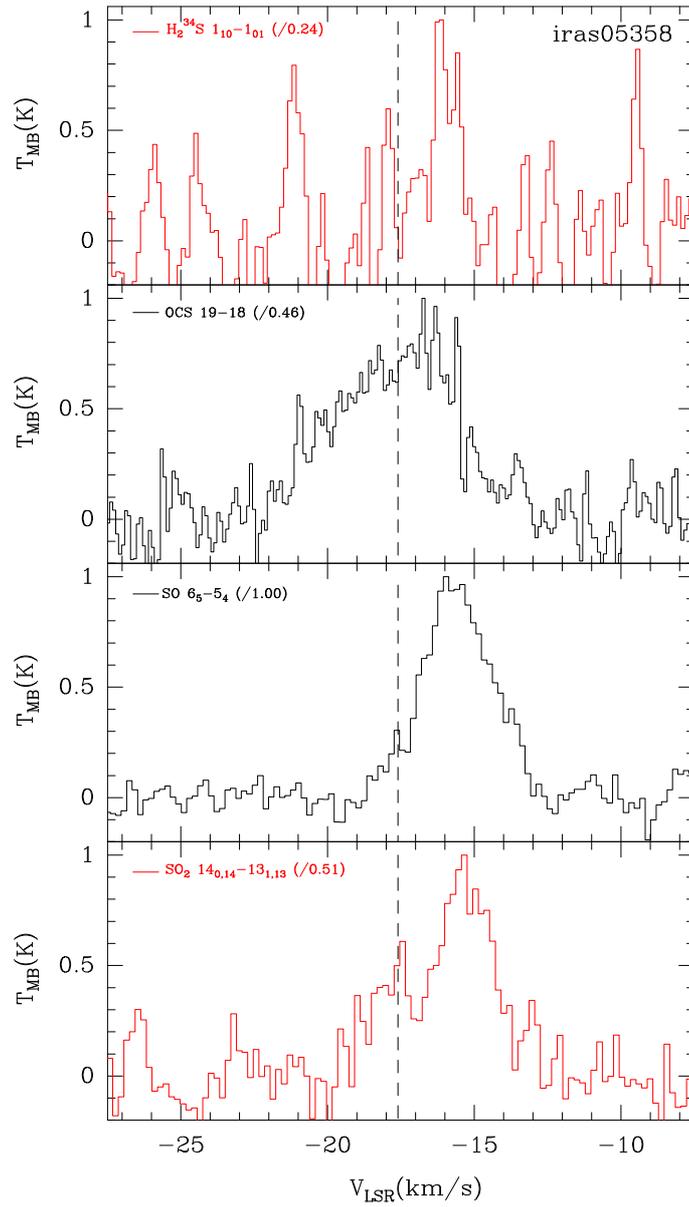


Fig. 16. Normalized emission of CS, H₂S, OCS, SO, SO₂ (and isotopic species) lines from IRAS05358+3543. Spectra velocity resolutions are 0.10-0.19 km s⁻¹. The dashed line shows the source LSR velocity.

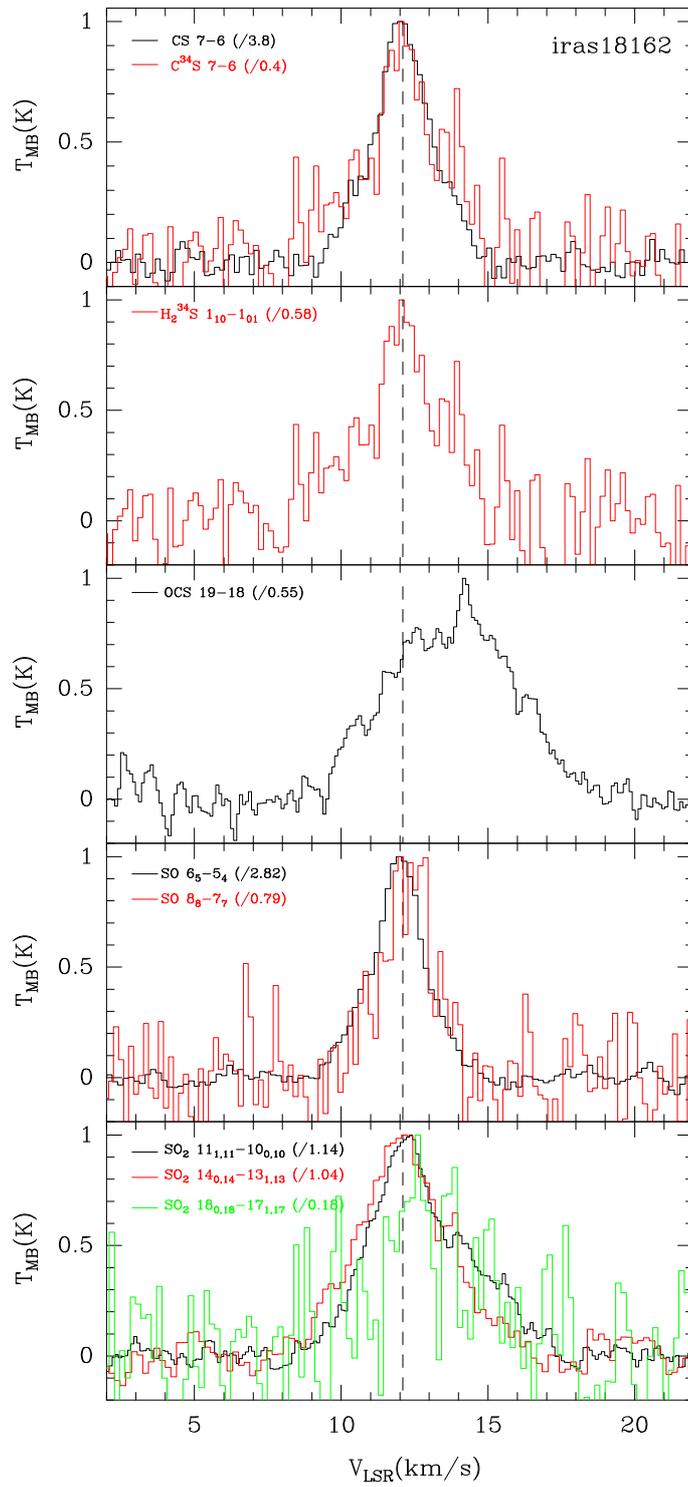


Fig. 17. Normalized emission of CS, H₂S, OCS, SO, SO₂ (and isotopic species) lines from IRAS18162–2048. Spectra velocity resolutions are 0.10-0.19 km s⁻¹. The dashed line shows the source LSR velocity.

Table 6. Observed line emissions parameters for W43MM1. Widths ($\Delta v_{3\sigma}$ is the linewidths at 3σ level; $\Delta v_{1/2}$ is the half power linewidth) and line fluxes are derived from gaussian fits (several components) made with CLASS software. For the non detection, 1σ upper limits are given.

Species	Transition	Δv km/s	T_{mb} K	σ mK	$\int T_{\text{mb}} \delta v$ K.km/s	$\Delta v_{3\sigma}$ km/s	$\Delta v_{1/2}$ km/s	comment
CS	3-2	9.3(0.2)	4.01	36	22.90(0.15)	15.69	9.21	^a
	5-4	9.68(0.04)	6.85	62	61.6(0.3)	14.50	9.36	^a
	7-6	4.2(0.3)	1.2	255	5.4(0.7)	4.5	4.5	^b
C ³⁴ S	3-2	5.69(0.02)	2.12	42	12.96(0.06)	11.23	6.02	
	7-6	6.1(0.3)	1.05	269	4.8(0.2)	2.7	5.6	
SO	3 ₄ - 2 ₃	6.10(0.01)	2.66	23	17.52(0.03)	13.24	6.62	
	5 ₆ - 4 ₅	4.40(0.06)	1.14	65	5.10(0.07)	7.22	4.51	
	6 ₅ - 5 ₄	2.6(0.1)	0.8	85	2.01(0.09)	3.47	2.54	
	8 ₈ - 7 ₇	5.4(0.3)	0.6	184	2.8(0.1)	5.4	5.4	weak det.
³⁴ SO	3 ₄ - 2 ₃	5.6(0.1)	0.39	26	2.42(0.04)	10.22	5.52	
	8 ₈ - 7 ₇			197	< 0.009			no det.
SO ₂	5 _{1,5} - 4 _{0,4}	5.05(0.1)	0.52	38	2.33(0.05)	8.63	3.91	
	10 _{0,10} - 9 _{1,9}	5.1(0.3)	0.33	43	1.41(0.06)	8.02	4.0	
	11 _{1,11} - 10 _{0,10}			47	<0.006			no det.
	14 _{0,14} - 13 _{1,13}			60	<0.01			no det.
	18 _{0,18} - 17 _{1,17}	7.8(0.3)	0.23	80	1.89(0.07)	7.8	7.8	
³⁴ SO ₂	28 _{4,24} - 28 _{3,25}			60	<0.01			no det.
	5 _{1,5} - 4 _{0,4}			32	<0.006			no det.
OCS	8 - 7	6.51(0.02)	0.90	11	6.20(0.02)	13.10	6.55	^a
	13 - 12	4.57(0.03)	1.58	39	7.33(0.05)	8.72	4.51	
	19 - 18	5.37(0.02)	1.92	35	10.46(0.04)	11.03	5.01	
OC ³⁴ S	8 - 7	7.26(0.03)	0.14	7	1.13(0.01)	13.63	6.92	
H ₂ S	1 _{1,0} - 1 _{0,1}	9.1(0.2)	1.06	72	12.52(0.6) ^a	12.50	2.76	^a
	2 _{2,0} - 2 _{1,1}	4.15(0.04)	1.26	45	5.40(0.05)	7.62	4.11	
H ₂ ³⁴ S	1 _{1,0} - 1 _{0,1}			72	<0.01			no det.

^a self-absorption at v_{source} ^b line blend with H₂CO line from image band.

Table 7. Observed line emissions parameters for IRAS18264–1152. Widths ($\Delta v_{3\sigma}$ is the linewidths at 3σ level; $\Delta v_{1/2}$ is the half power linewidth) and line fluxes are derived from gaussian fits (several components) made with CLASS software. For the non detection, 1σ upper limits are given.

Species	Transition	Δv km/s	T_{mb} K	σ mK	$\int T_{\text{mb}}\delta v$ K.km/s	$\Delta v_{3\sigma}$ km/s	$\Delta v_{1/2}$ km/s	comment
CS	3-2)	4.19(0.01)	7.2	54	31.49(0.07)	10.28	4.01	
	5-4	2.97(0.03)	2.26	45	6.81(0.05)	7.32	2.81	
	7-6	3.2(0.8)?	0.6?	500	1.9(0.5)?	?	?	^b
C ³⁴ S	3-2	3.67(0.04)	1.64	42	6.02(0.05)	8.32	3.41	
	7-6	5.1(0.5)	0.34	111	1.1(0.1)	3.7	4.7	tentative det.
SO	3 ₄ – 2 ₃	3.27(0.02)	3.11	44	10.38(0.05)	7.32	3.21	
	5 ₆ – 4 ₅	2.98(0.02)	2.33	53	7.08(0.05)	6.42	2.81	
	6 ₅ – 5 ₄	6.2(0.1)	1.72	45	11.8(0.2)	11.36	7.62	^a
	8 ₈ – 7 ₇	4.1(0.4)	0.44	116	1.3(0.1)	2.2	4.8	weak det.
³⁴ SO	3 ₄ – 2 ₃	3.02(0.2)	0.19	39	0.60(0.04)	4.01	4.01	^d
	8 ₈ – 7 ₇			132	< 0.006			no det.
SO ₂	5 _{1,5} – 4 _{0,4}	3.30(0.3)	0.24	33	0.91(0.05)	5.91	5.59	
	10 _{0,10} – 9 _{1,9}	2.9(0.2)	0.19	34	0.50(0.03)	3.03	3.03	weak line
	11 _{1,11} – 10 _{0,10}	4.1(0.1)	0.40	41	1.56(0.04)	7.02	3.31	
	14 _{0,14} – 13 _{1,13}	3.9(0.3)	0.34	59	0.99(0.07)	3.95	3.95	
	18 _{0,18} – 17 _{1,17}			79	< 0.004			no det.
	28 _{4,24} – 28 _{3,25}			63	< 0.01			no det.
³⁴ SO ₂	5 _{1,5} – 4 _{0,4}			64	< 0.01			no det.
OCS	8 – 7	3.73(0.1)	0.18	5	0.71(0.01)	9.19	3.51	
	13 – 12	3.3(0.1)	0.41	46	1.35(0.05)	4.13	3.58	
	19 – 18	2.7(0.1)	0.20	34	0.49(0.03)	3.21	3.21	bad data
OC ³⁴ S	8 – 7			4	< 0.001			no det.
H ₂ S	1 _{1,0} – 1 _{0,1}	3.63(0.04)	1.94	59	7.32(0.06)	7.22	3.61	
	2 _{2,0} – 2 _{1,1}	2.5(0.3)	0.14	28	0.33(0.03)	5.51	2.81	^c
H ₂ ³⁴ S	1 _{1,0} – 1 _{0,1}	2.7(0.1)	0.35	60	0.68(0.06)	3.72	3.72	

^a self-absorption at v_{source} ^b line blend with H₂CO line from image band.^c unidentified line @ 34.87 km/s (216.716 GHz).^d + other line @ 29.1 km s⁻¹ (135.78223 GHz), $T_{\text{mb}} = 0.14$ K, $\delta v = 1.1$ km s⁻¹, $\int T_{\text{mb}}\delta v = 0.17$ K·km·s⁻¹

Table 8. Observed line emissions parameters for IRAS05358+3543. Widths ($\Delta v_{3\sigma}$ is the linewidths at 3σ level; $\Delta v_{1/2}$ is the half power linewidth) and line fluxes are derived from gaussian fits (several components) made with CLASS software. For the non detection, 1σ upper limits are given.

Species	Transition	Δv km/s	T_{mb} K	σ mK	$\int T_{\text{mb}} \delta v$ K.km/s	$\Delta v_{3\sigma}$ km/s	$\Delta v_{1/2}$ km/s	comment
CS	3-2	5.54(0.06)	7.92	35	29.75(0.02)	11.07	2.77	^a
	5-4	3.60(0.10)	5.14	59	16.64(0.07)	7.37	3.31	^a
	7-6							no data
C ³⁴ S	3-2	4.30(0.16)	1.59	24	4.10(0.01)	7.12	2.51	^a
	7-6							no data
SO	3 ₄ - 2 ₃	3.97(0.05)	2.42	45	11.46(0.01)	8.42	4.71	^a
	5 ₆ - 4 ₅	3.31(0.05)	2.29	63	7.09(0.06)	6.62	2.91	^a
	6 ₅ - 5 ₄	2.81(0.08)	0.99	60	2.82(0.06)	4.54	2.81	^a
	8 ₈ - 7 ₇							no data
³⁴ SO	3 ₄ - 2 ₃	4.47(0.35)	0.26	50	1.1	4.13	4.4	^a
	8 ₈ - 7 ₇							no data
SO ₂	5 _{1,5} - 4 _{0,4}	4.9(0.2)	0.31	36	1.48(0.05)	5.91	4.55	
	10 _{0,10} - 9 _{1,9}	3.9(0.4)	0.24	49	0.70(0.06)	1.90	4.81	
	11 _{1,11} - 10 _{0,10}			55	<0.01			no det.
	14 _{0,14} - 13 _{1,13}	3.89(0.3)	0.50	68	1.49(0.09)	4.11	3.41	
	18 _{0,18} - 17 _{1,17}			45	<0.008			no data
³⁴ SO ₂	28 _{4,24} - 28 _{3,25}			45	<0.008			no det.
	5 _{1,5} - 4 _{0,4}			25	<0.005			no det.
OCS	8 - 7	4.69(0.05)	0.27	10	1.29(0.01)	12.9	5.01	^a
	13 - 12	3.08(0.05)	0.20	27	0.58(0.05)	3.11	3.01	^a
	19 - 18	5.2(0.2)	0.46	58	2.01(0.06)	5.61	5.51	^a
OC ³⁴ S	8 - 7			10	<0.003			no det.
H ₂ S	1 _{1,0} - 1 _{0,1}	4.8(0.15)	2.56	53	9.36(0.15)	8.46	3.03	^a
	2 _{2,0} - 2 _{1,1}	2.98(0.15)	0.37	44	0.89(0.04)	3.91	3.41	^a
H ₂ ³⁴ S	1 _{1,0} - 1 _{0,1}	1.2(0.3)	0.24	77	0.25(0.05)	0.83	1.01	very weak line ^b

^a self-absorption at v_{source} ^b detected at 2σ with two peaks @ -15.57 and -16.21 km/s

Table 9. Observed line emissions parameters for IRAS18162–2048. Widths($\Delta v_{3\sigma}$ is the linewidths at 3σ level; $\Delta v_{1/2}$ is the half power linewidth) and line fluxes are derived from gaussian fits (several components) made with CLASS software. For the non detection, 1σ upper limits are given.

Species	Transition	Δv km/s	T_{mb} K	σ mK	$\int T_{mb}\delta v$ K.km/s	$\Delta v_{3\sigma}$ km/s	$\Delta v_{1/2}$ km/s	comment
CS	3-2							no obs.
	5-4	2.93(0.01)	7.41	38	22.10(0.03)	6.78	2.91	
	7-6	2.46(0.04)	4.05	237	9.3(0.1)	4.08	2.14	
C ³⁴ S	3-2							no obs.
	7-6	2.1(0.3)	0.47	116	0.87(0.06)	1.17	2.63	
SO	3 ₄ – 2 ₃	2.24(0.01)	5.27	40	12.00(0.04)	6.46	2.10	
	5 ₆ – 4 ₅	2.20(0.01)	5.22	45	11.31(0.03)	5.42	4.84	
	6 ₅ – 5 ₄	2.24(0.03)	2.80	79	6.25(0.08)	4.52	1.78	
	8 ₈ – 7 ₇	2.2(0.2)	1.04	230	1.7(0.1)	1.1	1.7	
³⁴ SO	3 ₄ – 2 ₃			38	<0.007			no det.
	8 ₈ – 7 ₇			123	< 0.006			no det.
SO ₂	5 _{1,5} – 4 _{0,4}	3.3(0.1)	0.72	34	1.86(0.04)	6.46	1.68	
	10 _{0,10} – 9 _{1,9}	1.69(0.07)	0.43	33	0.75(0.02)	2.39	1.75	^a
	11 _{1,11} – 10 _{0,10}	3.86(0.08)	1.14	35	4.20(0.07)	7.88	3.49	
	14 _{0,14} – 13 _{1,13}	3.63(0.09)	1.02	59	3.71(0.07)	5.81	3.68	
	18 _{0,18} – 17 _{1,17}	1.2(0.5)	0.13	75	0.16(0.05)		3.7?	tentative det.
	28 _{4,24} – 28 _{3,25}			42	<0.007			no det.
³⁴ SO ₂	5 _{1,5} – 4 _{0,4}			38	<0.007			no det.
OCS	8 – 7	3.5(0.1)	0.12	8	0.40(0.01)	7.17	3.10	
	13 – 12	4.7(0.5)	0.23	51	0.75(0.06)	2.85	6.26	
	19 – 18	5.12(0.08)	0.55	33	2.53(0.04)	7.55	4.55	
OC ³⁴ S	8 – 7			9	<0.003			no det.
H ₂ S	1 _{1,0} – 1 _{0,1}	3.46(0.02)	2.92	50	10.00(0.05)	8.0	3.36	^a
	2 _{2,0} – 2 _{1,1}	3.2(0.3)	0.24	24	0.78(0.07)	4.26	2.97	^b
H ₂ ³⁴ S	1 _{1,0} – 1 _{0,1}	2.3(0.1)	0.60	65	1.15(0.06)	2.58	1.55	

^a self-absorption at v_{source}

^b unidentified lines @ 216.701026 and 216.71.6 GHz (25 and 4 km/s)

Table 10. Opacities derived from the modelling of the molecular emission of the sources. "ND" stands for no data.

Lines	W43-MM1	18264	05358	18162
CS 3-2	52.0	1.6	0.45	ND
CS 5-4	65.0	0.31	0.81	0.67
CS 7-6	300	0.94	ND	2.8
C ³⁴ S 3-2	2.8	0.18	0.09	ND
C ³⁴ S 7-6	16.0	0.51	ND	0.41
OCS 8-7	6.0	0.07	0.04	0.06
OCS 13-12	2.6	0.1	0.06	0.1
OCS 19-18	4.9	0.12	0.07	0.2
OC ³⁴ S 8-7	0.4	0.03	0.02	0.05
H ₂ S 1 _{1,0} – 1 _{0,1}	4.2	0.53	0.21	3.9
H ₂ S 2 _{2,0} – 2 _{1,1}	3.3	0.13	0.08	0.15
H ₂ ³⁴ S 1 _{1,0} – 1 _{0,1}	0.36	0.11	0.04	0.48
SO 3 ₄ – 2 ₃	6.3	0.25	0.32	0.36
SO 5 ₆ – 4 ₅	0.72	0.21	0.15	0.39
SO 6 ₅ – 5 ₄	0.52	0.21	0.10	0.28
SO 8 ₈ – 7 ₇	6.8	0.33	ND	0.59
³⁴ SO 3 ₄ – 2 ₃	0.45	0.05	0.11	0.89
³⁴ SO 8 ₈ – 7 ₇	1.6	0.26	ND	2.9
SO ₂ 5 _{1,5} – 4 _{0,4}	0.42	0.06	0.03	0.08
SO ₂ 10 _{0,10} – 9 _{1,9}	0.33	0.06	0.03	0.04
SO ₂ 11 _{1,11} – 10 _{0,10}	ND	0.11	ND	0.13
SO ₂ 14 _{0,14} – 13 _{1,13}	ND	0.21	0.23	0.42
SO ₂ 18 _{0,18} – 17 _{1,17}	6.0	0.24	ND	0.22
³⁴ SO ₂ 5 _{1,5} – 4 _{0,4}	0.18	0.61	0.02	0.03