MODEL OF THE CO MOLECULE EMISSION FROM THE CLOUD WITH BIPOLAR OUTFLOWS

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INTRODUCTION

A lot of interstellar clouds are the sources of star formation. Observations of bipolar outflows testify the process of star birth and their evolution in a cloud. Millimeter and infrared emissions from molecular clouds are under investigation in many observational programs. Interpretation of the observational data requires to develop molecular cloud models in order to compare the observed and simulated emission characteristics.

We propose a numerical model for calculation of radiation of molecular lines from a cloud having the bipolar structure. It is assumed that the cloud has two kinds of symmetry: axial symmetry around the Z axis, and symmetry relative to the plane XY (Fig. 1). In this paper we calculate the CO molecule radiation, but the method can be easily applied to the calculation of arbitrary molecules having known excitation coefficients. The first 6 rotation transitions of CO molecule are considered under its excitation by Hydrogen molecules with account of cosmic microwave background.

The model allows to specify any distribution laws for concentration of CO, H_2, the kinetic temperature, and velocities in the plane XZ. Using the linear approximation allows to obtain higher than in Monte-Carlo [1, 2] method accuracy of the determination of the mean intensity of the radiation field, and the excitation temperature in a cloud.

SOLVING RADIATIVE TRANSFER EQUATION

The cloud is considered as consisting of elementary volumes (cells) which have a toroidal form and locate equidistantly on axes X and Z. All the cloud parameters (CO, H_2 molecule densities, the kinetic temperature, micro turbulent and systematic velocities) are assumed to be constant within any cell. It should be noted that the method accuracy becomes higher with decreasing the space gradient of any parameter.

The radiation transport equation together with a system of equations of the population balance has been solved by an iterative method. Initially, it was assumed that the populations in any cell are defined by the Boltzman law. Then, for all the cells, the average intensity $\langle J(\vec{r})\rangle$ has been calculated by the formula:

$$\langle J(\vec{r})\rangle = \frac{1}{4\pi}\int\limits_{4\pi} d\Omega \int\limits_{-\infty}^{+\infty} d\nu\varphi(\nu) I(\nu,\vec{n},\vec{r}). \tag{1}$$

The integral over frequencies was approximated by a sum over fixed set of frequencies. The integral over solid angle was also calculated over limited number of random directions. The intensity $I(\nu,\vec{n},\vec{r})$ in the line of $\vec{n}$ was calculated by formulas for plane-parallel geometry:

$$I(\nu,n,r) = \sum_{p=1}^{k}\left[S_{ij}^{p}\left(1-e^{-\tau_{ij}^{p}}\right)\exp\left(-\sum_{m=p+1}^{k}\tau_{ij}^{n}\right)\right] + I_B\exp\left(-\sum_{p=1}^{k}\tau_{ij}^{n}\right), \tag{2}$$

$$\tau_{ij}^{p} = \frac{h\nu_{ij}}{c}\varphi\left(\nu-\nu_{ij}\left(1-\frac{\vartheta_{\vec{n}}^{p}}{c}\right)\right)\Delta l(B_{ji}n_j - B_{ij}n_i), \tag{3}$$

where I_B is the background radiation field, S_{ij}^{p} is the source function, τ_{ij}^{p} is the optical depth at the point P in the line of $\vec{n}$, i and j are the upper and lower energy level populations at the point P.

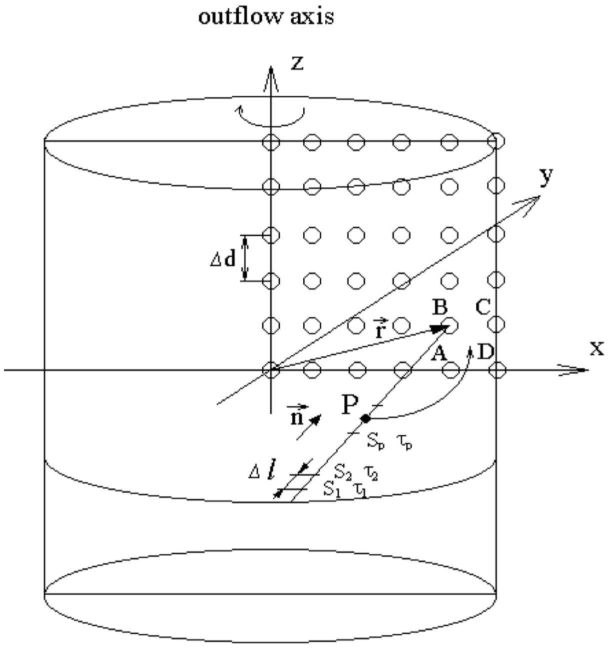

Figure 1: The structure of the cloud calculated:
$\vec{r}$ is the radius-vector of a cell for which $\langle J(\vec{r})\rangle$ is calculated;
$\vec{n}$ is the direction along which the intensity I is calculated;
Δl is the step on which the intermediate values I are calculated

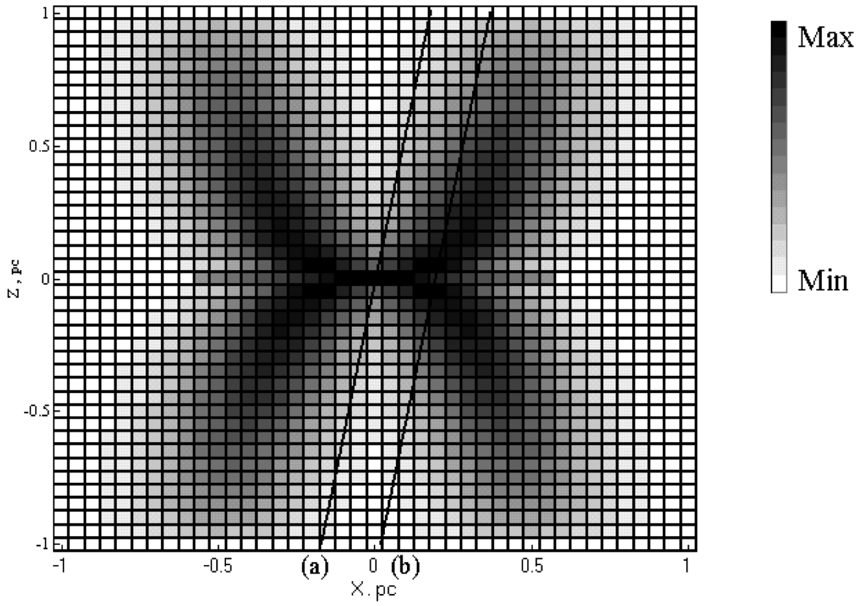

Figure 2: The CO molecule density distribution:
Min $n_{CO} = 0.001$ cm^{-3};
Max $n_{CO} = 0.01$ cm^{-3}

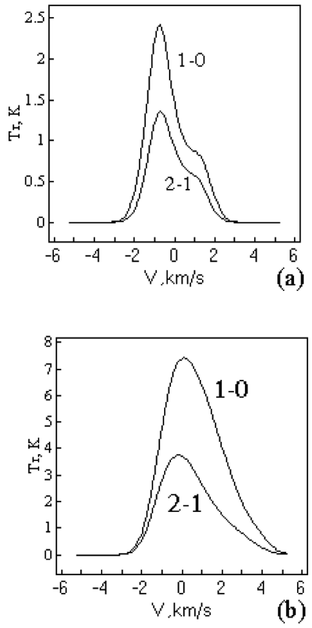

Figure 3: The profiles of lines corresponding to location of the telescope ray (a) and (b) in Fig. 2

The populations, velocities and other parameters at the point P were calculated using the linear approximation over the nearest four cells (A, B, C, D in Fig. 1). The step Δl must satisfy the conditions:

$$\frac{\Delta\vartheta_t}{\Delta l} \gg Q, \quad \Delta l > \Delta d, \tag{4}$$

where $\Delta\vartheta_t$ is the micro-turbulent velocity, Q is the systematical velocity gradient which are taken in the cloud point where the ratio $\dfrac{\Delta\vartheta_t}{Q}$ is maximal.

There after, for all cells the system of population balance equations was solved and the refined population values were calculated. The process was iterated till the given population error became obtained.

As an example, the molecular cloud was taken with disk and bipolar outflows. The CO concentration distribution is shown in Fig. 2. The outflow velocity is assumed to be proportional to the distance from the cloud center. The kinetic temperature distribution is the same as CO concentration (min $T_{kin} = 5$ K, max $T_{kin} = 20$ K). In Fig. 3 the line profiles of the transitions $J = 1-0$ and $2-1$ are shown which correspond to the telescope rays (a) and (b) in Fig. 2. In Fig. 4 (a, b, c) the calculated excitation temperatures are shown for transitions $J = 1-0$, $J = 2-1$ and $J = 3-2$ of the CO molecule. The population mean relative error obtained in calculation is near 1%; the program run time on PC IBM with a processor Pentium III 550 is nearly 3 hours.

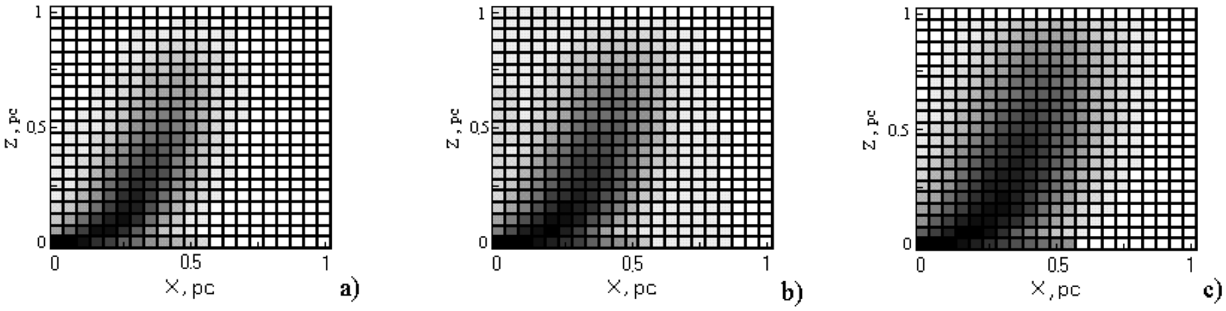

Figure 4: The calculated excitation temperatures for transitions $J = 1-0$ (a), $J = 2-1$ (b), $J = 3-2$ (c)

Min $Tex_{1-0} = 3$ K	Min $Tex_{2-1} = 3$ K	Min $Tex_{3-2} = 3$ K
Max $Tex_{1-0} = 25$ K	Max $Tex_{2-1} = 9.7$ K	Max $Tex_{3-2} = 8.5$ K

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