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LETTER

Letter to the Editor

Large atomic oxygen abundance towards the molecular cloud L1689N*

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Abstract. We present spectroscopic ISO-LWS observations of the [OI] (63 μm and 145 μm), the [CII] (158 μm) and the H_2O (179 μm) lines towards the molecular cloud L1689N. From the observed ratio of the two [OI] lines, we deduce a mean gas temperature of (26 $\pm$0.5) K, an H_2 density $\geq 3 \times 10^4$ cm^{-3} and an [OI] column density $\geq 5 \times 10^{19}$ cm^{-2}. Combining these observations with previous CO observations, we obtain [OI]/[CO] $\sim$ 50. This ratio implies that up to 98% of oxygen abundance is in atomic form in the gas phase. Furthermore, assuming all the gaseous carbon is locked into the CO, carbon has to be depleted by more than a factor 24. Finally, the upper limit derived for the H_2O (179 μm) line (3×10^{-13} erg s^{-1} cm^{-2}) implies that the water abundance in this region is less than 6×10^{-7} with respect to H nuclei.

Key words: stars: formation – ISM: jets and outflows – ISM: individual objects: L1689N – infrared: ISM: lines and bands

1. Introduction

Oxygen is the most abundant element after hydrogen and helium in the Universe. It is therefore of key importance to know in which form oxygen is found in the different phases of the Interstellar Medium. In the gas phase, all models (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 molecular oxygen is in fact not a major reservoir. Supporting this, recent observations of the [OI] 63 μm 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 [OI] 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, only 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.

2. Observations and results

We observed a raster map containing low resolution grating spectra around the protostar IRAS16293-2422 in the L1689N cloud (d = 120 pc, Knude and Hog 1998), using the LWS on the ISO satellite, in the LWS01 mode. These observations, obtained during revolution 85, consisted of a 4×3 grid covering a $400'' \times 300''$ field of view, centered at $\alpha_{1950} = 16^h\, 29^m\, 24^s.6$, $\delta_{1950} = -24^\circ\, 22'\, 03''$. The locations of the beams, and the half power beamwidth over the mapped region are shown in Fig. 1. A first analysis of these observations has been presented by Ceccarelli et al. (1998), where the detection of diffuse [CII] emission was reported, along with a detailed discussion of line emission from the central source. In this first analysis was not possible to evaluate the diffuse atomic oxygen fine structure line emission at 63 μm and 145 μm.

In this Letter we focus on a re-analysis of those positions of the map which do not include the outflow and the source itself. The objective is to derive reliable estimates of the line emission of atomic oxygen in the region of the molecular cloud.

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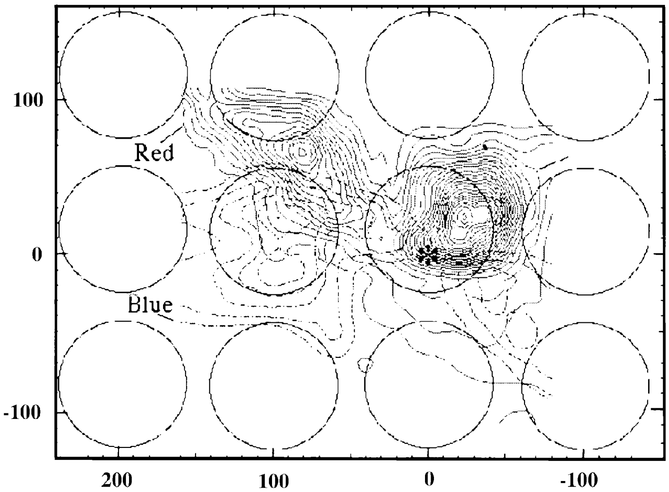

Fig. 1. Map of the ISO-LWS observations superimposed on the outflow mapped in the CO (2-1) line. The LWS beam at the observed positions in the L1689N molecular cloud is represented by circles. The star shows the position of the protostar IRAS16293-2422. Offsets are in arc seconds. The 2 central positions are not used in this work.

Table 1. Averaged fluxes of [OI], [CII] and H_2O lines over the ten positions of Fig. 1 in L1689N, in units 10^{-12} erg s^{-1} cm^{-2}.

[OI] (63 μm)	[OI] (145 μm)	[CII] (158 μm)	H_2O (179 μm)
0.75 $\pm$ 0.11	0.30 $\pm$ 0.05	3.9 $\pm$ 0.1	$\leq$ 0.3

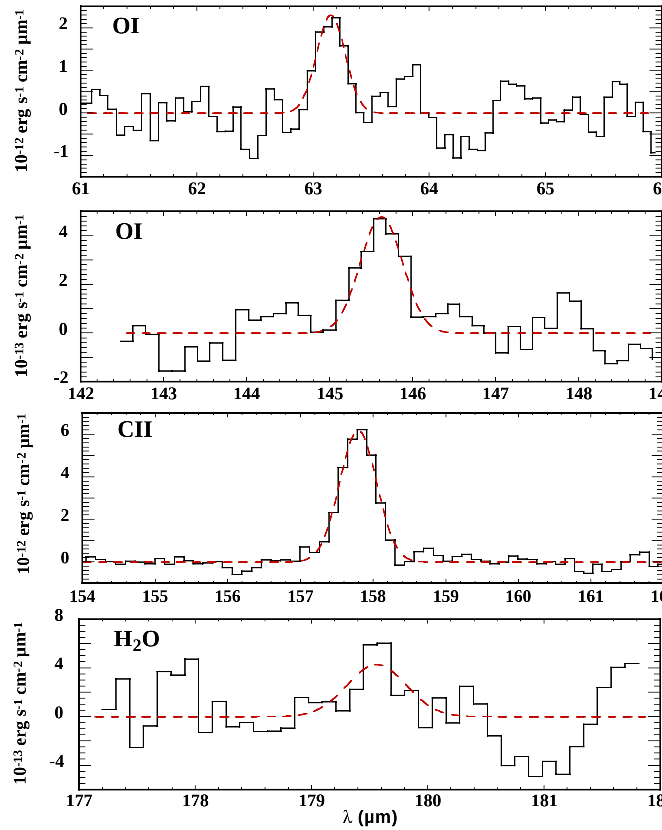

Fig. 2. Averaged ISO-LWS spectra obtained towards the molecular cloud L1689N.

To achieve this, the data were re-analysed taking advantage of latest improvements of the Off-Line-Processing pipeline (OLP version 7). The spectra were flux calibrated using Uranus, and the absolute accuracy has been estimated to be better than 30% (Swinyard et al., 1996). Final analysis was made using the latest version of standard package ISAP (version 1.6). Each spectrum was carefully deglitched scan by scan, and defringed. Then, the continuum background was removed on each position, with a first or second order polynomial. We averaged together the spectra obtained on each individual position (Fig. 2) and the line fluxes were measured by gaussian fitting.

Emission from the [CII] (158 μm) 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] and H_2O lines are too faint to be detectable at a single position, although the average on the ten positions allows the fluxes quoted in Table 1 to be estimated.

3. Discussion

3.1. Atomic oxygen and CO abundances

We analysed the [OI] lines by means of an LVG model, whose details have been reported in Ceccarelli et al. (1998). This model, which compute in a self-consistent way the opacities of the lines, has four free parameters: the [OI] column density, the H_2 density (all hydrogen is considered to be in molecular form in this cloud), the gas temperature 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 are shown in Fig. 3, where the parameter space consistent with the 63 μm and 145 μm line emission as function of the gas density and temperature is shown, for three choices of [OI] column densities. One can note on this figure that the 63 μm line is yet optically thick for all [OI] column densities quoted on the figure (for H_2 densities $\geq 3 \times 10^4$), while the 145 μm line starts to become optically thick only for [OI] column densities $\geq 3 \times 10^{19}$ cm^{-2}.

Fig. 3 shows that, in order to account for both [OI] line intensities simultaneously, the gas kinetic temperature has to be (26 $\pm$0.5) K and the [OI] column density has to be larger than 5×10^{19} cm^{-2}. With this [OI] column density, the H_2 density has to be larger than 3×10^4 cm^{-3}. Larger [OI] column densities would require smaller H_2 densities which would disagree with previous molecular line studies of the region that give an H_2 density of 3×10^4 cm^{-3} (cf. Wootten and Loren 1987). On the other hand, using larger [OI] column densities would only strengthen the conclusions of this work. In the following, we will assume the conservative value of N(OI) = 5×10^{19} cm^{-2}.

Van Dishoeck et al. (1995) report a CO column density through the molecular cloud of $(1.5 \pm 0.1) \times 10^{18}$ cm^{-2}, which was obtained from $C^{18}O$ observations and assumed the terres-

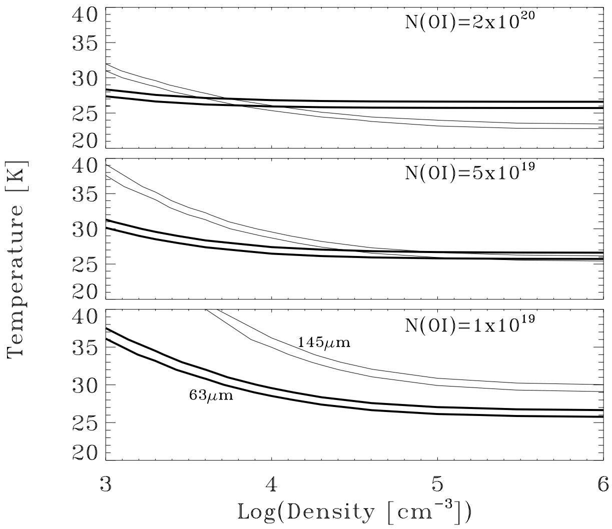

Fig. 3. Temperature – H_2 density plots from our LVG model to obtain the fluxes observed in the [OI] 63 μm (thick lines) and 145 μm (thin lines) lines, respectively. For each [OI] line, two curves are reported, which delimit the observed fluxes within the 30% error.

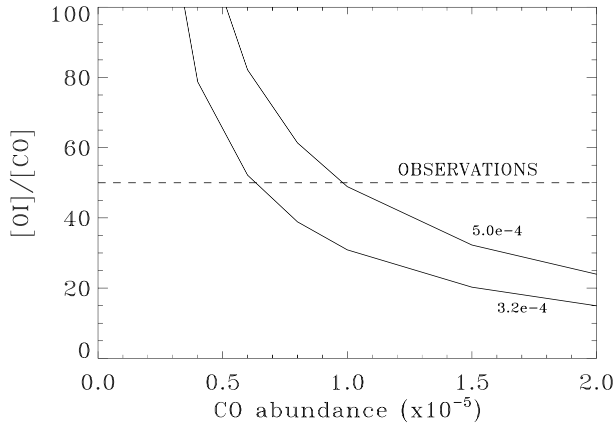

Fig. 4. The [OI]/[CO] ratio as function of the CO abundance (with respect to H nuclei) computed for two values of the oxygen in the gas phase: 5×10^{-4}, the *total (gas + dust)* cosmic abundance and 3.2×10^{-4}, the *gas-phase* cosmic abundance, both quoted by Meyer, Jura and Cardelli (1998).

trial ^{16}O over ^{18}O isotopic ratio and a gas temperature of 15 K. Correcting for a gas temperature of 26 K (to be in agreement with the temperature derived from the observed [OI] lines fluxes), the CO column density would be decreased by 30%, giving N(CO) = 1×10^{18} cm^{-2}. For an $A_V \leq 2$, $C^{18}O$ is dissociated by interstellar radiation (Warin, Benayoun and Viala 1996), leading to a small underestimation of the total CO column density from $C^{18}O$ intensity on the cloud edges. But, as the deduced visual absorption towards this cloud is larger than 25 (see below), this effect would not raise the total CO column density by more than 10%. Combining the determinations of the [OI] and CO column densities yields the abundance ratio [OI]/[CO] $\sim$ 50. 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 (except for an evolutionary time smaller than 1000 years, in models where initially the CO is artificially set to zero and all the oxygen is assumed to be in atomic form). At most these models predict [OI]/[CO] $\sim$ 3 at early times ($\geq 3 \times 10^4$ years) in the evolution of a cloud (Lee, Bettens and Herbst 1996, Bergin and Langer 1997).

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 OI abundances. Fig. 4 shows the [OI]/[CO] ratio, computed as [OI]/[CO] = ([O]-[$O_{\rm locked\ in\ CO}$])/[CO], as a function of the CO abundance, for 2 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, namely the total cosmic abundance, our observations imply a CO abundance with respect to H nuclei equal to 1×10^{-5} (Fig. 4), assuming that all the gaseous carbon is locked into the CO. This is a reasonnable assumption as the [CI] column density in the same region is only 10% of that of CO (Ceccarelli et al. 1998). This value, 1×10^{-5}, implies that the carbon is depleted by about a factor 24 with respect to the cosmic abundance of 2.4×10^{-4} (Cardelli et al. 1996). Reducing the gas phase oxygen abundance would result in even higher depletion factors: for example, adopting the more realistic and probably still conservative value of the *gas-phase* cosmic abundance of oxygen reported by Meyer et al. (1998) would imply a depletion factor of 40. Evidence is now mounting that this is a widespread characteristic of molecular clouds (cf. Lefloch et al. 1998 and references therein).

To summarise, our observations imply that a) a very large fraction of oxygen is in the atomic form in this molecular cloud, at levels of $\sim$ 98% of the total cosmic abundance, and b) carbon is depleted by at least a factor 24, and more probably by a factor 40, if we assume that all the gaseous carbon is locked into the CO and the oxygen abundance is 3.2×10^{-4}.

The determination of the gaseous oxygen and carbon abundances implies the need to revise the total H_2 column density through the cloud which was estimated by van Dishoeck et al. (1995), who assumed a CO abundance of 5×10^{-5} (with respect to H nuclei), i.e. at least 5 times greater than reported here. Using the value deduced form our observations (1×10^{-5}), we derive a H_2 column density larger than 5×10^{22} cm^{-2}, which corresponds to a visual extinction of 25 mag (assuming the "canonical" ratio of A_V / N(H_2) = 5×10^{-22}). This value of the extinction is consistent with the observations by Hodapp (1994), who imaged a $8' x 3'$ field around IRAS16293-2422 in the K$'$ band, and found a blank field with no stars visible which were brighter than magnitude 16.5. This corresponds to an $A_V \geq 30$ for the galactic coordinates of the field, using field star counts in the K band (Eiroa and Casali 1992), corrected for the galactic longitude and latitude dependence.

Finally, it is unlikely that L1689N is a peculiar case. Liseau et al. (1999) recently reported a low [OI] 63 μm/145 μm ratio, similar to the value found here, in the ρ Oph main cloud. We argue that a similar situation is present there and that this is

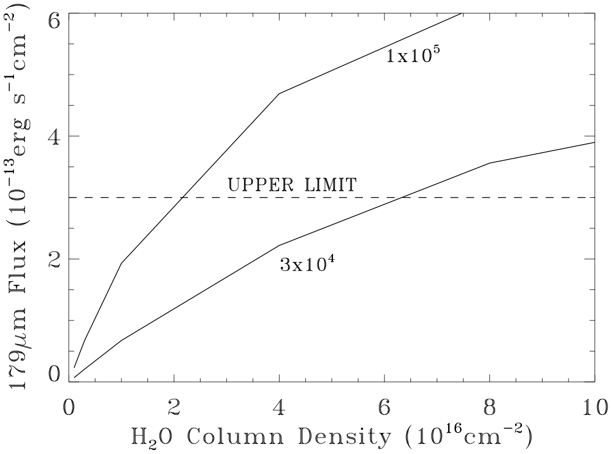

Fig. 5. H_2O 179 μm line intensity as function of the H_2O column density, for a gas at temperature 26 K and H_2 densities 10^5 cm^{-3} and 3×10^4 cm^{-3} respectively. The linewidth is taken equal to 1.4 km s^{-1}, as observed for the $C^{18}O$ (1-0) line (see text).

due to the presence of a very large column density of atomic oxygen, similar to what we find towards L1689N, which makes the 63 μm line optically thick, and to appear weak with respect to the 145 μm line. Furthermore, such low [OI] 63 μm/145 μm ratios have also been reported towards embedded Class I and/or Class 0 protostars (Saraceno et al. 1997). Also in these cases, the ratios can be explained if a large fraction of oxygen, close to 100% of the total oxygen cosmic abundance, is present in the massive envelopes that surround these sources. Direct evidence is provided by high resolution ($\sim 10^4$) observations of the [OI] lines towards a sample of such objects (Vastel et al. 1999). Finally, as mentioned in the introduction, Poglitsch et al. (1996) and Baluteau et al. (1997) have already noted that up to 90% of oxygen is in atomic form towards DR21 and SgrB2, two massive star forming regions.

3.2. H_2O abundance

As quoted in the previous section, the H_2O 179 μm line intensity is less than 3×10^{-13} erg s^{-1} cm^{-2}, this putting a stringent upper limit to the H_2O abundance in the region. An LVG model was used to derive the 179 μm line intensity as function of the H_2O column density on the LWS beam of 80$''$ (the details of the model are described in Ceccarelli et al. 1998). Here we used the collisional coefficients for the H_2 molecules as computed by Phillips, Maluendes & Green 1996 and assuming a 3:1 ortho-to-para ratio. Taking the results from the modeling of the atomic oxygen lines, i.e. assuming a H_2 density of 3×10^4 cm^{-3} and a gas temperature of 26 K, we obtain an H_2O column density N(H_2O) $\leq 6 \times 10^{16}$ cm^{-2} (see Fig. 5).

Combining the lower limit on the atomic oxygen column density with this upper limit gives [H_2O]/[O] abundance $\leq 1.2 \times 10^{-3}$. Equivalently, taking the total atomic oxygen abundance 5×10^{-4} (with respect to the H nuclei) implies an upper limit to [H_2O]/[H] of 6×10^{-7}, which is barely consistent with standard chemical models of quiescent molecular clouds (Bergin et al. 1997).

4. Conclusions

We report the detection of the fine structure lines of the atomic oxygen in the region surrounding the low-luminosity protostar IRAS16293-2422, in the L1689N molecular cloud. The [OI] 63 μm and 145 μm measured fluxes have been used to constrain the temperature, H_2 density and [OI] column density to be (26 ± 0.5) K, $\geq 3 \times 10^4$ cm^{-3} and $\geq 5 \times 10^{19}$ cm^{-2}, respectively.

We then computed the [OI]/[CO] ratio, by using the CO column density derived by van Dishoeck et al. (1995) and show that the [OI]/[CO] ratio in the region results to be larger than 50. Such a large ratio implies that *a very large fraction of the cosmic oxygen, up to 98%, is in the gas in the atomic form and that carbon is highly depleted, by more than a factor 24,* assuming all the gaseous carbon is locked into the CO.

Finally, we report an upper limit to the H_2O 179 μm line intensity in the region, which translates into a stringent upper limit to the H_2O abundance of 6×10^{-7}.

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