THE FAR INFRARED CO LINE EMISSION OF ORION BN/KL

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ABSTRACT

We present observations of the closest region of high mass star formation, Orion BN/KL, performed at both low resolution mode (grating mode) and high resolution (Fabry-Pérot mode) with the Long Wavelength Spectrometer (LWS) on board the Infrared Space Observatory (ISO). We detected the CO rotational transitions from J\text{up}\,=\,15 to J\text{up}\,=\,49. A LRG analysis of the line fluxes allows to distinguish three main physical components with different temperatures, densities and column densities. Our analysis yields to conclude than J\text{up}\,<\,15 arise from the photodissociation region (PDR), the emission between J\text{up}\,=\,20 and 30 arise from the high velocity outflow (plateau), and J\text{up}\,>\,32 arises from a hot and dense gas component. The latter exhibits broadened lines for the levels J\text{up}\,>\,32 and is thought to be due to shocked gas in a high velocity outflow. Future observations with HIFI, onboard the Far Infrared Space Telescope (FIRST) will allow the spectral separation of the PDR and the plateau components, unresolved with ISO, and characterise more precisely the Orion BN/KL star forming region.

1. Introduction

The Orion Molecular cloud, at a distance of 450 pc, is the closest region of high mass star formation. Its proximity and its large infrared luminosity allowed to perform plenty of observations in the past years, yielding the discovery of the first proto-stars candidates. Molecular emission mostly comes from OMC1, containing several condensations as the KL nebulae. The KL nebulae is composed by many infrared clusters (e.g. BN or IrC2), containing massive stars at early evolutionary states. Millimetre, sub-millimetre and infrared spectroscopy (see [Grenz & Shutzki 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 (\text{$\Delta v = 18$ km/s}) bipolar outflow originating from IrC2. Outside the bipolar outflow is a region of very hot (1000 to 2000 K) shock exited gas. Numerous observations have allowed to characterise this component in term of temperature, density and column density. Recently [Sempere et al. (2000)] reported of 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]). These observations revealed the presence of three gas components they identified as the ridge, the high velocity outflow and a hot and dense gas component detected at J\text{up}\,>\,30 due to the shocked gas in the high velocity outflow. Nothethess uncertainties remains on the data calibration, and high J grating data are probably contaminated by adjacent lines. We here present a large bandwidth survey of the far infrared CO lines of Orion BN/KL, performed with ISO-LWS in Fabry-Perot mode. Particular emphasis is given to the calibration of the FP data. Based on these new calibrated data we interpret the FIR lines by means of a LRG code to derive the temperature, density and column density of the several gas component.

2. Observations and results

We performed a spectral survey of the Orion BN/KL using ISO-LWS both in grating mode and FP mode. The 80″ beam was centred on Orion BN/KL (\text{$\alpha_{2000} = 5^h35^m14.2^s$, \text{$\delta_{2000} = -5^\circ22'\,33.6''$}). The grating spectral survey was done using LWS in with the L01 AOT. It was calibrated using Uranus, and the absolute accuracy is estimated to be better than 30% [Swinyard et al. 1998]. Theses 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. The grating spectrum was only used to calibrate the FP observations. The FP spectral survey was performed with the L03 AOT. Theses observations, covering the wavelength range 43 to 162 \text{$\mu$m} are the first performed with a single instrument in space at the same time. The continuum level of the observation was calibrated against the grating spectrum, after taking into account the dark, straylight and FP order sorting. The calibration uncertainties, estimated from RMS of measured fluxes of each transition, is between 30% and 40% for the weaker lines. We detected \text{$^{12}$CO} rotational lines between J\text{up}\,=\,15 and 49 in FP mode. Higher transitions fluxes are under $10^{-11}$ erg s$^{-1}$ cm$^{-2}$ and are not detected. The fluxes uncertainties, estimated from $\sigma$ measurements of each transitions, are about 30% for transitions between J\text{up}\,=\,15 and 40 and 40% between 40 and 45. Lines between J\text{up}\,=\,45 and 49 must be considered as upper limits. Higher transitions have a low RMS yielding uncertainties on width determination but the broaden-
Figure 1. Observed profiles of selected $^{12}$CO rotational transitions with LWS in FP mode. $J_{\text{up}} > 32$ transitions shows an important broadening.

ing observed is consistent with higher transitions measurement. This is clearly indicate that $J_{\text{up}} \geq 32$ lines emission comes from another gas component than lower transitions, necessary hotter and denser. We also detected $J_{\text{up}} = 18$ and 24 $^{13}$CO lines. We found a flux of respectively $3.7 \pm 1.1$ and $4.7 \pm 1.4$ erg s$^{-1}$ cm$^{-2}$. The $^{12}$CO/$^{13}$CO fluxes ratio is 27 for $J_{\text{up}} = 18$ and 12 for $J_{\text{up}} = 24$, indicating that these lines are optically thick.

3. Discussion

We analysed the $^{12}$CO lines fluxes by means of an LVG model developed by Ceccarelli et al. This model, which compute in a self consistent way the opacities of lines, has four free parameters: the $^{12}$CO column density, the $H_2$ density, the gas temperature and the linewidth. The results of our computations are shown on fig. 2 together with our observations and previous ones by Schultz et al. 1992, Graf et al. 1999, Schmid-Burgk et al. 1989, Howe et al. 1993, and Genzel et al. 1988. The differences between these previous measurements and our measurements are probably due to the different instruments beam. The first thing to note is that a single gas component can not explain the $J_{\text{up}} = 15$ to 44 observed emission. At least two components are needed to explain the emission peak observed at $J_{\text{up}} = 16$ and the “broad shaped” emission between $J_{\text{up}} = 20$ and 30. In addition the observed broadening at $J_{\text{up}} > 32$ implies a third physical component.

3.1. Low J Emission. Ridge, Compact Ridge and PDR

Because of the accurate calibration we used, the emission between $J_{\text{up}} = 15$ and 20 we observed is quite different than previous ISO observations. The fluxes we measure are 30% higher than those measured by Sempere et al. 2000. Such fluxes can’t be explain by the ridge emission as they previously said. The temperature, density and column density they adopted fail to reproduce the intensity of the emission we observed. In order to characterise the gas emitting at these transitions, we used the $^{12}$CO to $^{13}$CO line ratio at $J_{\text{up}} = 18$ to calculate the escape photon escape probability at this transition. Assuming that the relative abundance of $^{13}$CO with respect to $^{12}$CO is 60 and that the $^{13}$CO is optically thin, it gives a photon escape probability of 0.5 at $J_{\text{up}} = 18$. We also calculated $J_{\text{up}} = 15 / 20$ $^{12}$CO lines ratios. This ratio, both with the photon escape probability were used to constrain the temperature and density of the gas. The fig. 3 shows theoretical photon escape probability and lines ratios computed with our LVG codes, both with photon escape probability and ratio we observed. We found a lower limit for the CO column density of $10^{17}$ cm$^{-2}$. We adopted a column density of $10^{18}$ cm$^{-2}$ and a line width of 10 km/s. This parameters gives
a a temperature lower limit of 200 K. The best fit model is obtained for $T = 350$ K and $n(H_2) = 10^6$ cm$^{-3}$, but observed emission can also be explain by lower temperature and higher density, or inversely. The lack of data between $J_{up} = 7$ and 15 not allow to constrain more precisely the physical parameters. The parameters we adopted require a beam dilution factor of 1, which implies an extended emission. This, both with temperature limit of 200 K we obtain, indicates that the emission between 15 $J_{up}$ $<$ 20 can not only arise from the ridge, but may arise from a the PDR region, in agreement with Howe et al., 1993. Nonetheless, BN/KL is a complex region where a lot of gas component whith nearby physical characteristics are present. This components are not resolved with LWS. Even if a single gas component can explain the $J_{up} = 15$ to 20 emission we observed, a part of emission may arise from the ridge. Nonetheless, because of it low temperature, we estimated the $J$ emission contribution of ridge of 10 % of the PDR emission. The hot core, due to its small angular size towards the PDR, also certainly few contribute to the 15 $J_{up}$ $<$ 20 emission. The density and column density are in agreement with previous works (Howe et al., 1993), but the temperature we derive is significantly higher.

3.2. $J_{up} = 20$ to 30 emission. Plateau

Observed emission between $J_{up} = 20$ and 30 show a broad shaped emission necessary arising from an hotter and denser component than the PDR. Along the same lines, we used the $^{13}CO$ to $^{12}CO$ fluxes at $J_{up} = 24$ to constrain the physical parameters of the gas emitting at these transitions. This ratio give a photon escape probability of 0.2.

3.3. High $J$ emission. Shocked gas

Although high $J$ emission could be explain by higher plateau temperatures and densities, the observed broadening of $J_{up} > 32$ lines clearly shows that emission at this transitions arises from another hot and dense gas component. High temperatures and densities that requires this emission suggest that the emission arise from the gas shocked by the high velocity outflow, in agreement with Sempere et al., 2000 interpretation. We modelled this emission by a gas temparature of 1500 K, $n(H_2) = 4.10^6$ cm$^{-3}$, and $\Delta v = 50$ km/s. Theses requires a beam averaged column density of $10^{17}$ cm$^{-2}$. Assuming a angular size of 40 $''$, it implies a column density of $10^{16}$ cm$^{-2}$. This values are in good agreement with Sempere et al., 2000. At $J_{up} > 32$, the shocked gas emission become more important than the...
3.4. Agreement with observed lines profiles

In order to check the agreement of our model with observed lines profiles, we compared theoretical emission lines profiles of the three component with observed profiles. Theoretical profiles were obtained in convolving gaussian profiles by the PSF of the instrument. The line intensities were inferred from lines fluxes predicted by our LVG model. The PSF was obtained by Vastel et al. in observing thin [OI], [OIII] and [CII] lines in NGC7023 and G 0.6-0.6. The theoretical profiles, superposed on observed lines, are shown on fig. 5. The theoretical profiles are in good agreement with the observed ones. The predominance of shocked gas emission at $J_{\text{up}} = 32$ can explain the broadening of lines observed at theses transitions.

Table 1. Temperatures, densities, column densities and micro turbulent velocities of ridge, PDR, plateau and the shocked gas determined from our LVG model

|                | PDR | Plateau | Shocked gas |
|----------------|-----|---------|-------------|
| n(H$_2$) cm$^{-3}$ | $10^9$ | $2.10^8$ | $4.10^8$ |
| T (K)          | 400  | 350     | 1500        |
| N(CO) (cm$^{-2}$) | $10^{18}$ | $5.10^{19}$ | $10^{22}$ |
| $\Delta v$ (km/s)  | 10   | 30      | 50          |
| Filling factor (%) | 100  | 7       | 25          |

4. Conclusions

The Orion BN/KL observations with LWS allowed to detect $J_{\text{up}} = 15$ to 49 CO rotational transitions in Fabry-Perot mode. The modelling of observed fluxes by a LVG showed that molecular emission can be explained by three gas components that we characterised in term of temperature, density and column density (see tab. 1). We found that low J emission can not only arise from the ridge, too cold, but may arise from the PDR region. The emission between $J_{\text{up}} = 20$ and 30 certainly arise from the high velocity outflow. Finally, observed $J_{\text{up}} > 32$ lines broadening is though to be due to the gas shocked by the high velocity outflow. High J fluxes measurements lead to estimate a shocked gas temperature between 1000 and 2000 K, a H$_2$ density between $10^6$ and $10^7$ cm$^{-3}$ and a CO column density between $10^{15}$ and $10^{18}$ cm$^{-2}$. Our model both account of observed fluxes and lines profiles. This study show the necessity of high resolution observations of Orion BN/KL, as ISO-LWS observations not allow the spectral separation of the different gas components. Future observations with HIFI, onboard the Far Infrared Space Telescope (FIRST) will allow the spectral separation of the PDR and the plateau component, unresolved with ISO, and characterise more precisely the Orion BN/KL star forming region.

Acknowledgements

This study is based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA.

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