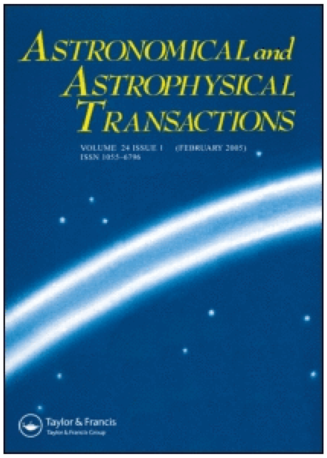

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A TWO-COMPONENT MODEL OF S201 IN $C^{18}O$ EMISSION LINES

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The observations of S201 were carried out in two $C^{18}O$ transitions: $J = 1 - 0$ and $J = 2 - 1$. The data obtained reveal two physically separated objects in S201 molecular cloud: an extended (~ 4.9 pc) envelope and more dense and compact (~ 0.8 pc) core. Assuming both objects microturbulent, isothermal and homogeneous the radiation transfer equations have been solved. The envelope parameters were determined as follows: H_2 number density of (1–4)10^3 cm^{-3}, $C^{18}O$ column density of (1.4–2.3)10^{14} cm^{-2} and its mass of $3.8 \times 10^3 M_{\odot}$. Analagous parameters of the core were estimated marginally: $\sim (0.8 - 1) \times 10^5$ cm^{-3}, $\sim 2 \times 10^{14}$ cm^{-2} and $\sim 600 M_{\odot}$. In the whole, the S201 molecular cloud is similar to an object at initial stage of gravitational collapse with the moderately hot core and contracting cold envelope.

KEY WORDS Interstellar medium, molecular clous, H II regions, star formation, CO emission, rotational lines

As it follows from our recent paper [1], the $C^{18}O$ ($J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions) data reveal similar physical conditions in molecular clouds associated with H II regions. Assuming homogeneous LVG-model, the hydrogen volume densities and $C^{18}O$ column densities were calculated. However, the S201 radiation temperatures in $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ transitions become incompatible if to adopt the LVG approximation. The radiation temperature is $T_R^*(J = 2 \rightarrow 1) = T_{21} = 0.77$ K, thus exceeding more than 4 times the peak temperature in the lower transition $T_R^*(J = 1 \rightarrow 0) = T_{10} = 0.17$ K (see Table 1). Usually, the opposite inequality $T_{10} > T_{21}$ is to be explained (see, for instance, [2]). The attempt to treat the S201 enhanced emission assuming close to LTE conditions [3] failed because it neglected the spatial and kinematic features of the $C^{18}O$ lines. In this paper we try to explain the S201 data using the microturbulent slab model [4] and taking into consideration the above mentioned features of the lines.

The observations were carried out in November–December, 1991, using the NRAO† 12-meter radiotelescope. Some details of the observations can be found in [1]. The S201 region was mapped in both transitions around the central point

†NRAO is operated by Associated Universities under agreement with the NSF of USA.

Table 1. The source list: coordinates and distance to the objects

Offset	$J = 1 \rightarrow 0$			$J = 2 \rightarrow 1$		
$\Delta\alpha$, $\Delta\delta$*(arc sec)*	ΔT, *K*	ΔV, *km/s*	*V,km/s*	ΔT, *K*	ΔV, *km/s*	*V, km/s*
0,0	0.17	1.35	-39.6	0.77	0.56	-40.0
-120,0	$\leq$ 0.06	–	–	–	–	–
120,0	0.17	0.5	-39.4	–	–	–
0,-120	0.12	1.6	-38.1	–	–	–
0,120	$\leq$ 0.1	–	–	–	–	–
-20,0	–	–	–	0.63	0.6	-39.8
20,0	–	–	–	$\sim$ 0.4	$\sim$ 3.2	-39.8
0,-20	–	–	–	0.62	0.5	-39.8
0,20	–	–	–	$\sim$ 0.3	$\sim$ 2.8	-39.5

$\alpha(1950.0) = 02^h58^m59^s.4$ and $\delta(1950.0) = 60°14'46''$. 5-point maps were obtained with the offsets of $2'$ at a frequency of 109.8 GHz ($J = 1 \rightarrow 0$) and $20''$ at a frequency of 219.6 GHz($J = 2 \rightarrow 1$). All the data obtained are summarized in Table 1.

Therefore, the 5-point mean value of T_{21} gives the radiation temperature of approximately the same region as T_{10} measured at the center position. The corresponding peak temperatures amount then to (0.48 ± 0.04) K and (0.17 ± 0.02) K under radial velocities equal to $V = -39.6$ km/s and $V = -40$ km/s. The $1 \rightarrow 0$ line is significantly wider than the $2 \rightarrow 1$ line: 1.35 km/s in comparison with 0.7 km/s (see Figure 1). At the emission maximum, the $J = 2 \rightarrow 1$ line becomes even narrower: about 0.56 km/s as can be seen from Table 1. The spatial distributions of 3-mm and 1-mm emission are quite different, the latter is more concentrated on the scale of $1'$. Taking into account the kinematic and spatial features mentioned above one can produce a two-component model of S201. The $J = 2 \rightarrow 1$ profile in Figure 1 can be considered as the superposition of two lines: an 1.35 km/s width line with the centrum velocity of -39.6 km/s plus a 0.56 km/s width line with the centrum velocity of -40 km/s. The first line belongs to the whole cloud while the second is generated within its comparatively narrow layer. Using the least-mean-squares method, the following intensities of the lines were obtained: 0.36 ± 0.05 K for the narrow component and 0.125 ± 0.05 K for the broad one. Unfortunately, the similar analysis of the $J = 1 \rightarrow 0$ line gives no success, and we can put only the upper limit for the narrow component: ~ 0.06 K. Nevertheless, the data obtained make it possible to roughly estimate some parameters of the molecular cloud in the direction of S201.

Let us consider the broad line component. The line approximation data give in this case

$$R = \frac{T_{21}}{T_{10}} = 0.73 \pm 0.31.$$

Under given kinetic temperature T_k, the R and T_{10} values determine the column density of $C^{18}O-N_1$ and the hydrogen volume density n_{H_2}. Assuming $T_k = 20$ K

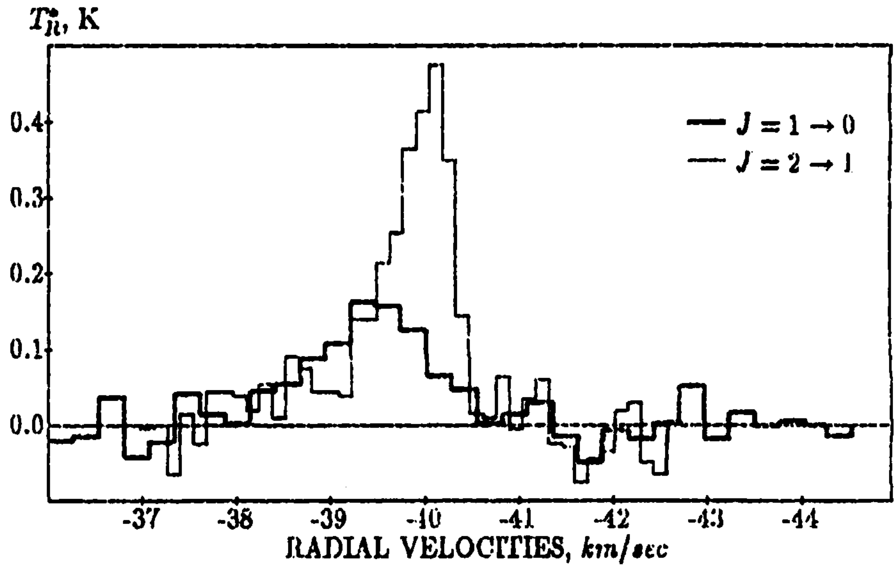

Figure 1 S201 line contours taken at the (0,0) position. Angular resolution is about 1′ in both transitions.

(in accordance with the CO $J = 1 \rightarrow 0$ emission data [5]) the microturbulent homogeneous slab model was calculated using a modified program from [4].

Figure 2 presents the results of calculations where the lines of constant R (square-curves) and T_{10} (dotted curves) are plotted against n_{H_2} and N_1 values. The corresponding R and T_{10} magnitudes are pointed near the curves. The probable parameters of the cloud fall into dashed region in Figure 2. Thus, the broad component data give following parameters of an envelope: $n_{H_2} = (1 \div 4) \times 10^3$ cm^{-3} and $N_1 = (1.4 \div 2.3) \times 10^{14}$ cm^{-2}. As it concerns of the narrow component, in this case the ratio $R \geq 5$ is incompatible with the results predicted by both microturbulent modelling and LVG-approximation (see [1]). Under conditions close to LTE, the quantity R is determined by [3]

$$R \simeq 4 \cdot \exp\left[\frac{2hB}{kT'}\right],$$

where $T' = T_1 T_2 (3T_1 - T_2)^{-1}$ and T_1, T_2 are the excitation temperatures for $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions, respectively. Under $T \simeq T_2 \simeq T_k$, and assuming optically thin lines, $T' = T_k/2$ and $R \approx 4$ if $T_k \geq 200$ K.

The corresponding investigations of the $R(T_k)$ dependence were performed using the above mentioned microturbulent model. It was supposed that $C^{18}O$ abundance ratio $X = n(C^{18}O)/n_{H_2} = 5 \times 10^{-9}$ is valid for the source core. This value lies midway the limits $X = (2 \div 8) \times 10^{-9}$ determined for the S201 envelope on the basis of the above results. The average diameter of the envelope was adopted to be equal to $D_E = 4.9 \pm 0.6$ pc as it follows from $J = 1 \rightarrow 0$ line observations [1].

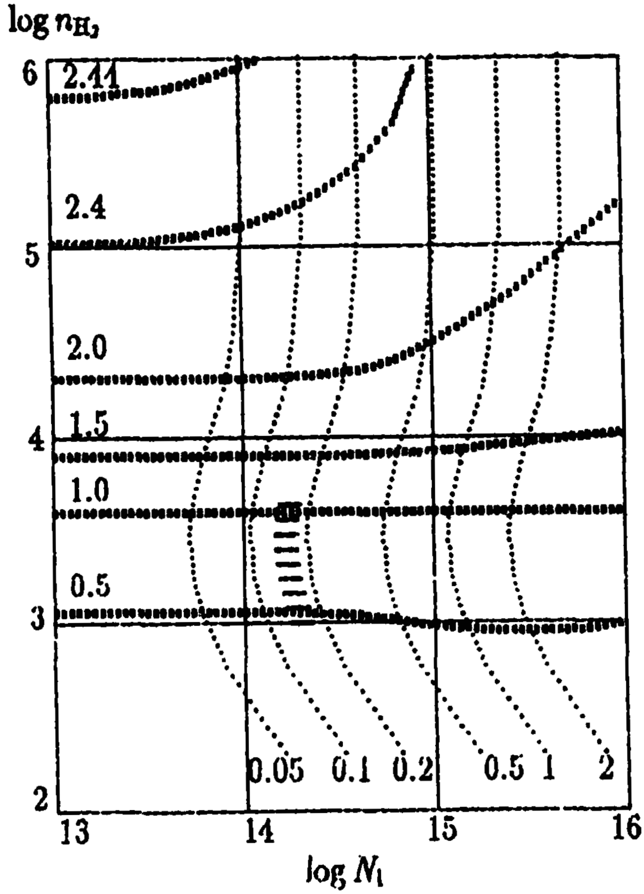

Figure 2 The radiative transfer equation solution under $T_k = 20$ K and $\delta V = 1.35$ km/s.

The size of the cloud core D_C can be determined from the source mapping data in the $J = 2 \rightarrow 1$ line. Besides, after averaging on $1'$ scale the narrow component intensity decreases from 0.65 K to 0.36 K. This decrement corresponds to the core size of $45''$ not contradicting to the mapping itself. The distance of S201 from the Sun amounts to $d \sim 3.53$ pc (kinematic estimation [5]) or, more likely, equals to $d \sim 3.96$ pc as it follows from recent paper [6]. Thus, the core size can be estimated as $D_C \sim 0.8$ pc. Adopting the above values of X, D_C and d, and assuming the core to be spherically symmetric, the $R(n_{H_2})$ curves were calculated which peak under $n_{H_2} \sim 10^4 \div 10^5$ cm^{-3}. The position of the maximum is shifting toward lower densities as kinetic temperature is increasing (under kinetic temperature ranging in 20–80 K). On the other hand, the $T_{21}(n_{H_2})$ dependences calculated under the same assumptions show very steep rise near $n_{H_2} \geq 10^4$ cm^{-3}. Thus, the value $T_{21} = 0.65$ K corresponds to $n_{H_2} = 4.3 \times 10^4 \div 2.7 \times 10^5$ cm^{-3} if $T_k \sim 80$ K. This uncertainty corresponds to the limit values of X mentioned above. Most likely,

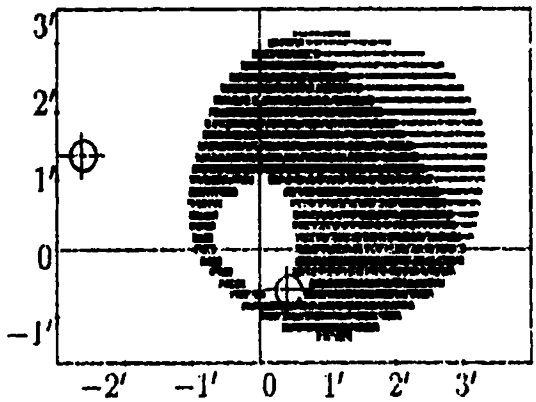

Figure 3 A sketch representing the molecular cloud geometry.

the core density ranges in (0.8–1) $\times$ 10^5 cm^{-3}. Therefore, the core density in S201 is almost two orders of magnitude greater than that of its envelope. The kinetic temperature of the core cannot be reliably determined. However, it is very likely that its magnitude does not exceed significantly 100–200 K because of the upper limit $T_{10} < 0.06$ K established for a narrow $J = 1 \rightarrow 0$ line. Besides, the thermal line broadening under $T_k = 400$ K gives $\Delta V_T = 0.76$ km/s thus exceeding the observed $J = 2 \rightarrow 1$ linewidth. On the other hand, $T_k < 80$ K seems implausible as leading to too low values of R.

Let us discuss briefly the results of modelling of S201. As it was mentioned above the mean diameter of the envelope $D_E = 4.9$ pc exceeds significantly the core size $D_C = 0.8$ pc. The Table 1 data allow to propose the Figure 3 drawing which describes roughly the molecular cloud geometry. The core (marked by white on Figure 3) is located near the eastern edge of the cloud where the $J = 1 \rightarrow 0$ line intensity falls steeply. On the other hand, the $J = 2 \rightarrow 1$ line intensity falls rapidly toward the cloud interior so that there is a ridge of 1-mm enhanced emission at the cloud periphery. There are two IRAS sources [7] in vicinity of S201, both of them having the $\lambda = 100\mu$m fluxes equal to 2100 Jy. One of these sources lies just on the border between the core and the envelope. The core size is significantly less than that of the envelope, nevertheless, their masses are comparable; indeed, $M_C \simeq 600 M_\odot$ while $M_E = 3.8 \times 10^3 M_\odot$. The latter value is determined with the accuracy of $\pm 70\%$ while the M_C magnitude is estimated rather marginally. These masses can be compared with other determinations of H II-associated molecular cloud masses using the $C^{18}O$ lines data (see, for instance, [1]). The envelope mass agrees satisfactorily with the mean dependence derived in [1]

$$M(D) = \left(56^{+24}_{-16} \cdot D^{(3.2 \pm 0.3)}\right) \tag{1}$$

where M is in solar masses and D in pc. The value $M_E = 3.8 \times 10^3 M_\odot$ can be compared with the virial mass corresponding to $D_E = 4.9$ pc of the cloud and to its turbulent velocity. A virial mass can be estimated from equation [8]:

$$M_V = \frac{5}{16 \ln 2} \cdot \frac{D}{G} \cdot \overline{\Delta V^2}, \tag{2}$$

where G is the gravitational constant and ΔV is the linewidth. Taking into account that for a population of molecular clouds associated with H II regions the following relation $\Delta V(D)$ is valid [1]:

$$\Delta V = (0.9 \pm 0.03) \cdot D^{(0.31 \pm 0.04)}, \tag{3}$$

one can combine (2) and (3) thus obtaining a simple relation

$$M_V = 85.3 \cdot D^{1.62}, \tag{4}$$

where D is in pc and M_V in solar masses. Under $D_E = 4.9$ pc from (4), it follows that $M_V = 1.12 \times 10^3 M_\odot$, about 3 times lower than M_E. It implies the probabal gravitational instability of the envelope. Substituting $D_E = 4.9$ pc in (3) one can obtain $\Delta V = 1.47$ km/s in accordance with the observed value. All this means that the envelope itself belongs on its physical properties to the population described by equations (1) and (3).

The core mass exceeds about 20 times the value $M(D) = 27 M_\odot$ calculated for $D_C = 0.8$ pc from (1). Besides, the values D_C and $\Delta V = 0.56$ km/s do not satisfy equation (3). Substituting $D = 0.8$ pc and $\Delta V = 0.56$ km/s in (2) we obtain $M_V \simeq 26 M_\odot$ almost coincident with the value calculated from (1). Therefore, the core of the cloud forms a much more massive object than those described by equation (1) and its mass exceeds ~ 20 times the corresponding virial value. Although the estimation of the core mass is unreliable, in the whole, the S201 molecular cloud looks like an object at initial stage of gravitational collapse with a moderately hot core and contracting cold envelope. The existence of an IRAS point source at the core position reveals some kind of activity in this region.

In conclusion of this discussion we should note that for better elucidation of S201 physics, additional observations are necessary with the spatial and frequency resolutions increased. A $J = 3 \rightarrow 2$ transition data seem also very valuable.

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