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Structure and excitation conditions of the southern part of the Orion B molecular cloud: a CO multiline study

Carsten Kramer (IRAM, Granada, Spain), Jürgen Stutzki, Gisbert Winnewisser (Universität zu Köln, Germany)

We present extended maps of ^{12}CO and ^{13}CO (J=2→1 and J=3→2) of the southern part of the Orion B region covering a $\sim 20' \times 60'$ area (in ^{13}CO(2→1)), and encompassing the NGC 2024 H II region, the interface region between NGC 2024 and the optical nebula IC434, the reflection nebula NGC 2023, and the Horsehead Nebula B33. The physical conditions in these different regions vary significantly due to the influence of the OB association lying to the west and due to the embedded stars. The CO emission originates from many clumps, most apparent in individual velocity channel maps. The observed low-J CO and isotopic CO line ratios are inconsistent with the standard interpretation in terms of a single temperature gas component along the line of sight in LTE. They require an outward temperature gradient on the cloud surface, as is naturally expected to arise from external UV heating. A consistent interpretation for both absolute line brightnesses and the intensity ratios can be reached in terms of PDR models. These indicate densities within the bulk of Orion B of at least close to 10^5 cm^{-3}. In addition we analyse the structure by subdividing the ^{13}CO(2→1) emission of Orion B into clumps using an automated procedure. The shape, orientation, LTE mass, virial mass, and stability of these clumps is examined. The mass spectrum of the clumps follows a power law, $dN/dM \propto M^{-\alpha}$, with $\alpha = 1.65 \pm 0.24$.

OBSERVATIONS

The analysis presented here is based on CO data obtained with the KOSMA (Kölner Observatorium für Submm-Astronomie) 3m telescope located on Gornergrat, Switzerland (Winnewisser et al. 1986, 1990). The data set was acquired during several observing runs between November 1990 and January 1992. We used two cooled GaAs Schottky heterodyne receivers built at Cologne with noise temperatures (DSB) of about 400 K at the frequencies of the J=2→1 and the J=3→2 transitions near 230 and 345 GHz respectively. As backend, we used for both receivers an acousto optical spectrometer with 1720 channels, a resolution bandwidth of 287 kHz, and a channel

spacing of 167 kHz (Schieder et al. 1989), which corresponds to 0.22 (0.14) kms^{-1} at 230 (345) GHz.

SUMMARY

The observed J=2→1 and J=3→2 transitions of CO and ^{13}CO are used to analyse the excitation conditions and the structure of the cloud. The maps of integrated ^{13}CO and ^{12}CO(2→1) intensities both have a filamentary or clumpy appearance extending over at least two orders of magnitude: from 70 pc, the size of the total Orion B region as seen in ^{13}CO(1→0) (Bally et al. 1991), down to the resolution of our maps, 0.2 pc, or less. The corresponding channel maps show that the temperature distribution traced by ^{12}CO is comparable in complexity to the column density structure traced by ^{13}CO. We find and discuss the interaction of the nearby OB association on the observed large scale spatial and velocity distribution of the ^{13}CO emission.

To better quantify the structure found, we subdivided the ^{13}CO(2→1) emission line data into clumps, using the Gaussian clump decomposition algorithm developed by Stutzki & Güsten (1990). The 288 clumps found are mostly elongated with an average aspect ratio of 3. The position angles of the long clump axis show a general alignment with the global filamentary cloud structure. The clump mass spectrum, derived from LTE ^{13}CO column densities, is well fitted by a power law $dN/dM \propto M^{-\alpha}$ with $\alpha = 1.65$. This index is similar to that found by Lada et al. (1991a) in her CS-survey of Orion B. We find indications for a continuation of the linear mass spectrum beyond typical critical (Jeans) masses. The five most massive clumps constitute 35% of the total mass, 3145 M$_\odot$, of all clumps found. The most massive clumps have virial masses which are only a factor of three larger than the LTE-masses. We note that a slight optical thickness of the ^{13}CO lines leads to an underestimate of the clump masses indicating that the most massive clumps might well be gravitationally bound. Clumps more massive than about 25 M$_\odot$ follow the relation $M_{\rm vir}/M_{\rm LTE} \propto M_{\rm LTE}{}^{-2/3}$ derived by Bertoldi & McKee (1992). The less massive clumps are not gravitationally bound and do not show any correlation between $M_{\rm vir}$ and $M_{\rm LTE}$. Expansion times derived from a comparison of virial- and LTE-masses are of the same magnitude as typical collision times: several 10^5 years. Thus the clumps should be dissolving at a high rate unless external pressures in the range between 10^3 and 10^6 K cm^{-3} are present to confine the clumps.

In order to derive local densities we analysed the line temperatures and line ratios. We find:

$$\frac{T_R^*(^{12}\mathrm{CO}(3\rightarrow2))}{T_R^*(^{12}\mathrm{CO}(2\rightarrow1))} \equiv {}^{12}\mathcal{R}_{3,2} \sim 1 \qquad \frac{T_R^*(^{13}\mathrm{CO}(3\rightarrow2))}{T_R^*(^{13}\mathrm{CO}(2\rightarrow1))} \equiv {}^{13}\mathcal{R}_{3,2} \sim 1 \qquad (1)$$

constant across the line profile and at nearly all positions. For the line center at 10 kms^{-1} we find

$$\frac{T_R^*(^{12}\mathrm{CO}(2\rightarrow1))}{T_R^*(^{13}\mathrm{CO}(2\rightarrow1))} \equiv {}^{12,13}\mathcal{R}_2 = 3. \qquad (2)$$

The ratio $^{12,13}\mathcal{R}_2$ rises to values above 10 within the line wings as the ^{13}CO lines are generally narrower than the ^{12}CO lines.

It is shown that these ratios cannot be explained by homogeneous clouds with constant excitation conditions along the lines of sight, equal excitation temperatures for ^{12}CO and ^{13}CO, and optically thin ^{13}CO emission. Instead, the data are consistent with PDR models (e.g. Köster et al. 1994) assuming radially varying excitation temperatures and densities along the lines of sight within UV-irradiated molecular clouds/clumps. We estimate the strength of the UV-field within Orion B by summing up the contributions of the surrounding OB stars. Given the typical clump diameter of 0.32 pc and the average volume filling factor of 0.3, we find a 1/e scale length of 1 pc for the UV attenuation within the cloud. The UV fluxes range between 100 in the south-eastern outskirts and more than 10^4 in the inner regions of NGC 2024. The average line temperatures and ratios arise in regions of moderate UV-fluxes of several 10^2. Applying the PDR-model of Köster et al. (1994) shows that local densities of about 10^5 cm^{-3} or higher are needed to explain the observed line ratios.

Two regions exhibit deviations from this general picture. The line ratios and shapes found in the NGC 2024/IC434 interface region suggest very high volume densities of more than 10^6 cm^{-3} when analysed with the PDR models of Köster et al. (1994). The gas apparently consists of small, dense clumps emerged in a diluted gas. The Horsehead region on the other hand exhibits smaller line temperatures and widths than the bulk of the Orion B cloud. In addition, the line ratios indicate local densities of less than about 10^4 cm^{-3}. These findings are in accordance with the interpretation of the Horsehead Nebula as a cold, isolated density fragment emerging from the more complex parental main cloud. In the Horsehead region the density contrast between the local densities $n_{\rm loc}$ and the average volume densities $n_{\rm av}$ is $\sim$20, whereas it is greater than 200 within the main cloud. The general ratio between local density and average clump density $n_{\rm loc}/n_{\rm cl}$ still is 60 or higher. This indicates that the clumps identified are not homogeneous units but exhibit strong substructure themselves.

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