АСТРОФИЗИКА

ТОМ 48 | НОЯБРЬ, 2005 | ВЫПУСК 4

УДК: 524.5

MOLECULAR CLOUDS TOWARD A NEW OB ASSOCIATION IN PUP-CMA

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Received 27 April 2005
Accepted 12 August 2005

We have mapped 16 molecular clouds toward a new OB-association in the Pup-CMa region to derive their physical properties. The observations were carried out in the ^{12}CO ($J=1-0$) line with the Southern millimetre-wave Telescope at Cerro-Tololo, Chile. Distances have been determined kinematically using the rotation curve of Brand with $R_\odot = 8.5$ kpc and $V_\odot = 220$ km/s. Masses have been derived adopting a CO luminosity to H_2 conversion factor $X = 3.8 \cdot 10^{20}$ molecules cm^{-2} $(K\,km/s)^{-1}$. The observed mean radial velocity of the clouds are comparable with the mean radial velocity of stars composing OB-association in Pup-CMa, it is in favor of close connection of clouds with these stars.

Key words: *ISM:clouds - ISM:molecules - Galaxy:general - radio lines*

1. ***Introduction.*** The main purpose of this paper is to present physical properties of 16 molecular clouds, coincident with recently discovered OB-association, in the Pup-CMa region [1]. Although this region was included in the wide latitude survey of the third galactic quadrant by May et al. [2], the low angular resolution (0°.5) of this survey prevent us of using it in the present study. Unfortunately a deep survey of third galactic quadrant (May et al. [3]) with improved sensitivity and angular resolution, did not have enough coverage in latitude in the Pup-CMa region. Therefore new observations of the molecular clouds in this area have been carried out and are presented in the next section.

2. ***Observations.*** The 16 molecular clouds, detected in the direction of a new OB-association in Pup-CMa region [1], have been mapped in the ^{12}CO ($J=1-0$) line with the Southern millimeter-wave Telescope at Cerro Tololo, Chile. This telescope is a 1.2-m Cassegrain with a full beam width at half-maximum (FWHM) of 8'.8 at 115 GHz, the frequency of the ^{12}CO ($J=1-0$) and a main beam efficiency of 0.82 [4,5]. The first stage of the receiver consists on a Schottky barrier diode mixer and a GaAs field-effect transistor amplifier cooled to 77 K by liquid nitrogen. The receiver noise temperature, excluding the atmospheric contribution, is 370 K (SSB). The spectrometer is a 256-channel filter bank of 100 KHz channel width, providing a 0.26 km/s velocity resolution, at 115.3 GHz and a spectral range of

66.6 km/s. A sampling interval of less than every beam width (7'.5) was used for all the observations reported in this work.

Position switching with equal times dedicated to the source and the reference position was used for all the observations. Reference positions were chosen to be free of emission at a level of 0.2 K (T_a^* scale) or better, corresponding to 1σ noise level for a 0.26 km/s velocity resolution.

Spectra were intensity calibrated individually against a blackbody reference by the chopper-wheel method (e.g. Kutner and Ulich [6] and the references therein), yielding a temperature scale T_a^* corrected for the atmosphere attenuation, resistive losses, and rearward spillover and scattering. Orion A was used as a standard CO calibration source and was observed daily as a check on the calibrations. Pointing was checked periodically by radio continuum observations of the Sun (Dame [7]); the maximum pointing error was 1', or less than 10% of beamwidth.

Integration time for each spectrum was automatically set to achieve a noise level ≤ 0.2 K rms at a velocity resolution of 0.26 km/s, this generally requiring 7-11 minutes, depending on the elevation and the amount of atmospheric water vapor. All observations were made above 30° in elevation, and many close to elevation limit of the telescope (85°). The main parameters of observations are summarized in Table 1.

Table 1

OBSERVATIONAL PARAMETERS

Sampling interval	0°.125 (7'.5)
Telescope HPBW	0°.147 (8'.8)
Velocity resolution	0.26 km/s
Velocity coverage	66 km/s
RMS sensitivity ($\sigma[T_a^*]$)[a]	≤ 0.2 K
SSB receiver temperature	370 K
Typical SSB system temperature[b]	750 K

[a] At velocity resolution of 0.26 km/s.
[b] Including atmospheric and radiation losses.

Observations were carried out only under good weather conditions, i.e. when the zenith opacity of water vapor at 115 GHz was between 0.05 and 0.20. During the observations the spectra were examined visually and fitted with linear baselines. If a spectrum showed evidence of baseline distortion it was discarded and the observation repeated. Typical spectra corresponding to cloud C are shown in Fig.1.

3. *Cloud properties*. The velocity-integrated CO emission detected in the direction of new OB-association Pup-CMa, integrated from 13 to 31 km/s, is shown in Fig.2.

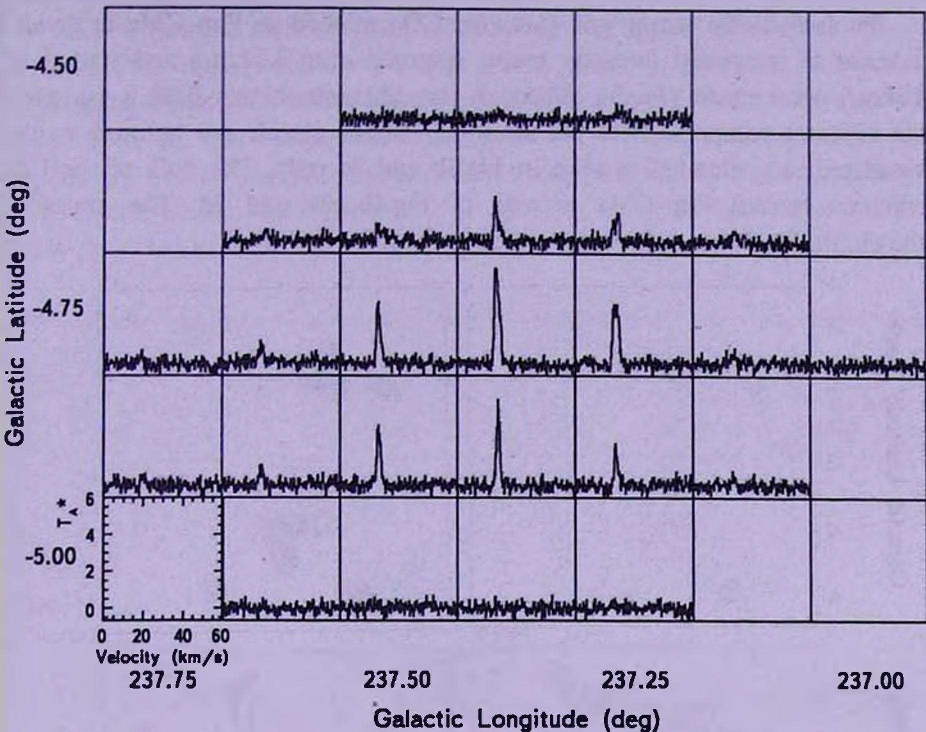

Fig.1. Spectra corresponding to cloud C.All spectra cover ~67 km/s with 256 channels, each 0.26 km/s wide. A linear baseline fit was removed from each spectrum. Typical integration times were about 7 minutes, yielding a noise of ~0.2 K rms per channel.

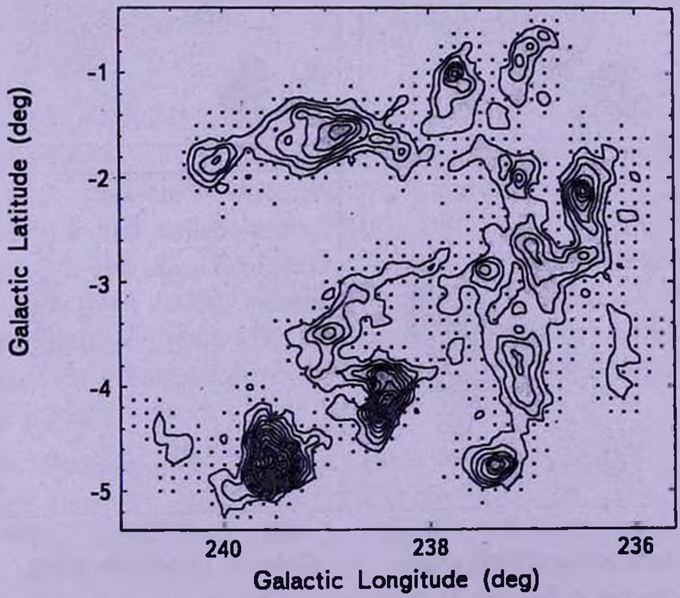

Fig.2. Integrated intensity map of CO emission toward a new OB-association Pup-CMa. 16 different clouds have been identified. The integration range is from 13 km/s to 31 km/s. The contours are from 2 K km/s up to 30 K km/s in steps of 2 K km/s.

To analyze the strong and extended CO emission in Pup-CMa in detail, a series of integrated intensity maps, summed over 2.5 km/s and started at 15 km/s were made (Fig.3). Although the emission in this field is complex the different components of the arbitrarily named clouds can be more easily visualized; e.g. cloud C is seen in Fig.3b and 3c only. The bulk of the CO emission toward Pup-CMa is seen in Fig.3b, 3c and 3d. The emission shown in Fig.3e and 3f corresponds to clouds E and F.

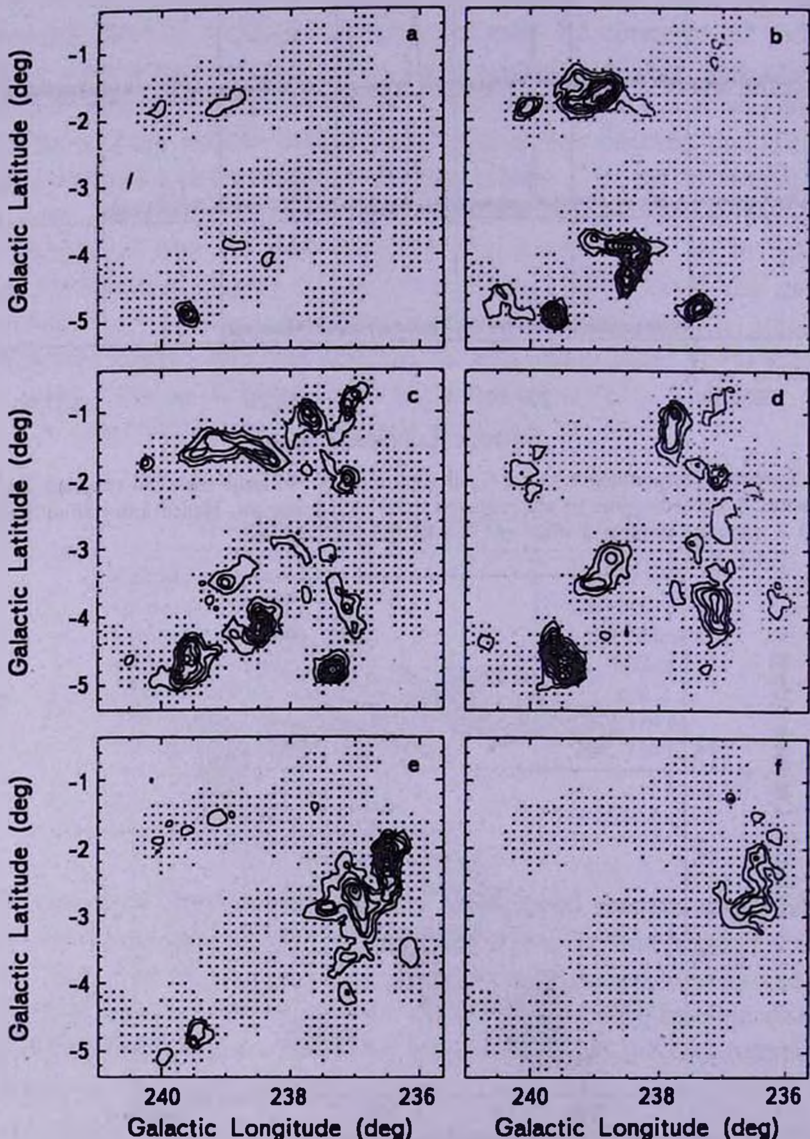

Fig.3. Velocity channel maps of the CO emission in the direction of Pup-CMa. Each map is integrated over a velocity interval of 2.5 km/s starting at 15 km/s. a) 15 - 17.5 km/s. b) 17.5 - 20 km/s. c) 20 - 22.5 km/s. d) 22.5 - 25 km/s. e) 25 - 27.5 km/s. f) 27.5 - 30 km/s.

Table 2 lists the main physical characteristics of the 16 mapped clouds in the Pup-CMa region. Columns 1 and 2 correspond to positions, in galactic coordinates, of the peak of CO emission of each cloud. Columns 3 and 4 include V_{LSR} and ΔV_{obs} that correspond to the peak and FWHM of the gaussian fit, respectively. Notice that the parameters have been determined from the gaussian fit to the cloud composite spectrum, i.e. the sum of all the spectra across the cloud projected surface. Fig.4 shows the composite spectrum of cloud C.

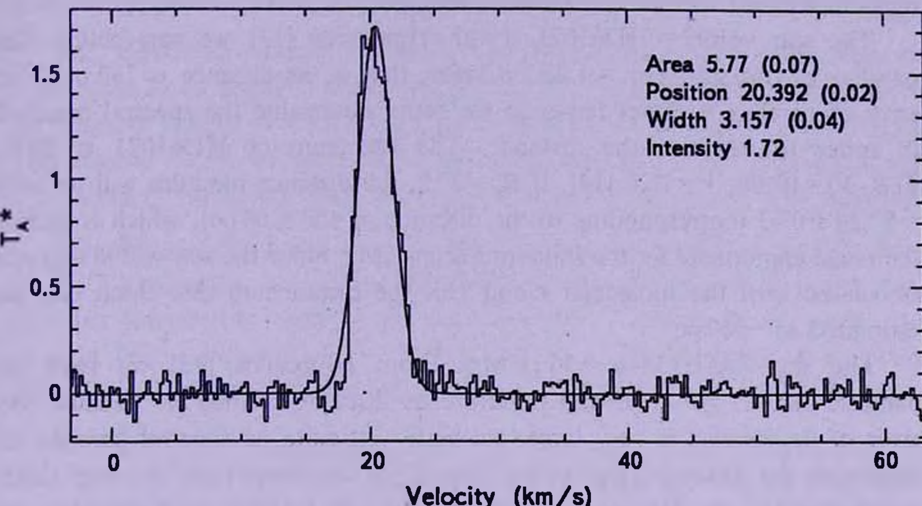

Fig.4. Gaussian fit of the composite spectrum of cloud C. The parameters of the fit have been used to determine the V_{LSR}, ΔV_{obs} and I_{CO} for each cloud.

3.1. *Distance.*

3.1.1. ***Kinematical distance.*** Since outside the solar circle there is no distance ambiguity, heliocentric distances to all clouds in Table 2 (column 5) have been determined kinematically, using the rotation curve of Brand [8] and Brand and collaborators [9,10], with the new galactic constants, $V_{\odot} = 220$ km/s and $R_{\odot} = 8.5$ kpc [11]. However, these determinations should be taken with some caution because the rms line-of-sight velocity dispersion of galactic clouds is 6 km/s [12], and therefore, a typical ~±0.5 kpc error can be expected for kinematically derived distances to clouds towards Pup-CMa ($237° \le l \le 240°$).

3.1.2. ***Optical determination.*** However there is the possibility of estimating the distance to some molecular clouds by another method. Some stars appears to be associated with molecular clouds mentioned above: they illuminate different parts of molecular clouds and form reflection nebulae, so we can assume that estimating the distances to these stars we can also estimate the distances to the molecular clouds with which they are associated.

The star vdB96 = HD57281. From Hipparcos [13] we have the parallax of this star: Par. = 7.73 ± 3.46 mas, and hence the distance is 130 pc. Since the error of parallax is too large we must try to determine the spectral parallax. The spectrum of this star is B5V, $V = 8^m.97$, $B - V = -0^m.06$, $M(V) = -1^m$ [14]. Taking $R_V = 3^m.2$, the distance modulus of this star turns out to be $m(r) = 9^m.68 \pm 0^m.3$ (corresponding to a distance of 850 ± 100 pc), which is within the range appropriate for the stars from Pup-CMa ($m(r) = 7^m.91$ - $9^m.7$) [2]. Since this star appears associated with molecular cloud C, then the distance to this molecular cloud can be estimated as 850 pc.

The star vdB98 = HD61071. From Hipparcos [13] we can obtain the parallax of this star, Par. = 1.28 ± 0.7 mas, that is, its distance is 780 pc. The error of parallax is rather large, so we better determine the spectral parallax in order to estimate the distance. The spectrum of HD61071 is B6V, $E(B - V) = 0^m.08$, $V = 7^m.6$ [14]. If $R_V = 3^m.2$, the distance modulus will be $m(r) = 8^m.24 \pm 0^m.3$ (corresponding to the distance of 450 ± 60 pc), which is within the range appropriate for the stars from Pup-CMa. Since the star vdB98 appears associated with the molecular cloud D5, the distance to this cloud can be estimated as ~500 pc.

The star SAO173446 = 30 τ CMa. From Hipparcos [13] we have its parallax Par. = 1 ± 0.7 mas and therefore its distance is 1000 pc. Because the error of its parallax is very large, we better estimate its spectral parallax to determine the distance. This star is one of the members from the Pup-CMa association [1], its distance modulus is $m(r) = 8^m.8 \pm 0^m.3$ (corresponding to a distance of 550 ± 80 pc), and is within the range acceptable for the stars from Pup-CMa. On the PSS prints we can see that around 30 τ CMa an HII region is present, which penetrates into molecular clouds A, B and E, so that we can estimate the distance to these clouds as 550 pc.

In Brand's thesis [8] the data concerning the stars associated with molecular cloud B1 (BBW23) [15] are given. The distance moduli for 16 stars situated in the region of that cloud are measured in [8]. If we calculate the mean distance modulus for these stars, we will obtain $7^m.34 \pm 0^m.3$, corresponding to a distance of 300 pc. If we exclude 4 stars with small distance moduli ($1^m.42$ - $4^m.89$), that differs significantly from the others as foreground stars, we obtain $9^m.036 \pm 0^m.3$ which corresponds to a distance of 650 ± 90 pc.

As all 16 molecular clouds mentioned in this paper have very similar radial velocities and they are situated close to each other (forming two groups, see e.g. Fig.1 in [16], where two more clouds are added, BBW63 and BBW89), we can conclude that most of these clouds are at the same distance.

The discrepancy between the kinematical distances and the distances obtained using stars spectra is not rare case. For example, in a paper by Tapia et al. [17] two such cases are given. 1) For the cloud associated with the object HHL49 [18], Tapia et al. found that the kinematical distance given by Wouterloot&Brand [9] is half the distance determined for the object HHL49 using the data of its optical observations. 2) For the cloud associated with the object HHL31 [18] the kinematical distance obtained from [9] is about four times larger than the distance obtained by Tapia et al. for the object HHL31, using its optical properties. Therefore, if we assume that the optical method is the correct one, we must multiply r_e and M_{VT} in Table 2 by a factor of about 0.3, while L_{CO} and M_{cloud}, in the same Table, has to be corrected by a factor of about 0.09. Then M_{VT} will be about 3.3 times larger than M_{cloud}.

3.2. *Effective radius.* We define the effective radius of a cloud (column 6 in Table 2) as $(A/\pi)^{1/2}$ where A is the actual projected area obtained from the angular extent of each cloud, measured from the spatial map (Fig.5). The angular extent of each cloud was measured within 3σ contour of the line intensity integrated over the velocity range of the cloud CO emission.

3.3. *Mass.* The mass, M_{cloud}, of each cloud was estimated directly from its ^{12}CO luminosity on the empirically based assumption that the integrated CO line intensity is proportional to the column density of H_2 along line of sight (e.g. Lebrun et al. [19], Sanders et al. [20], Bloemen et al. [21]). Thus, the masses were computed using the relation

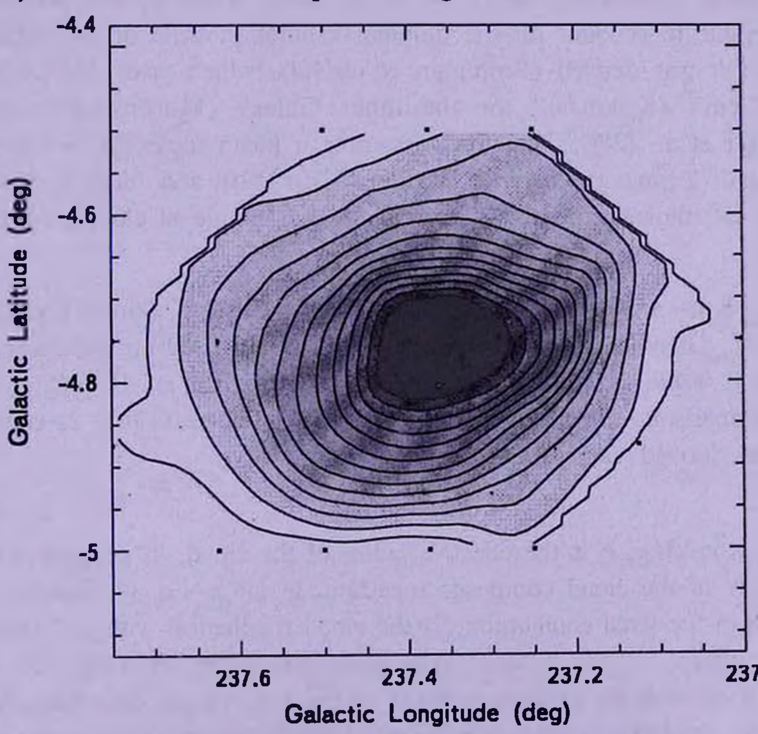

Fig.5. Integrated intensity map of cloud C. The integration range is from 17 km/s to 27 km/s. The contours are from 1 K km/s to 16 K km/s in steps of 1 K km/s.

$$M_{cloud} = w \cdot X \cdot L_{CO} \,, \tag{1}$$

where w is the mean molecular weight per H_2 molecule, X is the constant ratio of H_2 column density to integrated ^{12}CO intensity and L_{CO} is the CO luminosity given by

$$L_{CO} = d^2 \cdot I_{CO} \,, \tag{2}$$

where I_{CO} is the ^{12}CO line intensity integrated over all velocities and lines of sight within the boundaries of the cloud, and d is the heliocentric distance of the cloud. In practice, I_{CO} is computed by integrating the emission over the full velocity extent of the cloud and over the face of the cloud, defined by its 3σ contour in the spatial map.

Several authors (Mead&Kutner [22], Digel et al. [23], Sodroski [24]) have claimed that X in the outer Galaxy is larger than in the inner Galaxy, varying from a factor of 2 (Mead&Kutner [22]), between 2 and 3 (Sodroski [24]), to 4 ± 2 (Digel [25]). We have adopted here a value for X equal to twice the value for the inner Galaxy because it minimizes the differences with the calculated masses assuming they are in the virial equilibrium. Strong et al. [26], through an improved analysis of the work by Bloemen et al. [21] together with new data, derived a value of $X = (2.3 \pm 0.3) \cdot 10^{20}$ molecules cm^{-2} (K km/s)$^{-1}$. However, this X has to be scaled down by 0.82 from the published value to account for the different calibration scale of the database from which it was derived (Bronfman et al. [6]), which gives $X = 1.9 \cdot 10^{20}$ molecules cm^{-2} (K km/s)$^{-1}$ for the inner Galaxy (Murphy&May [27], Mauersberger et al. [28]). Therefore, assuming a mean molecular weight H_2 molecule of 2.72 times the mass of H atom (Allen [29]), and adopting a value of $X = 3.8 \cdot 10^{20}$ molecules cm^{-2} (K km/s)$^{-1}$ for our sample of clouds, we have

$$M_{cloud} = 2.5 \cdot 10^3 \, L_{CO} \,, \tag{3}$$

where M_{cloud} is in $M_\odot$ and L_{CO} (Table 2, column 7) is in K (km/s) kpc^2 deg^2. Note that M_{cloud} denotes the total mass of molecular gas based on the integrated CO intensity. Table 2 (column 8) includes M_{cloud} in units of 10^4 $M_\odot$.

For comparison, the virial mass, M_{VT} of each cloud (Table 2, column 9) was also derived using the relation

$$M_{VT} = 126 \, r_e (\Delta V_{obs})^2 \,, \tag{4}$$

where M_{VT} is in $M_\odot$, r_e is the effective radius of the cloud, in pc, and ΔV_{obs} is the HPFW of the cloud composite spectrum, in km/s. Eq. (4) assumes: 1) the cloud is in the virial equilibrium, 2) the cloud is spherical with a r^{-2} density distribution, where r is the distance from its center, 3) the observed ^{12}CO line width of the cloud is an accurate measure of the net velocity dispersion of its internal mass distribution, which is believed to be clumpy on many scales (e.g. Zuckerman&Evans [30], Blitz&Stark [31]); or in other words, the cloud is free from the magnetic or other non-gravitational forces of pressure (e.g. MacLaren et al. [32]). We are aware that magnetic forces and specially pressure terms may be important for clouds located in the galactic disk near spiral arms and regions of strong activity, like HII regions, supernovae, young stars, etc. (e.g. Myers&Goodman [33], Elmegreen [34], Mouschovias [35]). However, for simplicity we have not considered in Eq. (4) the magnetic and pressure terms. We have adopted the r^{-2} density distribution considering the work of Fitzgerald et al. [36], Dickman [37], Snell [38], Lorent et al. [39], Arquilla&Goldsmith [40] and Brand&Wouterloot [41].

Table 2

MOLECULAR CLOUDS TOWARD A NEW OB-ASSOCIATION PUP-CMA*

l (°)	b (°)	V_{LSR} (km/s)	ΔV_{obs} (km/s)	d (kpc)	r_e (pc)	L_{CO} 10^{-3}	M_{cloud} $10^4\ M_\odot$	M_{VT} $10^4\ M_\odot$	Dens. cm^{-3}	Cloud
238.50	-4.25	19.68	3.82	1.8	11.5	7.9	1.97	2.1	46.3	A1
239.00	-3.50	23.05	2.96	2.1	12.0	4.8	1.21	1.3	24.7	A2
238.00	-2.88	21.51	1.56	1.9	5.8	0.2	0.06	0.2	11.0	A3
239.63	-4.63	18.42	3.58	1.7	10.5	2.7	0.66	1.7	20.6	$B1_1$
239.63	-4.63	20.98	1.95	1.9	11.9	2.5	0.63	0.6	13.1	$B1_2$
239.63	-4.63	23.62	2.60	2.1	13.5	15.0	3.75	1.1	54.6	$B1_3$
240.50	-4.50	19.38	2.84	1.8	5.3	0.7	0.18	0.5	43.1	B2
237.38	-4.75	20.39	3.16	1.8	8.6	5.4	1.35	1.1	74.7	C
237.13	-0.88	21.59	3.72	1.9	8.8	2.2	0.55	1.5	28.4	D1
237.13	-2.00	22.43	3.80	2.0	9.5	4.0	1.00	1.7	41.4	D2
237.75	-1.00	22.75	3.09	2.0	12.5	6.7	1.68	1.5	30.6	D3
238.88	-1.50	19.62	3.23	1.8	15.7	13.9	3.48	2.1	32.3	D4
240.13	-1.88	18.00	1.93	1.6	7.3	1.4	0.35	0.3	32.6	$D5_1$
240.13	-1.88	23.32	3.55	2.1	9.4	2.4	0.61	1.5	25.7	$D5_2$
236.50	-2.13	26.91	2.69	2.4	17.2	19.7	4.92	1.6	34.2	E
237.00	-2.75	26.74	3.50	2.4	14.4	13.1	3.27	2.2	38.8	F1
237.50	-2.88	25.67	2.33	2.3	12.3	3.7	0.94	0.8	17.8	F2
237.13	-3.75	23.55	4.27	2.1	12.9	8.2	2.06	3.0	34.1	F3
236.13	-3.75	25.09	2.98	2.2	8.2	1.5	0.37	0.9	23.5	F4

* Clouds B1 and D5 are composed of subcondensations, that is why there are data on 19 objects in Table 2.

4. ***Summary.*** The results of observations of 16 molecular clouds toward a new OB association in Pup-CMa are given. The observations in ^{12}CO (J = 1 - 0) were carried out with the 1.2-m radio telescope at Cerro Tololo, Chile. The obtained mean radial velocity of the clouds, from Table 2, is 22.2 km/s ± 0.6 km/s, which is in good agreement with the mean radial velocity of the stars which are members of the OB association in Pup-CMa (26 km/s ± 13 km/s, see in [2]). This agreement favors the association of

these molecular clouds and the stars of Pup-CMa. For these 16 clouds the kinematical distances are computed. These distances are larger than those calculated optically (for the stars illuminating some of these clouds). Such a discrepancy is not a rare phenomenon (see e.g. [17]). The masses and sizes of clouds are also calculated, the masses are in the range (0.06 - 4.92) $\cdot 10^4$ $M_{\odot}$ and the diameters in the range (10 - 35) pc. The clouds compose two groups.

Acknowledgements. We are grateful to Dr. M.Smith, Director of Cerro-Tololo Inter-American Observatory, by supporting of the operation of 1.2-m radio telescope. We thank J.Aparici and F.Olmos for assistance with the observations and the operation of the radio telescope. We also thank F.Azagra for helping with the data reduction. J.M. and H.A. acknowledge support from FONDECYT through grant 1010431 and J.M. acknowledges support from the Chilean Centro de Astrofisíca FONDAP 15010003.

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МОЛЕКУЛЯРНЫЕ ОБЛАКА В НАПРАВЛЕНИИ НОВОЙ ОВ-АССОЦИАЦИИ В PUP-CMA

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Мы составили радиокарты для 16 молекулярных облаков в направлении новой ОВ-ассоциации в районе Pup-CMa для нахождения физических свойств этих облаков. Наблюдения в линии ^{12}CO ($J = 1 - 0$) были проведены на 1.2-м Южном миллиметровом телескопе в Серро-Тололо, Чили. Расстояния были определены кинематически, употребив кривую вращения Бранда с $R_{\odot} = 8.5$ кпк и $V_{\odot} = 220$ км/с. Массы были получены, приняв для коэффициента конверсии излучения в CO к излучению в H_2 значение $X = 3.8 \cdot 10^{20}$ молекул см$^{-2}$ (К км/с)$^{-1}$. Наблюденная средняя радиальная скорость облаков сравнима со средней радиальной скоростью звезд ОВ-ассоциации в Pup-CMa, что свидетельствует о близкой связи облаков с этими звездами.

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