LARGE ATOMIC OXYGEN ABUNDANCES OBSERVED TOWARDS MOLECULAR CLOUDS

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Abstract

We present ISO-LWS observations of the [OI] 63 and 145 μm lines towards the molecular cloud L1689N and towards the high mass star formation region W49N. From the analysis of the [OI] lines, we derived the physical parameters of the regions. Combining these observations with CO observations, we obtain [O]/[CO] $\sim$ 50 towards L1689N and towards the molecular clouds on the line of sight of W49N. In both observed regions, the derived [O]/[CO] ratio implies that up to 98% of gaseous oxygen is in atomic form in the gas phase. If we assume that all the gaseous carbon is locked into the CO (a reasonnable assumption), carbon has to be depleted by more than a factor of 10 with respect to the cosmic abundance.

1. Introduction

Oxygen is the most abundant element after hydrogen and helium in the Universe. It is therefore of prime importance to know in which form oxygen is found in the different phases of the Interstellar Medium. In the gas phase, all models (see Lee, Bettens and Herbst 1996 and references therein) predict that O and O_2 are the major oxygen bearing species in molecular clouds. Recently, studies by Pagani, Langer and Castets (1993), Maréchal et al. (1997) and Olofsson et al. (1998) have concluded that O_2 is in fact not a major reservoir. Supporting this, recent observations of the [OI] 63μm absorption line towards two massive star formation regions, DR21 (Poglitsch et al. 1996) and SgrB2 (Baluteau et al. 1997), have suggested that most of the oxygen is in the atomic form. These observations refer to O in partly transluscent clouds between these sources and the Sun. So far, no conclusions have been drawn about the amount of atomic oxygen in dense molecular clouds, where absorption observations are generally not possible. In such clouds, the [OI] lines seen in emission can give an insight to the amount of atomic oxygen that is present in the gas phase. The ISO satellite (Kessler et al. 1996), and in particular the Long Wavelength Spectrometer instrument (hereafter LWS: Clegg et al. 1996), have allowed us to perform such measurements towards L1689N, the molecular cloud around the protostar IRAS16293-2422, using LWS in its low resolution mode (Grating). Towards W49N, one of the most luminous regions of active star formation in the Galaxy, we used LWS in the high resolution mode (FP). Atomic and molecular clouds are present along the W49N line of sight, which crosses twice the Sagittarius spiral arm. Such high resolution observations are needed towards sources presenting a strong continuum around 60μm, as the [OI] line at 63μm can be easily in absorption. This is the case for W49N, where LWS grating observations show a very low ratio of [OI] 63μm versus [OI] 145μm.

2. Observations and data reduction

Towards L1689N, around the protostar IRAS16293-2422 (d $\sim$ 120 pc), we observed a raster map (Caux et al. 1999), containing low resolution LWS spectra (AOT L01). These observations, consisted of a 4×3 grid covering a $400'' \times 300''$ field of view, centered at $\alpha_{1950} = 16^h\ 29^m\ 24^s.6$, $\delta_{1950} = -24^\circ\ 22'\ 03''$ (see Fig. 1).

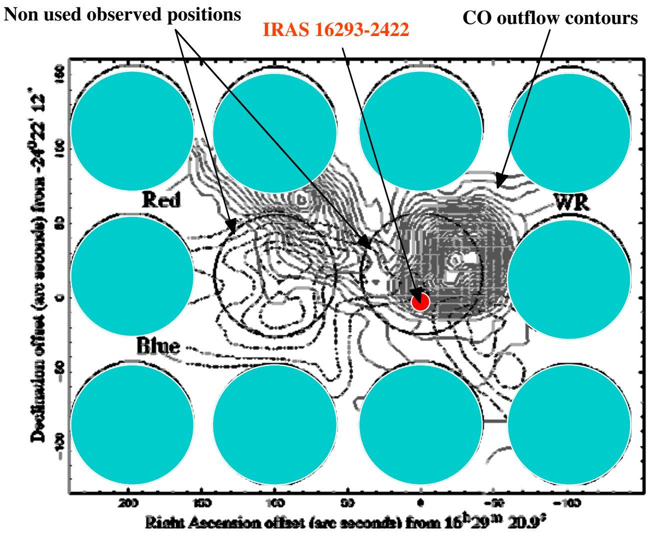

Figure 1. ISO-LWS observations (circles) superimposed on the outflow map (CO 2-1). The protostar IRAS16293-2422 is marked by the small circle.

Towards W49N (d $\sim$ 11.4 kpc), we performed LWS high spectral resolution Fabry-Pérot (AOT L04) observations (Vastel et al. 2000), centered on the [OI] 63 μm and 145 μm lines (W49N : $\alpha_{2000} = 19^h\ 10^m\ 14^s.06$, $\delta_{2000} = 9^\circ\ 06'\ 22.3''$), see Fig. 2.

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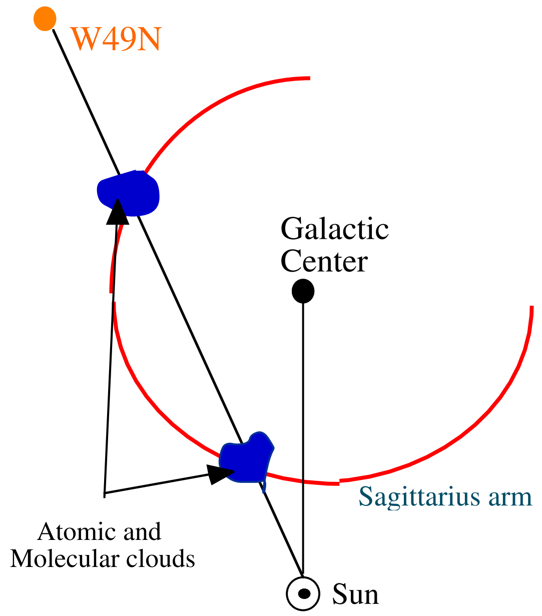

Figure 2. Sketch of the line of sight towards W49N.

Table 1. Averaged fluxes of [OI] and [CII] lines over the ten positions of Fig. 1 in L1689N, in units 10^{-12} erg $s^{-1} cm^{-2}$.

Line	[OI] (63μm)	[OI] (145μm)	[CII] (158μm)
Flux	0.75 ± 0.11	0.30 ± 0.05	3.9 ± 0.1

The data were processed using the Off-Line-Processing pipeline OLP (v7), and the LWS Interactive Analysis LIA (v7.3) for FP mode observations. A final analysis was made using the latest version of the standard package ISAP (v1.6). Each spectrum was carefully deglitched scan by scan. The continuum level of the FP data was calibrated against observations of the same line of sight with LWS in the grating mode (L01). L01 spectra are flux calibrated using Uranus, and the absolute accuracy is estimated to be better than 30% (Swinyard et al. 1998).

3. Results and discussion

3.1. L1689N

Emission from the [CII] (158μm) line was detected with good S/N ratio at all positions in the map, and the averaged emission over the ten positions agrees with, within the errors, the value quoted in Ceccarelli et al. (1998). By contrast, the [OI] lines are too faint to be detectable at a single position, although the average on the ten positions allows to quote the fluxes given in Table 1.

We analysed the [OI] lines by means of an LVG model (Ceccarelli et al. 1998), which compute in a self-consistent way the opacities of the lines. It has four free parameters: N(O), n(H_2) (all hydrogen is considered to be molecular in this cloud), T_k and the linewidth. We assumed the source was filling the LWS beam, and the width of the [OI] lines was the same as that of the $C^{18}O$ line in the ambient cloud, namely 1.4 km s^{-1} (van Dishoeck et al. 1995). The results of the computations show that $T_k \sim 26$ K ± (0.5), N(O) $\geq 5 \times 10^{19}$ cm^{-2}, and n(H_2) $\geq 3 \times 10^4$ cm^{-3}. Larger O column densities would require smaller n(H_2), which would disagree with previous molecular line studies of the region (Wootten and Loren 1987). Through the molecular cloud, N(CO) = 1 ± (0.1) $\times 10^{18}$ cm^{-2} (van Dishoeck et al. 1995, from $C^{18}O$ observations, corrected for a gas temperature of 26 K). Combining the determinations of the N(O) and N(CO) yields the abundance ratio [OI]/[CO] = 50.

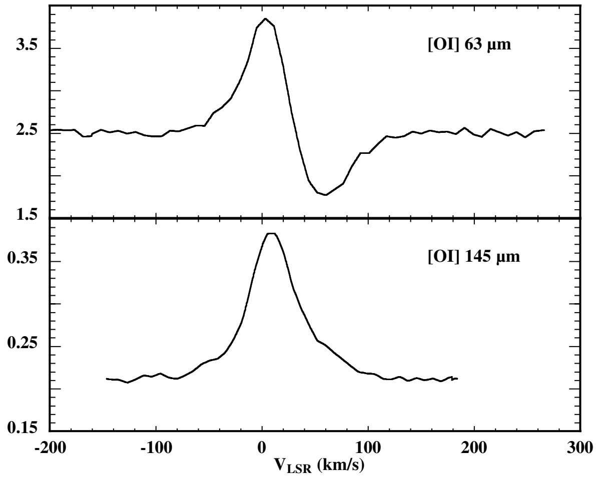

Figure 3. ISO-LWS high resolution spectra obtained towards W49N. a) [OI] (63 μm), b) [OI] (145 μm). Units are 10^{-8} ergs s^{-1} cm^{-2} μm^{-1}.

3.2. W49N

Fig. 3 presents the observed [OI] 63 μm and 145 μm line profiles. While the 145 μm line show only an emission component, the 63 μm line, as suspected analysing the grating observations, shows both emission and absorption components.

Observations of the HI 21 cm line by Lockhart and Goss (1978) were obtained in a beam comparable to the LWS one. Assuming a spin temperature of 50 K, which is an upper limit in such clouds, we derived the upper limit of the HI column density as function of V_{LSR} using the standard following relation :

$$N(HI) = 1.823 \times 10^{18} \times T_{spin} \times \int \tau(v)dv$$

To compute N(O) from N(HI), in the HI clouds along the W49N line of sigth, we assumed (from Afflerbach et al. 1997) an averaged value of [O]/[H] = 5.6×10^{-4}, as the mean galactocentric distance of the intercepted clouds is 6 kpc (see Figure 2), and we assumed that all oxygen is in the atomic form. The derived n(H) and N(O) for the four components are reported in Tab. 2. The 63 μm absorption due to the HI clouds, obtained after convolution with the

Table 2. Derived physical parameters and associated column densities of the four HI components identified towards W49N.

V_{LSR} km s^{-1}	FWHM km s^{-1}	N(HI) $10^{21}cm^{-2}$	N(O) $10^{18}cm^{-2}$	τ_0(O)
35	10	2.4	1.4	0.6
40	5	1.1	0.6	0.6
59.8	17	4.9	2.7	0.8
63.5	12	1.5	0.8	0.3

instrumental profile, is presented in Fig. 5, which clearly shows that the O associated with the HI clouds, although responsible for a fraction of the absorption, *cannot* entirely reproduce the observed 63 μm absorption.

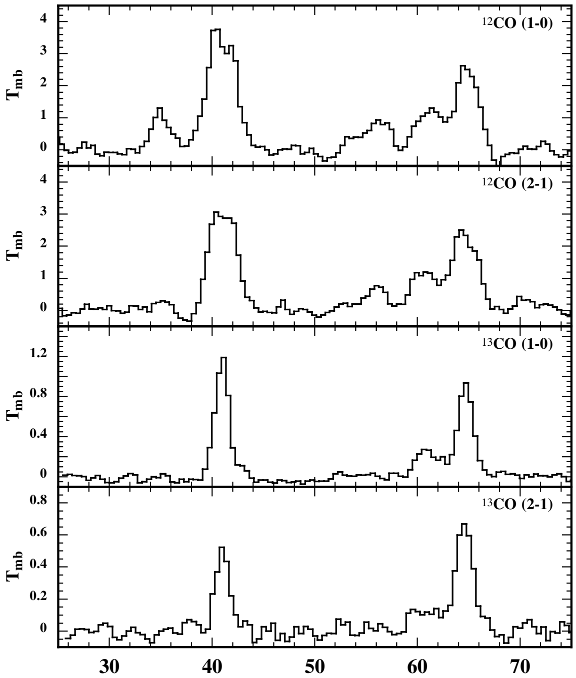

Figure 4. ^{12}CO and ^{13}CO (1-0) and (2-1) lines spectra as observed at SEST. Units are main beam temperature in Kelvins.

Observations of the ^{12}CO and ^{13}CO (1-0) and (2-1) lines were performed at SEST as a five point cross around the nominal position of W49N (30" spacing) to measure the emission in the LWS 80" beam. The HII region itself presents a very complex emission profile between -10 km/s and +25 km/s obviously not responsible of the absorption we detected at 63μm, centered at V_{LSR} = 60 km/s. Figure 4 shows the obtained averaged spectra for the ^{13}CO and ^{12}CO (1-0) and (2-1) lines in the ISO-LWS beam in the range of velocities where the [OI] is seen in absorption. Seven velocity components are present in the ^{12}CO lines, corresponding to seven molecular clouds in the line of sight between us and W49N. Three of these clouds are also detected in the ^{13}CO lines, implying optically thick ^{12}CO lines.

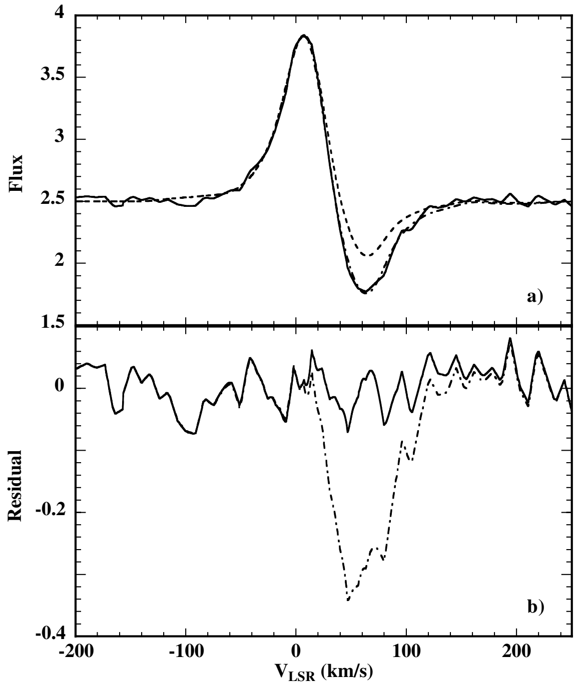

Figure 5. a) Comparison between the observed spectrum (full line), the derived spectrum for both CO and HI (dot-dashed line) and the computed spectrum for HI only (dashed line); b) residuals between the observed spectrum and the constructed spectra: CO and HI (full line) and HI only (dot-dashed line); Units are 10^{-8} erg $s^{-1}cm^{-2}$ μm^{-1}.

The column densities were derived using a LVG model described in Castets et al. (1990). In the three clouds with ^{13}CO emission detected, both ^{13}CO and ^{12}CO lines were used to *simultaneously* compute n(H_2), T_k and N(CO). In the remaining four clouds we assumed T_k = 7 K and n(H_2) = 5× 10^3 cm^{-3}, conservative values for this kind of molecular clouds. We then compute an upper limit of N(CO), using as inputs of the LVG model the upper limits of the ^{13}CO lines emission from our observations. For each component, the derived total N(CO) using the isotopic ratio $^{12}C/^{13}C = 60$ are reported in Table 3. We considered the oxygen absorption from the material in the seven molecular clouds *simultaneously* with the O absorption from the material in the HI clouds. We used a constant value for the [O]/[CO] ratio in the molecular clouds and varied this value to obtain the best fit to the observations.

The [O]/[CO] obtained with this procedure is an average value on the seven clouds, but the procedure has the advantage to minimize the number of free parameters of the fit. Also in this case, we convolved the absorption from the CO and HI clouds with the instrumental profile. In the procedure to obtain the best fit, we also considered the emission component as a gaussian of FWHM equal to that derived from the 145 μm line (16 km s^{-1}).The best fit is obtained for [O]/[CO] $\sim$ 90 and is shown in Fig. 5. The oxygen column densities derived with this procedure are

Table 3. Computed temperature, density and CO and O column densities towards the seven molecular clouds in the line of sight.

Cloud	T K	n_{H_2} $10^3 cm^{-3}$	$N(^{12}CO)$ 10^{15} cm^{-2}	$\tau_0(O)$	N(O) $10^{17} cm^{-2}$
abs1	7	5	< 18	< 4.0	< 16.5
abs2	7	4.2	140	35.0	126.0
abs3	7	5	< 18	< 4.0	< 16.5
abs4	7	5	< 18	< 4.5	< 16.5
abs5	5	87	41	8.1	37.5
abs6	9	80	100	27.0	91.5
abs7	7	5	< 18	< 4.0	< 16.5

reported in Tab. 3. Since the [O]/[CO] is an average value, we cannot exclude that some of the seven CO clouds have the more canonical [O]/[CO] ~ 1 value, but this would imply a much higher [O]/[CO] for the remaining ones.

3.3. DISCUSSION

For these molecular clouds, L1689N and clouds on the line of sight of W49N, we obtain a [OI]/[CO] ≥ 50. This ratio is rather large and certainly larger than the canonical [O]/[CO] ~ 1 value predicted by chemical models (Lee, Bettens & Herbst 1996). This implies that very likely the almost totality of gaseous oxygen is in the atomic form and not locked into CO in these molecular clouds. To our knowledge, there are no standard chemical model that predicts such a large ratio, in either the pseudo-time dependent or steady state limits. At most these models predict [OI]/[CO] = 3 at early times in the evolution of a cloud (Lee, Bettens and Herbst 1996).

In the most extreme case, the oxygen in the gas phase would be in the atomic form and locked into the CO. Even in this case, the observed [OI]/[CO] ratio places stringent limits to the CO and O abundances. Fig. 6 shows the ratio [OI]/[CO] = ([O]-[$O_{locked\ in\ CO}$])/[CO], as a function of the CO abundance, for two different total oxygen abundances values in the gas phase: the *total (gas + dust)* cosmic abundance, 5×10^{-4} and the *gas-phase* cosmic abundance, 3.2×10^{-4} (Meyer, Jura and Cardelli 1998). Taking the largest possible oxygen abundance in the gas phase, our observations imply a ratio [CO]/[H] $\leq 1 \times 10^{-5}$, assuming that all the gaseous carbon is locked into the CO. This CO abundance implies that the carbon is depleted by about a factor larger than 10 with respect to the cosmic abundance of 2.4×10^{-4} (Cardelli et al. 1996).

In these molecular clouds, there is definitively a *deficit of CO with respect to atomic oxygen.* Since carbon cannot be in the C^+ or C form, it follows that *carbon is largely deficient in these molecular clouds with respect to O.* Given the low T_k of these molecular clouds, it is very likely that most of carbon is locked into the grain mantles as iced CO and/or CO_2. In fact the evaporation temperature of pure CO ice is ~ 20 K and higher for CO_2 (Tielens et al.

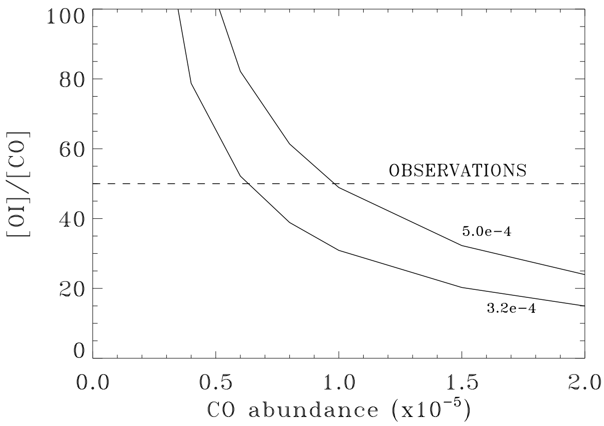

Figure 6. The [OI]/[CO] ratio as function of the [CO]/[H] ratio computed for two values of the oxygen in the gas phase: 5×10^{-4}*, the total (gas + dust) cosmic abundance and* 3.2×10^{-4}*, the gas-phase cosmic abundance.*

1991) so that in cold enough clouds CO and/or CO_2 could remain sticked onto the mantles.

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