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# Determination of the structure of Orion A cloud from spectral data for carbon monoxide

Balaram Bhattacharyya, Swati Ray and A K Barua

Department of General Physics & X-rays
Indian Association for the Cultivation of Science Calcutta-700032

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**Abstract.** By assuming a spherical collapse model and the simultaneous existence of density and velocity gradients attempt has been made to interpret the rotational lines for CO ($2 \to 1$ and $1 \to 0$) obtained from Orion A cloud. The brightness temperature $T_B$ as function of right ascension (R.A.) and velocity have been considered. A structure for Orion A has been determined by us to interpret the more recent data for $2 \to 1$, $1 \to 0$ transitions of CO as function of R.A. All the calculations have been done using accurate values of the rate constants for rotational transitions in CO induced by collisions with $H_2$. This structure could also explain the velocity profile for CO fairly well.

## 1. Introduction

With the availability of spectral data from the dense intersteller clouds, work has recently been started for the determination of the various physical parameters viz., density, temperature, velocity gradient etc. in such clouds.

Model calculations of the various factors determining the intensity of a spectral line have been done by Goldsmith (1972), Scoville and Soloman (1974) and Goldreich and Kwan (1974) and in more detail by De Jong *et al* (1975). Clark *et al* (1974) first attempted to determine the structure of the innermost portion of Orion A by using the data for HCN. They, however, used a static model which is physically unrealistic due to the definite existence of velocity fields in the cloud. Gerola and Sofia (1975) first attempted to determine the structure of Orion A cloud on a realistic basis. They considered the spectral lines for the rotational transitions $1 \to 0$ and $2 \to 1$ for CO (Phillips *et al* 1973) and $1 \to 0$ line for HCN (Snyder and Buhl 1973) The data for CO as functions of R.A. and velocity of cloud and for HCN the data as function of R.A. which were very scanty were interpreted. For these calculations, the spherical collapse model which is mathematically tractable was used and the radiative transfer theory of Sobolev (1960) was applied. By considering the simultaneous existence of a velocity field increasing outwards and a density gradient they were moderately successful in obtaining a model for the Orion A clouds which could explain the experimental data available at that time. Gerola and Sofia (1975) had the additional difficulty as at that time no reliable rate coefficient data for $H_2$-CO collisions were available, an accurate knowledge of which is important.

However, subsequent to the work of Gerola and Sofia (1975) more recent and reliable experimental data for 2–1 and 1–0 lines of CO from Orion A cloud as function of R.A. and velocity of the cloud have been reported (Wannier *et al* 1976). The most interesting feature of the more recent data is that even at large distances from the centre of the cloud the $2 \rightarrow 1$ and $1 \rightarrow 0$ lines of CO have almost equal intensity whereas for the data reported by Phillips *et al* (1973) this feature was present only near the centre of the cloud. The equality of the brightness temperature for the $2 \rightarrow 1$ and $1 \rightarrow 0$ lines normally indicates the existence of local thermal equilibrium. However at large distances from the centre of the cloud where densities are small, L.T.E. condition is not likely to hold. Thus it is interesting to see whether a suitable model for Orion A cloud may be constructed which may explain the experimental data under non-LTE conditions. At present accurate rate—coefficients for $H_2$-CO collisions under interstellar conditions are available (Green and Thaddeus 1976) so that more reliable determination of the structure of Orion A cloud is possible.

It is relevant here to point out that the spherical collapse model is probably too simple for the actual conditions existent in the molecular clouds. However, it will have very little effect on calculated line profile toward the centre of the cloud as the latter primarily depend on the velocity, density and temperature distributions along the line of sight (Kwan 1978). Also, it is the only model which is at present mathematically tractable. Thus, it is necessary to exploit fully this model for the interpretation of the spectral data and see its suitability.

In this paper we have constructed a model for Orion A cloud to interpret the more recent experimental data for CO. We have concentrated on the data for CO only as those are quite extensive and reliable. For HCN the experimental data are very scanty and the rate-coefficients for $H_2$-HCN collisions are not available. Thus their consideration may lead to erroneous results.

## 2. Theory

For the determination of the population distribution of molecules in different rotational levels we consider the simultaneous existence of the radiative transitions and collision induced rotational transitions. In statistical equilibrium (De Jong *et al* 1975)

$$n_i(r) \sum_j P_{ij}(r) = \sum_j n_j(r) P_{ji}(r) \tag{1}$$

where $n_i(r)$ is the population per c.c. of level $i$ at the point $r$. The transition probability $P_{ij}(r)$ between the two rotational states $i$ and $j$ can be expressed as,

$$P_{ij} = A_{ij} + B_{ij} < J_{ij}(r) > + C_{ij}, \quad (i > j), \tag{2}$$

$$= B_{ij} < J_{ij}(r) > + C_{ij}, \quad (i < j), \tag{3}$$

where $A_{ij}$ and $B_{ij}$ are the Einstein's transition probabilities and $C_{ij}$ is the collision induced transition probability $< J_{ij}(r) >$ is the mean integrated radiation field at the frequency $\nu_{ij}$ for the transition $i \rightarrow j$.

The Einstein's coefficients $A_{ij}$ and $B_{ij}$ may be expressed as,

$$A_{j+1,j} = 16hB^3c(j+1)^3 B_{j+1,j} \tag{4a}$$

$$B_{j+1,j} = \frac{32\pi^4\mu^2(j+1)}{3ch^2(2j+3)} \tag{4b}$$

and

$$g_i B_{ij} = g_j B_{ji}$$

where $B$ is the rotational constant in $\mathrm{cm}^{-1}$, $\mu$ the dipole moment, $g_i$ and $g_j$ are respectively the statistical weights for levels $i$ and $j$.

$< J_{ij} >$ may be determined from the equations of transfer of radiation. The problem is considerably simplified when a macroscopic velocity field with a velocity gradient much larger than the thermal velocities of the molecules exists in the cloud (Sobolov 1960). In a spherically symmetric cloud with a large velocity gradient, photons emitted at a particular point in the cloud can be absorbed only within a small distance of the order of $l \approx v_t R/V$ ($v_t$ being the thermal velocity, $V$ the macroscopic velocity and $R$ is the radius of the cloud). Thus some of the photons will escape, the probability of which is denoted by $\beta_{ij}$. The method of Sobolov (1960) has been extended by Castor (1970) and Lucy (1971). $< J_{ij} >$ may thus be expressed as

$$< J_{ij}(r) > = [1-\beta_{ij}(r)]S_{ij}(r)+\beta_{ij}(r)B_{ij}(\nu_{ij}, T_{BB}), \tag{5}$$

where $B_{ij}$ $(\nu_{ij}, T_{BB})$ is the black body radiation field and $T_{BB}$ is the Cosmic black body radiation temperature taken as 2·7K.

The source function $S_{ij}(r)$ can be written as

$$S_{ij}(r) = \frac{2h\nu_{ij}^3}{c^2} \left[\frac{n_j(r)g_i}{n_i(r)g_j} - 1\right]^{-1} \tag{6}$$

where $n_i$, $n_j$ are the population densities of levels $i$ and $j$ and $g_i$, $g_j$ the corresponding weight factors, $\nu_{ij}$ is the frequency of the emitted radiation.

The escape probability $\beta_{ij}$ is given by,

$$\beta_{ij}(\sigma, \tau) = \int_0^1 \frac{1+\sigma x^2}{\tau_{ij}} \quad \text{-exp} \left(\frac{-\tau_{ij}}{1+\sigma x^2}\right)\Bigg] dx, \tag{7}$$

where $\sigma = \frac{d \ln V(r)}{d \ln r} - 1$, $V(r)$ being the velocity at $r$. The optical depth $\tau_{ij}$

may be written as,

$$\tau_{ij} = \frac{A_{ij}c^3 n_i}{8\pi\nu^3_{ij}} \left[\frac{n_j g_i}{n_i g_n} - 1\right] \frac{r}{V(r)} \tag{8}$$

The absolute intensity of the spectral line can be expressed as (Gerola and Sofia 1975),

$$I_{ij} = S[(p^2+z_0^2)^{\frac{1}{2}}]\{1-\exp[-\tau_{ij}(\nu_{ij}, p)]\} \tag{9}$$

where $r = (p^2+z_0^2)^{\frac{1}{2}}$, $p$ being the impact parameter which gives the position in the cloud that we look at and $z_0$ may be determined from the relation

$$\frac{\nu_0}{C} \frac{V(p^2+z_0^2)^{\frac{1}{2}}}{(p^2+z_0^2)^{\frac{1}{2}}} z_0 = -(\nu-\nu_0), \tag{10}$$

$\nu_0$ being the central frequency of the line The brightness temperature $T_B$ in K is given by

$$T_B = \frac{\lambda^2_{ij}}{2k}(I_{ij} - I_{BB}),$$

where $k$ is Boltzmann constant and $I_{BB}$ being the intensity of the cosmic background.

## 3. Calculation and Results

In order to interpret the more recent data on brightness temperature of $2 \rightarrow 1$ and $1 \rightarrow 0$ lines of CO (Wannier *et al* 1976) we have used the accurately calculated values of the rate coefficient for $H_2$-CO given by Green and Thaddeus (1976). For the purpose of extrapolation to higher $j$ values the empirical formula obtained by De Jong *et al* (1975) which fitted the calculated values of rate coefficients have been used. To solve the equation of statistical equilibrium (equation 1) we have considered 20 rotational levels of CO and applied matrix inversion technique. For the determination of population distribution $n_i$ at different values of $r$ (the distance from the centre of the cloud), iterative method has been followed

Due to the penetration of the cosmic ultraviolet radiation, near the edges of the Orion A cloud, there may be significant density of electrons which we have not considered. Moreover, as stated earlier, the effect of departure of the cloud from spherical symmetry is likely to be more at larger distances from the centre. We have therefore confined our calculations upto an impact parameter of $8 \times 10^{18}$ cm. The $T_B$ values at different impact parameters were calculated by using the relevant equations in Section 2. We could obtain the best agreement with the experimental data as function of R.A. by using the physical parameters of Orion A cloud given in Table 1. The results obtained by us are shown in figure 1 together with the experimental data (Wannier *et al* 1976). The results obtained for the velocity profile of $1 \rightarrow 0$ line by using our model are shown in figure 2 together with the experimental data (Wannier *et al* 1976).

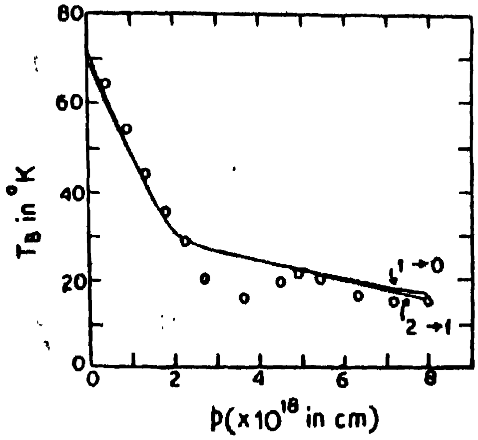


**Figure 1.**

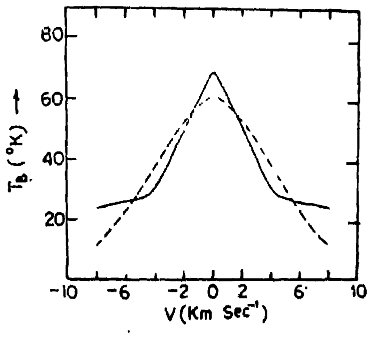


**Figure 2.**

## 4. Discussion of results

The results obtained (figures 1 and 2) using the model for Orion A cloud determined by us show that with the spherical collapse model it is possible to represent the basic features of the experimental data. The most interesting point is the capability of our model to explain the almost equality of the $T_B$ values of $2 \rightarrow 1$

and $1 \rightarrow 0$ lines of CO at comparatively large distances from the centre without assuming thermalization. The recent data on the velocity profile of $1 \rightarrow 0$ line may also be represented fairly well by our model. The discrepancy in the calculated and experimental values of the velocity profiles at larger values of the impact parameter is probably mainly due to the assumption of spherical symmetry of the cloud.

It is relevant here to point out certain features of the model of Orion A cloud obtained by us. In our model, beyond $r = 1{\cdot}8 \times 10^{18}$, we have assumed a much slower variation of the temperature of the cloud so that the kinetic temperature is higher than the brightness temperature of CO lines. This is realistic because at larger distances from the centre of the cloud, the departure from the local thermodynamic equilibrium condition will be more so that the kinetic temperature will be higher than the brightness temperature. In our model the density of $H_2$ in the Orion A cloud varies from $10^5$ to $10^3$ cm$^{-3}$ which agrees with the other estimates (De Jong *et al* 1975, Wannier *et al* 1976)

Our results show that fair success in interpreting the CO line intensities from Orion A cloud can be achieved by using the spherical collapse model. However, it is relevant to point out the factors which have not been considered viz. (i) the existence of maxima and minima in the $T_B$ values at distances from the centre of the cloud, the physical reason of which is not at present clearly understood, (ii) the departure from the spherical structure assumed by us.

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