Anomalies of the $J = 1-0$ HCN hyperfine structure and clumpiness of dense molecular cloud cores. Implications for S140 IRS1

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Introduction

$J = 1-0$ HCN observations toward dense molecular cloud cores associated with Galactic high-mass star forming regions (Pirogov, 1999) reveal prominent anomalies of hyperfine component intensities $R_{12} = T(F = 1-1)/T(F = 2-1) \leq 0.4$ and $R_{02} = T(F = 0-1)/T(F = 2-1) \geq 0.2$ in many cases. A standard explanation of this effect includes thermal line overlaps in higher HCN transitions (Guilloteau and Baudry, 1981, hereafter GB), yet, the observed line widths in the sources demonstrating anomalies are highly suprathermal (> 2 km/s). It is shown (Pirogov, 1999) that microturbulent models with local line profiles having both thermal and microturbulent contributions fail to reproduce $J = 1-0$ HCN anomalies together with high line widths. These models often produce saturated or self-reversed HCN profiles which are rarely observed in that kind of objects.

On the other hand, there are many indications that molecular clouds and their cores are clumpy on all spatial scales down to telescope resolution limits (see Goldsmith, 1995). One might expect that in the case of small-scale clumpiness the anomalies of the $J = 1-0$ HCN hyperfine structure can originate in clumps with nearly thermal local line widths. If the clump's volume filling factor is sufficiently small, the emission from a single clump can escape from the cloud without significant scattering thus providing information about its parameters. Observed line widths in this case reflect velocities of interclump motions.

A clumpy model

We developed a program that calculates HCN excitation parameters as well as emergent $J = 1-0$ HCN profiles within a spherically-symmetric model that can consist of many clumps unresolved by a telescope beam. The model utilizes the multi-zone radiative transfer code developed earlier for a cloud with smooth density distribution (Turner et al., 1997).

Model cloud consists of a set of concentric zones, each of which is divided into cells having dimensions lower or equal to zone's width. Each cell can be filled with gas or be empty according to integer random number generator which gives 1 with probability P (clump) or 0 (empty cell) with probability $(1-P)$ The probability P which has the same statistical meaning as clump volume filling factor can be varied from zone to zone, thus changing number of clumps in each zone. No interclump gas is assumed. Clumps are considered to be homogeneous isothermal balls of the same size without internal structure. Clump parameters (kinetic temperature, density and microturbulent velocity) as well as velocity of bulk motions of clump ensemble can be varied from zone to zone.

HCN excitation is computed for one representative clump per zone using GB approach and assuming constant excitation conditions within the clump. All clumps in the zone are assumed to be identical to the given clump. Local line profile for each clump is assumed to be Gaussian with both thermal and microturbulent contributions to its width. Angular integration while computing mean radiation field is calculated by summing radiation coming along number of rays separated by a fixed angular step. Radiation along particular ray summarizes contributions from clumps crossed by this ray. Each clump has randomly oriented velocity component. Its absolute value called velocity of interclump bulk motions is the same for each clump in the given zone. A projection of random velocity component on a given ray gives particular Doppler shift for emission coming from distant clump. Spatial distribution of clumps is kept fixed during calculation of HCN excitation for given clump in the zone. Because next representative clump can take arbitrary place in the next zone, new spatial distribution of clumps is considered because all possible clumps configurations are statistically equivalent (see Pagani, 1998).

Iteration process is similar to the one described by Turner et al. (1997). After the iteration process converges, emergent line profiles are calculated for all independent lines of sights separated by angular size of single clump. To reduce statistical fluctuations, the resultant profiles are averaged over independent lines of sight within projection of each zone on a plane of a sky. These profiles can be convolved with telescope beam to be compared with real spectra.

L1204/S140 IRS1 dense core – implications for clumpy structure

The clumpy model was examined by fitting model profiles to the HCN and $H^{13}CN$ spectra observed toward the bright infrared source S140 IRS1. This well-known high-mass star forming region demonstrates very strong HCN lines with prominent anomalies. S140 IRS1 has been widely observed and modeled in various lines giving a possibility to compare with the parameters found by other authors.

The dense core of the L1204 molecular cloud is located northeast of the S140 optical H II region and contains a cluster of three infrared sources, IRS 1-3, which are identified with high-mass stars of spectral type B (Evans et al., 1989). The multitransitional CS observations of the core (Zhou et al., 1994) reveal two different components on a subarcminute spatial scale: a spherical one centered on IRS1 and an arc component being closer to the photon-dominated interface region between the H II region and molecular cloud. The arc component demonstrates resolved clumpy structure (Hayashi and Murata, 1992) while the spherical component shows a central disk surrounded by a cavity embedded in an inhomogeneous dense envelope (Wilner and Welch, 1994; Minchin et al., 1993; Harker et al., 1997).

The $J = 1 - 0$ HCN observations toward S140 IRS1 performed at RT-22 (Pirogov et al., 1995) and at 20-m OSO (Pirogov, 1999) reveal the following line parameters: $T_{MB}(F = 2 - 1) = 10$ K, $\Delta V = 2.6$ km/s and $R_{12} = 0,37$, $R_{02} = 0.24$. The $J = 1 - 0$ $H^{13}CH$ line parameters are the following: $T_{MB}(F = 2 - 1) = 1.2$ K, $\Delta V = 2.2$ km/s and $R_{12} \approx 0,6$, $R_{02} \approx 0.2$ (Pirogov et al., 1995). Our observations with 40 beam toward IRS1 covered most of the spherical component and, probably, a part of the arc component.

In order to reproduce the observed $J = 1 - 0$ HCN and $H^{13}CH$ spectra toward S140 IRS1 we performed detailed model calculations of the spherical component. We took 0.44 pc for the outer radius (Zhou et al., 1994) and divided the model core into 17 zones, each zone having 0.026 pc width. Clump parameters: number density, kinetic temperature as well as volume filling factor and velocity of bulk motions were kept constant within each zone and could be varied from zone to zone as power-law functions of a zone's radius. Microturbulent velocity was set to zero in order to obtain the effect of thermal line overlaps alone. The velocity of bulk interclump motions was set to 1.3 km/s according to the optically thin $H^{13}CN$ line width. Following Zhou et al. (1994) we assumed the central zone to be empty in order to account for the cavity around IR sources. The HCN abundance was assumed constant and its value was varied in order to fit the calculated $F = 2 - 1$ intensity to the observed value.

The resulted spectrum was calculated by averaging individual spectra for all independent lines of sight within the projection of each zone on the plane of the sky and then convolving the averaged model spectra corresponding to different projections with a $40''$ beam. The quality of fitting was controlled by the sum of squares of residual between model and observed values of line profile temperatures.

A clump's number density and volume filling factor were set to be power-law functions of radius: $n = n_0(r/R)^{-\alpha}$ and $P = P_0(r/R)^{-\beta}$ respectively, where n_0 and P_0 corresponds to the second zone and R is the outer radius. While searching for suppressed R_{12} ratios together with $R_{02} \geq 0.2$ we found that the best fits occur at kinetic temperatures ≤ 20 K. This could be related to the fact that the overlaps of the second pair of closely located components in the $J = 2 - 1$ transition ($F = 2 - 2$ and $F = 1 - 0$, see GB) which lead to suppressed R_{02} ratio are still effective at temperatures higher than 20 K. We set the following law for kinetic temperature dependence: $T_{KIN} = 30(r/R)^{-0.4}$ which gives 30 K in the second zone and 10 K at the edge of the cloud. The best fit parameters correspond to $n_0 = 1.8 \cdot 10^6$ cm^{-3}, $\alpha = 0.6$, $P_0 = 0.2$, and $\beta = 0.3$. Microturbulent CS modeling performed by Zhou et al. (1994) resulted in the following radial dependence of number density: $n = 1.4 \cdot 10^6 (r/R)^{-0.8}$ which has a power-law index close to the total $n(r)$ and $P(r)$ index from our results. Lower kinetic temperatures (e.g. 13 K for all zones) can give even better fits, yet, low temperatures contradict with high HCO^+ line intensities observed toward S140 IRS1 with $20''$ resolution (Hasegawa et al. 1991). The number of clumps within the first 4 zones which give the main contribution to the resulting spectrum is ~ 16000 with an average volume filling factor of 0.11 which is somewhat lower than estimates made by other authors (Zhou et al., 1994; Spaans and Dishoeck, 1997). The HCN abundance is $\sim 5 \cdot 10^{-9}$.

The $H^{13}CN$ lines are nearly optically thin and the R_{12} and R_{02} ratios are approximately equal to 0.6 and 0.2, respectively, being insensitive to particular forms of density and volume filling factor laws. We used the power-law parameters from the HCN fitting and fit only the $F = 2 - 1$ peak intensity varying $H^{13}CN$ abundance. The best $H^{13}CN$ fit was found at $X(H^{13}CN) \approx 1.8 \cdot 10^{-10}$. The HCN and $H^{13}CN$ spectra are shown in Fig. 1 together with the best fitting curves.

The results of recent HCN and $H^{13}CN$ observations toward S140 IRS1 obtained at OSO with high spectral resolution are also discussed.

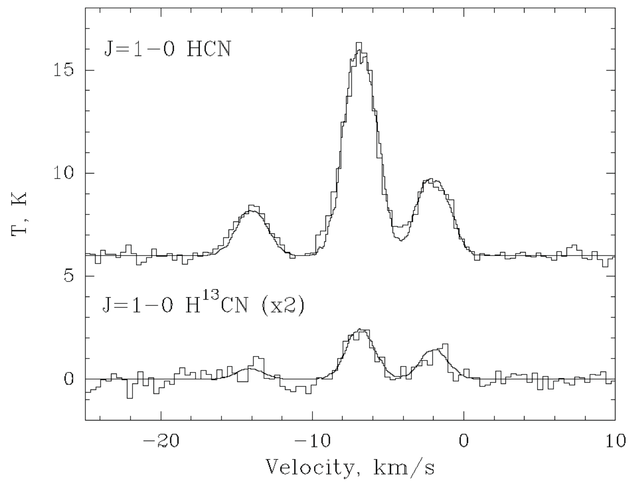

Figure 1: The $J = 1 - 0$ HCN and $H^{13}CN$ profiles toward S140 IRS1 (Pirogov et al., 1995). Smooth curves correspond to the clumpy model results

Conclusions

Anomalies of the $J = 1 - 0$ HCN hyperfne structure ($R_{12} \leq 0.4$ and $R_{02} \geq 0.2$) are often observed toward dense molecular cloud cores associated with high-mass star forming regions where line widths are highly suprathermal (Pirogov, 1999). These effects can be explained if the cores are clumpy on scales unresolved by telescope beam. Detailed clumpy model calculations give good fits between model and observed HCN and $H^{13}CN$ spectra toward the bright infrared source S140 IRS1 confirming that well-known HCN hyperfine intensity anomalies observed in regions of high-mass star formation can be an indicator of small-scale clumpiness.

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