THE FAR INFRARED CO LINE EMISSION OF ORION BN/KL

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Abstract

We present observations towards one of the closest regions of high mass star formation, Orion BN/KL, performed at both low resolution mode (grating mode) and high resolution mode (Fabry-Pérot) with the Long Wavelength Spectrometer on board the Infrared Space Observatory. We detected the CO rotational lines from $J_{up} = 15$ to $J_{up} = 45$. While the lines with $J_{up} \leq 32$ are spectrally unresolved, the higher lying lines show a broadened profile. Finally, we detected two ^{13}CO lines, namely at $J_{up} = 18$ and 24, from which we could derive the opacities of the relative ^{12}CO lines. The LVG analysis of the observed line spectrum allows to distinguish three main physical components with different temperatures, densities and column densities: 1) lines with $J_{up} < 20$ originate mainly in the diffuse photodissociation region surrounding the source; 2) lines with J_{up} between 20 and 30 originate in the high velocity outflow (plateau) emanating from IrC2; 3) lines with $J_{up} > 32$ originate in the hot and dense gas of the shocked component of the outflow. We discuss how future observations with HIFI, onboard the Far Infrared Space Telescope (FIRST) will allow to spectrally and spatially disentangle the three components, and, consequently, characterise more precisely the Orion BN/KL star forming region.

1. Introduction

The Orion Molecular cloud, at a distance of 450 pc, is one of the closest region of high mass star formation. Its proximity and its large infrared luminosity have allowed to perform plenty of observations in the past years, yielding the discovery of the first protostars candidates. Molecular emission mostly comes from OMC1, which contains several condensations, as the KL nebula. The KL nebula is composed by many infrared clusters (e.g. BN and IrC2) of massive stars at early evolutionary states. Millimeter, sub-millimeter and infrared spectroscopy (see Genzel & Stutzki 1989 for a review) have shown copious molecular emission arising from physically distinct regions: the ridge, the compact ridge, the hot core, the PDR region surrounding the quiescent gas and a high velocity bipolar outflow originating from IrC2. At the edge of the bipolar outflow there are spots of very hot (1000 to 2000 K) shock excited gas. Numerous observations have allowed to charaterise the mentioned components in term of temperature, density and column density. Recently Sempere et al. 2000 reported low resolution (~ 200) FIR CO observations towards BN/KL with the Long Wavelength Spectrometer (hereafter LWS: Clegg et al. 2000) on board of the Infrared Space Observatory (ISO: Kessler et al. 1996). Those observations suffer of some uncertainty on the data calibration and on the relatively low resolution of the observations. This is a problem expecially for the determination of the high J CO line fluxes, which can be contaminated by adjacent lines, as also noted by Sempere et al. 2000. In this contribution we report observations of the CO lines obtained with the same instrument, namely ISO-LWS, but with the higher resolution, i.e. $\sim 10^4$. Particular emphasis is given to the calibration of the FP data (§2). Based on these new calibrated data we re-interprete the FIR CO lines by means of a LVG code in §3.

2. Observations and results

We performed a spectral survey between 45 and 198 μm of the Orion BN/KL using ISO-LWS both in grating and FP mode. The 80″ beam was centred on Orion BN/KL ($\alpha_{2000} = 5^h35^m14.2^s$, $\delta_{2000} = -5°22'33.6''$). The grating spectral survey was obtained using LWS with the L01 AOT. It was calibrated using Uranus, and the absolute accuracy is estimated to be better than 30% (Swinyard et al. 1998). These observations required the use of the bright source data reduction package (Leeks et al. 1999) as the brightness of the source saturated the detectors LW2 to LW4. In practice we used the grating spectrum only to calibrate the FP observations. The FP spectral survey was performed with the L03 AOT. These observations, covering the wavelength range from 43 to 162 μm, are the first performed with a single instrument in space at the same time in this wavelenght range and with such a high spectral resolution. The continuum levels of the FP data were calibrated against the grating spectrum, after taking into account the dark, straylight and FP order sorting. We detected the ^{12}CO rotational lines between $J_{up} = 15$ and 45 and the ^{13}CO lines at $J_{up} = 18$ and 24. Higher J transitions have fluxes lower than 10^{-11} erg s^{-1}cm^{-2}. The statistical plus calibration uncertainty on the flux determination is about 30% for transitions with J_{up} between 15 and 40 and 40% between 40 and 45 (for further details see Maret et

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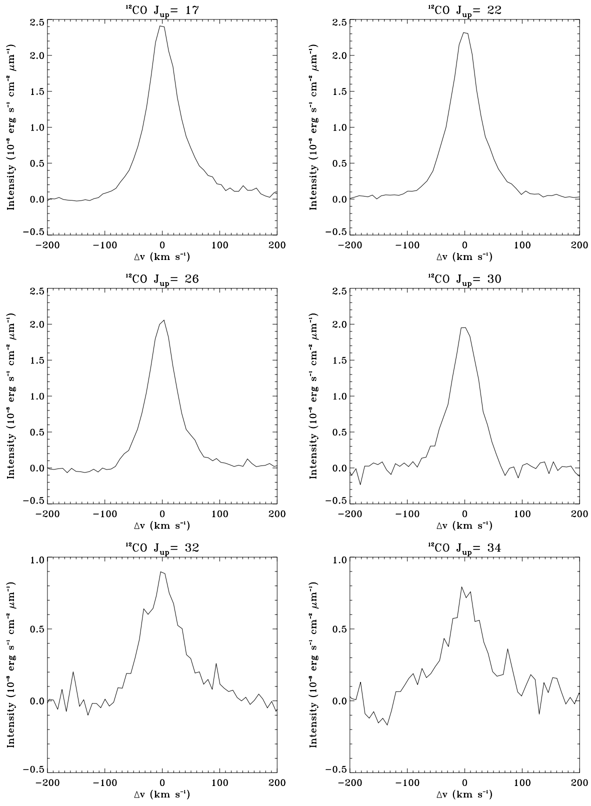

Figure 1. Observed profiles of selected ^{12}CO rotational transitions with LWS in FP mode. $J_{up} \geq 32$ transitions show broadened profiles.

al. in preparation). $J_{up} \geq 32$ lines have a broadened profile, as shown in Fig. 1. Finally, the ^{13}CO lines have a flux equal to (3.7 ± 1.1) and (4.7 ± 1.4) $\times 10^{-11}$erg s^{-1} cm^{-2} respectively. The ^{12}CO/^{13}CO flux ratio is 27 for $J_{up} = 18$ and 12 for $J_{up} = 24$ respectively, indicating that theses lines are optically thick. As suspected, we find line fluxes which differ on average by more than a factor 2 with respect to those quoted by Sempere et al. (2000) and even a factor ten in the highest lines. We therefore re-interpreted the CO line spectrum, as discussed in the next section.

3. Discussion

The observed CO spectrum is shown in Fig. 2. The figure shows clearly that a single gas component can not explain the $J_{up} = 15$ to 45 observed emission. At least two components are needed to explain the emission peak at J_{up}=16 and the "broad shaped" emission between $J_{up} = 20$ and 30. In addition the observed broadening at $J_{up} \geq 32$ implies a third physical component. With this in mind, we interpreted the CO line spectrum by means of a LVG model described in Ceccarelli et al. (1998). This model, which computes in a self consistent way the opacities of lines, has four free parameters : the CO column density, the H_2 density, the gas temperature and the linewidth. The results of our analysis are shown on Fig. 2, and compared with the present and previous observations (Schultz et al. 1992, Graf et al. 1990, Schmid-Burgk et al. 1989, Howe et al. 1993, Genzel et al. 1988). Note that the differences between the present and some of the previous measurements are likely due to the different used beams. In the next three paragraphs we discuss in detail the modeling of the three components respectively.

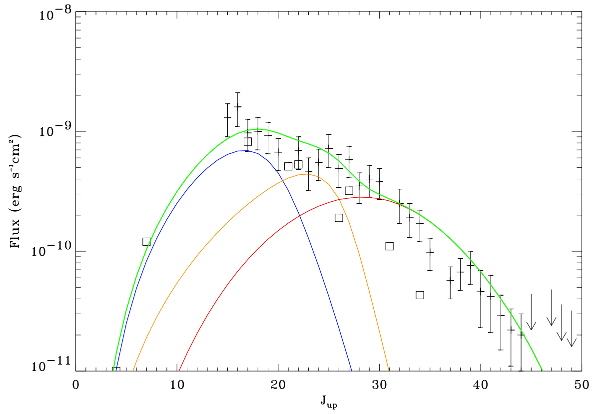

Figure 2. The observed ^{12}CO line spectrum of Orion BN/KL. Crosses show the present observations, whereas open squares show previous observations from the literature (see text). The green line shows the best fit to the observations, obtained by summing up the emission originating in the PDR (blue line), plateau (orange line) and shocked gas (red line) respectively (see text).

3.1. $J_{up} \leq 20$: PDR

First we used the ^{12}CO to ^{13}CO line ratio at $J_{up} = 18$ to calculate the line opacity of the ^{12}CO transition. Assuming that the relative abundance of ^{13}CO with respect to ^{12}CO is 60 (Langer et al. 1994). and that the ^{13}CO line is optically thin, we obtain that the ^{12}CO line is attenuated by about a factor 2. This implies a CO column density larger than $\sim 10^{18}$ cm^{-2}, assuming a linewidth of 10 km s^{-1} (Howe et al. 1993)[1]. Figure 3 shows the temperatures and densities needed to reproduce the observed $J_{up} = 18$ ^{12}CO to ^{13}CO flux ratio *and* the observed $J_{up} = 15$ over $J_{up} = 18$ ^{12}CO flux ratio, as computed by our LVG model, with a CO column density of 10^{18} cm^{-2}. Note that much larger CO column densities would require a filling factor less than unity, which seems unjustified. The figure suggests that the gas responsible for the $J_{up} \leq 20$ component is relatively warm (≥ 200 K). We obtain a good fit assuming T = 350 K and n(H_2) = 10^6 cm^{-3}, but the observed emission can also be explain by a somewhat lower temperature and relatively higher density, or inversely (3). The lack of data between $J_{up} = 7$ and 15 does not allow to con-

[1] A smaller linewidth would imply a proportional smaller column density.

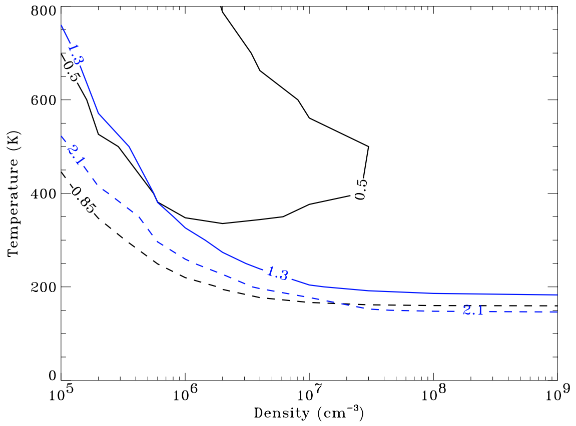

Figure 3. *Theoretical J_{up} = 15/18 ^{12}CO lines ratios (in blue) and opacity of the J_{up} = 18 line (in black) predicted by our LVG model. The observed values are represented by continuous lines and the errors bar by dashed lines lines. We assumed N(CO) = 10^{18} cm^{-2} and Δv = 10 km s^{-1}.*

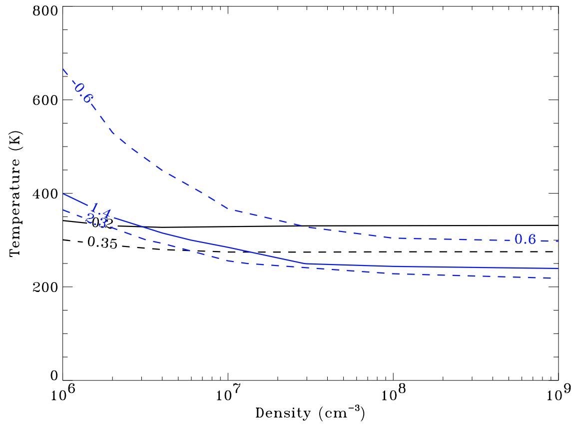

Figure 4. *Theoretical J_{up}=26/20 ^{12}CO lines ratios (in blue) and line opacity at J_{up}=24 (in black) predicted by our LVG model. In these calculations N(CO)=5$\times 10^{19}$ cm^{-2} and Δv=30 km s^{-1}.*

strain more precisely these two parameters. The values we obtain are neverthless consistent with the emission from the PDR, as characterized by Genzel et al. 1988, who find a density $10^5 - 10^6$ cm^{-3} and a temperature $\geq$ 400 K. We wish to emphasize that BN/KL is a complex region where several components coexist, which are not resolved neither spatially or spectrally by LWS. For example the ridge could contribute for at least 10% to the emission in the 15 < J_{up} < 20 interval. The hot cores, on the other hand, do not contribute significatively to the observed CO emission in this range.

3.2. 20≤J_{up}≤30: Plateau

The CO line spectrum between J_{up} = 20 and 30 show a broad shaped emission, which originates in a hotter and/or denser component than the PDR. Following the same method of the previous paragraph, we used the ^{13}CO to ^{12}CO fluxes at J_{up} = 24 to constrain the CO column density and the ^{12}CO J_{up} = 20/26 line ratio simultaneously to constraint the temperature and density. In the theoretical computations we took the observed linewidth Δv = 30 km s^{-1} (§2). We found a lower limit to the CO column density of 10^{19} cm^{-2}. Using N(CO) = 5 $\times$ 10^{19} cm^{-2}, we obtain a density of $\sim 10^7$ cm^{-3} and a temperature of 350 K (see Fig. 4). These values are consistent with those derived for the plateau by Schultz et al. 1995. Besides, the derived beam filling factor is 7%, equivalent to an angular size of 20″ for the emitting region. This value is in good agreement with the extent measured by ground based observations of the CO 7-6 line (40 ″; Howe et al. 1993), when taking into account that higher energy transitions have a sligthly smaller extent.

3.3. $J_{up} \geq 30$: shocked gas

The observed broadening of the J_{up} >32 lines (Fig. 1) clearly shows that the emission from these transitions arises in a different component than the plateau. In order to excite such high lying lines, relatively high temperatures ($\sim$ 1000 K) and densities ($\geq 10^6$ cm^{-3}) are required, suggesting that the emission originates in the gas shocked by the high velocity outflow, as already noted by Sempere et al. 2000. We obtain a good fit to the data with a gas temperature of 1500 K and density 4 $\times$ 10^6 cm^{-3}, taking the observed linewidth Δv = 50 km s^{-1}. Assuming an angular extent of 40″ (Genzel & Stutzki 1989), we find a CO column density of 4$\times 10^{17}$ cm^{-2}. In practice at J_{up} > 32, the emission from the shocked gas dominates over that from the plateau, explaining the line broadening observed at these transitions.

3.4. Agreement with observed lines profiles

In order to check the agreement of our model with the observed line profiles, we compared the theoretical emission line profiles from the three components with the observed profiles. The theoretical profiles are obtained convolving gaussian profiles with the PSF of the instrument (following Vastel et al. 2000), where the linewidth and integrated line intensities are those computed by our LVG model. The predicted and observed line profiles are shown in Fig. 5. The theoretical profiles are in good agreement with the observed ones. As already noted, the predominance of the shocked gas emission at J_{up} = 32 explains the observed broadened line.

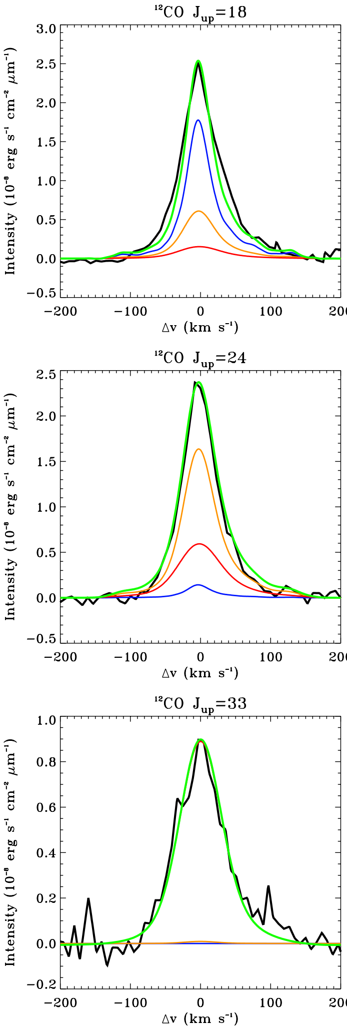

Figure 5. Observed (black) and predicted J_{up} = 18, 24 and 33 ^{12}CO line profiles: PDR emission (blue), plateau (orange), shocked gas (red), and total (green).

4. Conclusions

The Orion BN/KL observations obtained with ISO-LWS in Fabry-Perot mode allowed to detect the J_{up} = 15 to 45 CO rotational transitions. Modeling of observed fluxes with a LVG code shows the presence of three components with different temperatures, densities and column densities (see tab. 1). We found that the lowest J line emission arises from the PDR region; the emission with J_{up} between 20 and 30 arises from the high velocity outflow, namely the plateau; and finally, lines with $J_{up} > 32$ originate in the gas shocked by the high velocity outflow. Our model account for the observed line fluxes *and* profiles. On the other hand, this study shows the necessity of high spectral resolution observations of Orion BN/KL to gain further insight on the structure of this region. Future observations with HIFI, onboard the Far Infrared Space Telescope (FIRST) will allow to disentangle spectrally an spatially

Table 1. Temperatures, densities, CO column densities and linewidths of the three components responsible for the observed FIR CO emission: PDR, plateau and the shocked gas.

	PDR	Plateau	Schocked gas
$n(H_2)$ cm^{-3}	10^6	10^7	4×10^6
T (K)	350	350	1500
N(CO) (cm^{-2})	10^{18}	5.10^{19}	4×10^{17}
Δv (km s^{-1})	10	30	50
Filling factor (%)	100	7	25

the emission from the three components, namley the PDR, the plateau and the shocked gas components.

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