АСТРОФИЗИКА

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INVESTIGATION OF CONSPICUOUS INFRARED STAR CLUSTER AND STAR-FORMING REGION "RCW 38 IR CLUSTER"

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An infrared star cluster RCW 38 IR Cluster, which is also a massive star-forming region, is investigated. The results of observations with SEST (Cerro La Silla, Chile) telescope on 2.6-mm ^{12}CO spectral line and with SIMBA on 1.2-mm continuum are given. The ^{12}CO observations revealed the existence of several molecular clouds, two of which (clouds 1 and 2) are connected with the object RCW 38 IR Cluster. Cloud 1 is a massive cloud, which has a depression in which the investigated object is embedded. It is not excluded that the depression was formed by the wind and/or emission from the young bright stars belonging to the star cluster. Rotation of cloud 2, around the axis having SE-NW direction, with an angular velocity $\omega = 4.6 \cdot 10^{-14}\,s^{-1}$ is also found. A red-shifted outflow with velocity ~+5.6 km/s, in the SE direction and perpendicular to the elongation of cloud 2, has been also found. The investigated cluster is associated with an IR point source IRAS 08573-4718, which has IR colours typical for a non-evolved embedded (in the cloud) stellar object. The cluster is also connected with a water maser. The SIMBA image shows the existence of a central bright condensation, coinciding with the cluster itself, and two extensions. One of these extensions (the one with SW-NE direction) coincides, both in place and shape, with cloud 2, so that it is not excluded the possibility that this extension might be also rotating like cloud 2. In the vicinity of these extensions there are condensations, resembling HH objects.

Key words: *star-forming region:rotation of molecular clouds*

1. *Introduction.* There are two types of star-forming regions (SFR): 1. regions where massive star formation is taking place; and 2. SFR where middle and/or low mass stars are originating. Sometimes clusters of stars can occur in SFR. In this paper a young star cluster, RCW 38 IR Cluster, is investigated. This object is being named IR cluster because it is invisible in optics and was discovered through 2MASS images [1,2]. The presence of outflows, an IRAS point source, a water maser and a bright IR nebula, suggests that this object is also a star-forming region of massive stars.

The observations of the region connected with RCW 38 IR Cluster, were carried out on SEST telescope: on 2.6 mm (^{12}CO (1-0)) and with SIMBA on 1.2 mm. ^{12}CO observations revealed the existence of a rotating molecular cloud (cloud 2), and of a second huge molecular cloud (cloud 1), in which the star cluster might has made a depression. There are two extensions on SIMBA image, one of these extensions coincides with a rotating molecular cloud (cloud 2) and follows the shape of that cloud. A red CO outflow, perpendicular to the elongation of cloud 2, is also investigated. A rather strong magnetic field was discovered in one of the clouds belonging to the large complex of clouds (our clouds 1 and 2 also belong to that complex). The OH Zeeman measurements of magnetic field strength showed that the Zeeman effect was clearly detected in the cloud associated with the HII region RCW 38, with field strength of $38 \pm 3 \mu G$ [3]. A bright IRAS point source IRAS 08573-4718 [4] and a water maser (with a radial velocity $V_R = -3$ km/s) [5] are also connected with the cluster.

The 1.2 mm SIMBA image consists of a central bright condensation (which coincides with the cluster and IRAS 08573-4718) and two possible bipolar outflows, with one of these outflows coinciding, both in place and in shape, with cloud 2. There are also small condensations in the region of RCW 38, resembling HH objects.

2. *The object RCW 38.* The Brazilian astronomers [1,2] searched for embedded clusters and stellar groups in the regions of known nebulae, using the 2MASS images (mainly invisible in optics). The method was rather successful in different regions of the sky. One of the conspicuous IR clusters is situated in the region of RCW 38-Gum22. This cluster contains an IRAS point source IRAS 08573-4718, which has IR colours typical for non evolved sources, embedded in a dark cloud. Unusual is the IR colour $R(2,3)$ with high negative value (see below). Fig.1 is the 2MASS K image

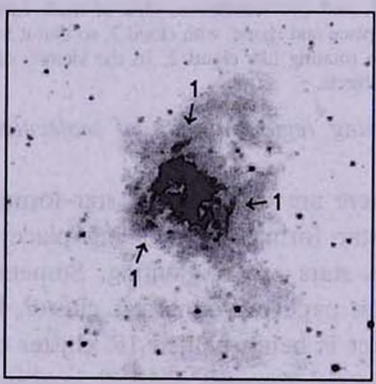

Fig.1. 2MASS K image of RCW 38. N to the top, E to the left. Size of the image is 6'x 6'. 1 - condensations, resembling SFR (or HH objects).

of the object RCW 38. There are several bright stars and many faint stars in the cluster RCW 38, a bright nebula and nebular condensations (perhaps SFRs or HH objects) are also connected with the cluster (see Fig.1).

3. *Distance to the object RCW 38.* HII region RCW 38 (and also the infrared cluster RCW 38) is located in the Vela Molecular Ridge. The Vela

Molecular Ridge was discovered by May et al. [6]. These authors interpreted the ridge as evidence that toward Vela we are looking along a spiral arm (Local arm). Murphy and May [7] mentioned, that this region is rather complex, where we can find different objects at quite different distances along the line of sight. Murphy and May [7] considering the CO emission of the Vela Molecular Ridge and photometric distance indicators conclude that the ridge lies between 1 and 2 kpc and that the Vela B cloud (where RCW 38 is located) is at a distance of about 2 kpc.

There were also other attempts to find the distance to RCW 38. Radhakrishnan et al. [8] using 21 cm absorption determined the distance to RCW 38 between 1 and 2 kpc. Muzzio [9] discovered a new young open cluster related to the HII region RCW 38, and located it at 1.7 kpc from the Sun. Zinchenko et al. [10] give the distance to the cloud connected with water maser G267.94-1.06 (this cloud is coincident with the region investigated in the present paper) as 1.7 kpc.

Following most authors we have adopted 1.7 kpc as the distance to RCW 38 and to the IR cluster.

4. *Results of ^{12}CO (1-0) observations.* The IR star cluster RCW 38 is situated in a complex of molecular clouds with different velocities and sizes. The ^{12}CO (1-0) observations toward the region of RCW 38 were carried out in 2003 with the 15-m SEST (Swedish-ESO Submillimetre Telescope) telescope at Cerro La Silla, Chile. The telescope beam size at 115 GHz is 45" and the beam efficiency is 0.70. The positions toward the source were observed with a spacing of 40" in frequency-switched mode with a frequency throw of 10 MHz. The telescope was equipped with a SIS detector and a

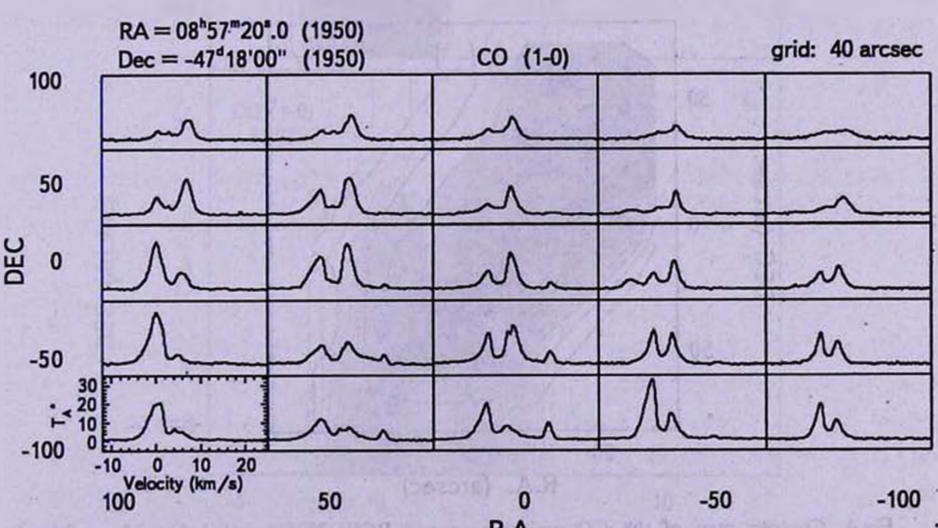

Fig.2. ^{12}CO (1-0) spectra of the region around RCW 38.

high-resolution acousto-optical spectrometer with 1000 channels and a velocity resolution of 0.112 km/s.

Fig.2 shows the ^{12}CO (1-0) spectra observed toward RCW 38, arranged in a map-like distribution. When looking at Fig.2 it is evident the existence of at least three clouds in the direction of RCW38. However, because of its distance (~1.7 kpc) RCW 38 appears connected to two clouds only (clouds 1 and 2). In Fig.3 the radio map distribution of ^{12}CO in the velocity range (-3 − 2) km/s is shown (cloud 1), while in Fig.4 the radio map in the velocity range (3 − 8) km/s is presented (cloud 2). The object RCW 38 is situated in a depression in the huge cloud 1 (the velocity of cloud 1 is

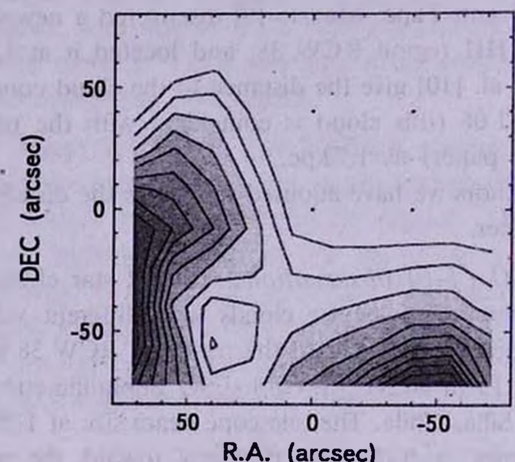

Fig.3. Contour map of the CO emission toward RCW 38 integrated from -3 to 2 km/s (cloud 1). Contour levels every 5 K km/s from 30 to 90 K km/s.

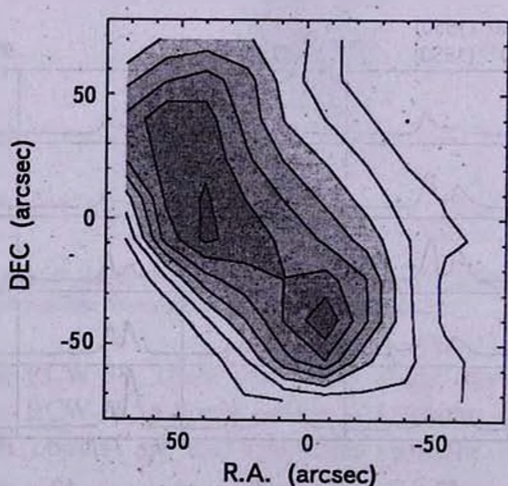

Fig.4. Contour map of the CO emission toward RCW 38 integrated from 3 to 8 km/s (cloud 2). Contour levels every 5 K km/s from 30 to 60 K km/s.

about 0.54 km/s). It is not excluded that this depression was formed by the object itself (by blowing away the material by stellar winds of young bright stars of star cluster RCW 38). The cloud 2 (mean velocity 5.4 km/s) is situated in the neighborhood of RCW 38 and has an elongation in SW-NE direction.

Zinchenko et al. [10] present the results of the observations in CS $J=2-1$ line of that region. The contour maps in Fig.1 of their paper resemble the results obtained in our paper: the contour map in the region

Table 1

DISTRIBUTION OF RADIAL VELOCITY ALONG THE CLOUD 2

80"	40"	0"	-40"	-80"
7.57	7.03	5.95	5.68	--
6.76	6.46	5.41	5.41	5.95
5.68	6.22	5.41	5.14	4.87
4.87	5.68	5.40	4.59	4.33
4.33	5.14	4.59	4.33	4.05

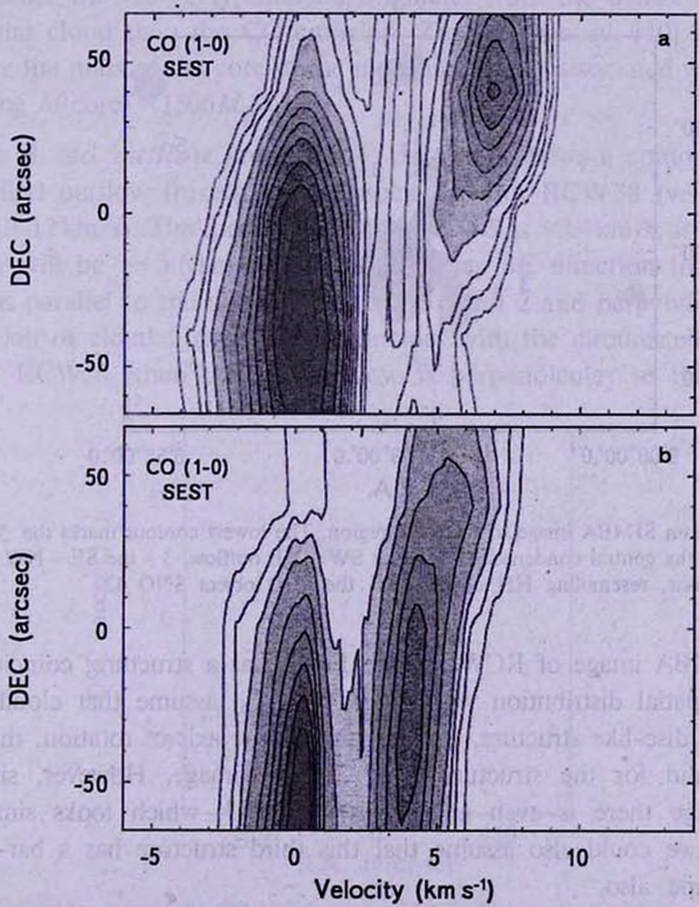

Fig.5. (DEC-V) diagrams: a - for RA offset 80, b - for RA offset -80.

(0 - 4) km/s of paper [10] resembles our cloud 1 and contour map in the region (4 - 8) km/s of paper [10] resembles our cloud 2.

4.1. ***Rotation of cloud 2.*** In Table 1 the distribution of ^{12}CO (1-0) velocity, obtained from Fig.2, is given. The columns correspond to right ascension (2000), increasing from right to left, while the rows correspond to declination (2000), increasing from bottom to top. The width of each column is 40" and the width of each row is also 40". The coordinates of centre are: R.A.(2000) = $08^h59^m02^s.0$, DEC(2000) = -47°29'43". The existence of a velocity gradient is evident in Table 1. The velocity gradient is in SW-NE direction, from 4.05 km/s to 7.57 km/s. This gradient means that there is a rotation of cloud in SW-NE direction, with an axis of rotation having SE-NW direction. The existence of a velocity gradient is evident also in the (DEC - V) diagrams (see Fig.5). If we look at Fig.5, we can see that there is no gradient near the velocity corresponding to cloud 1 (~0.54 km/s), but there is an evident velocity gradient near 5.4 km/s, which corresponds to cloud 2.

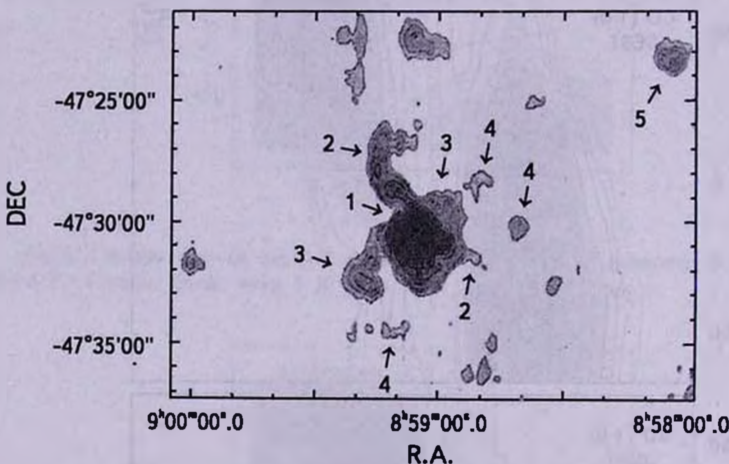

Fig.6. 1.2 mm SIMBA image of RCW 38 region. The lowest contour marks the 3σ r.m.s. noise level. 1 - the central condensation, 2 - the SW - NE outflow, 3 - the SE - NW outflow, 4 - condensations, resembling HH objects, 5 - the YSO object SNO 42.

The SIMBA image of RCW 38 (see Fig.6) has a structure, coinciding in shape and spatial distribution with cloud 2. If we assume that cloud 2 has a bar-like or disc-like structure, rotating around the axis of rotation, the same could be valid for the structure 2 of SIMBA image. However, since in SIMBA image there is even another structure, 3, which looks similar to structure 2, we could also assume that this third structure has a bar-like or disc-like shape also.

We can calculate the momentum of inertia, angular velocity of rotation, specific angular momentum and energy of rotation of cloud 2.

The angular velocity of rotation of the cloud is $\omega = \Delta V/\Delta R$, it means that it is equal to the gradient of the radial velocity. The gradient of rotation is maximal in SW-NE direction (see Table 1). Since the extension of cloud 2 in that direction is 284" (we obtained from Table 1), and because the distance to the object is ~1700 pc, its extension will be ~2.41 pc. The velocity difference along cloud 2, in the SW-NE direction, is 3.52 km/s (we obtained from Table 1). Hence we have: $\omega = \Delta V/\Delta R = 3.52\,\mathrm{km/s}/2.41\,\mathrm{pc} = 4.6\cdot10^{-14}\mathrm{s}^{-1}$. The period of rotation will be $T = 2\pi/\omega = 4.4\cdot10^{6}$ year. We can compare this value with the known so far values for other rotating objects. In [11] a rotating isolated globule is investigated. The angular velocity for that globule is $\omega = 4\cdot10^{-14}\mathrm{s}^{-1}$. In paper [12] there are data on several rotating clouds (Bok globules) with angular velocities within the range $\omega = (0.3-3)\cdot10^{-14}\mathrm{s}^{-1}$, so that cloud 2, from the present paper, has an angular velocity similar to the velocities of fast rotating globules.

Because the CS (2-1) emission originates from the denser regions of a molecular cloud than the CO emission, Zinchenko et al. [10] were able to estimate the mass of the core of the molecular cloud associated with RCW38, obtaining $M(\mathrm{core}) = 1500 M_0$.

4.2. *A red outflow from RCW 38.* Fig.7 shows a contour map of a red-shifted outflow from a cloud associated with RCW 38 (velocity in the range 10-12 km/s). The mean velocity of cloud 2 is ~5.4 km/s, so the outflow velocity will be ~+5.6 km/s. This outflow has SE direction from RCW38, which is parallel to the axis of rotation of cloud 2 and perpendicular to the elongation of cloud 2 (if cloud 2 coincides with the circumstellar dust disc around RCW38, then the red outflow is perpendicular to the dust disc,

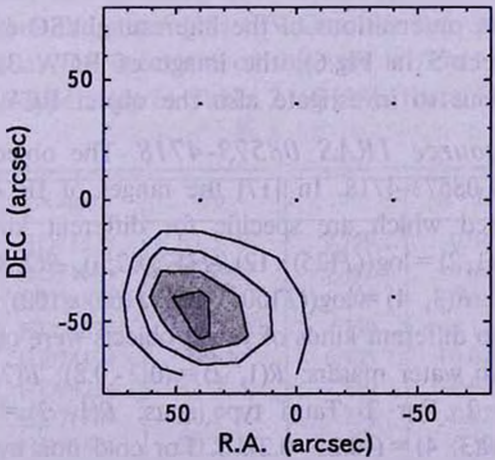

Fig.7. Contour map of the CO emission toward RCW 38 integrated from 10 to 12 km/s (red-shifted outflow). Contour levels every 1 K km/s from 2 to 5 K km/s.

which is rather common for YSO's).

5. *1.2 mm SIMBA observations of RCW 38.* These observations were carried out with the 15m SEST telescope at Cerro La Silla, Chile, with SIMBA. The beam size (FWHM) is 24". The observations were made on August 1, 2002. The flux calibration was achieved with Uranus maps. The reduced and coadded map of RCW 38 is shown in Fig.5 (more complete results are given in [13]). The 1.2 mm map of RCW 38 shows that there is a central bright source (condensation 1 in Fig.6), coinciding with RCW 38 and with IRAS 08573-4718. There are also two extensions in the SW-NE (structure 2 in Fig.6) and SE-NW (structure 3 in Fig.6) directions, not coinciding with the central bright source. Fig.5 of our paper [14] shows the SIMBA image of an interesting star-forming region, SNO 41, consisting of a central bright condensation and one bipolar outflow. At the ends of this outflow there are condensations resembling HH objects, such condensations are present also near RCW 38 (see structures 4 in Fig.6 of present paper). In [15] there is an object (IRAS 20386+6751, embedded in L1157 in Cepheus) resembling images of present paper. That object has a continuum (1.3 mm) image, consisting of two perpendicular bipolar extensions (in [15] one of these extensions is described as an envelope around the object). The ^{12}CO image of IRAS 20386+6751 shows one bipolar outflow (the N-S one, see [15]). In [15] the similarity between the spatial ^{12}CO distribution and the 1.3 mm continuum maps, which is obvious from the corresponding images, indicates that the closer relationship between the outflow of ^{12}CO gas and the dust is very likely, and their interaction is almost certain. The absence of similarity between the second extension (the E-W extension in the case of IRAS 20386+6751) can be explained by the absence of ^{12}CO in the second bipolar extension (there is emission of dust only in that extension).

During the SIMBA observations of the interesting YSO (SNO 42) from the list [16] (see object 5 in Fig.6), the image of RCW 38 appeared so intriguing that forced us to investigate also the object RCW 38 itself.

6. *IRAS point source IRAS 08573-4718.* The object RCW 38 is connected with IRAS 08573-4718. In [17] the ranges of IR colour indexes are statistically obtained which are specific for different kinds of objects (mainly YSOs). For $R(1,2) = \log((F(25) \times 12)/(F(12) \times 25))$, $R(2,3) = \log((F(60) \times 25)/(F(25) \times 60))$ and $R(3, 4) = \log((F100) \times 60)/(F(60) \times 100))$ the following ranges corresponding to different kinds of young objects were obtained. 1. For objects, connected with water masers: $R(1, 2) = (0.2 - 0.8)$; $R(2, 3) = (0 - 1.3)$; $R(3, 4) = (-0.3 - 0.3)$. 2. For T Tauri type stars: $R(1, 2) = (-0.25 - 0.15)$; $R(2, 3) = (-0.5 - 0.1)$; $R(3, 4) = (-0.25 - 0.2)$. 3. For cold non evolved sources, embedded in dark clouds: $R(3, 4) > 0.3$. For IRAS 08573-4718 we have:

$R(1,\ 2) = 0.32$; $R(2,\ 3) = -3.42$; $R(3,\ 4) = 3.68$ (we used the data from [4]). These IR colours are typical for type 3 sources from [17] (cold non evolved sources, embedded in dark clouds). Unusual is $R(2,\ 3)$ with high negative value ($R(2,\ 3) = -3.42$).

7. *Several stars connected with RCW 38.* We decided to investigate the population of RCW 38 and for that purpose we have chosen from Vizier several stars in the central part of star cluster RCW 38. The coordinates and near IR data on these stars are presented in Table 2. In Table 2 the following information is given: the number of each star (column 1), the coordinates of the stars (columns 2 and 3), the value of J (column 4), and IR colours (columns 5 and 6) (from Vizier).

Table 2

THE NEAR IR COLOURS OF SEVERAL STARS IN THE CENTRAL PART OF RCW 38

NN	α(2000)	δ(2000)	J	$J-H$	$H-K$
1	$08^h 59^m 02^s.00$	-47°30'27".9	12.707	-0.223	1.134
2	08 59 02.08	-47 30 24.0	12.600	-0.860	1.591
3	08 59 01.72	-47 30 24.0	12.497	-0.879	2.848
4	08 59 02.72	-47 30 26.7	13.567	2.265	1.360
5	08 59 02.60	-47 30 34.4	12.595	-0.609	1.138
6	08 59 01.70	-47 30 37.2	11.137	0.811	0.433
7	08 59 01.47	-47 30 22.1	12.497	-1.057	2.979
8	08 59 01.12	-47 30 31.7	13.047	-2.944	0.951
9	08 59 01.09	-47 30 26.1	13.976	-0.032	3.104

If we compare these stars with middle and low mass non stable stars (T Tauri, Herbig Ae/Be, FU Ori type stars) in Table 2 of [18], we will see that there is only one similarity in $J-H$ and $H-K$: of star 4 of Table 2 from the present paper and star 6 [18] (PV Cep, the star, connected with variable cometary nebula, the spectrum of this star is A5e + shell). There are also occasional late-type stars in Table 2 of [18], there is no similarity of near

Table 3

NN	Name	Sp	J	$J-H$	$H-K$
1	HD71528	B2.5 V	7.729	-0.047	+0.017
2	HD71609	B2.5 IV	7.497	+0.007	+0.046
3	HD73882	O8 V	6.107	+0.087	+0.103
4	HD74375	B2 III	4.730	-0.122	+0.266
5	HD74194	O9 k	6.935	+0.048	+0.079
6	HD74234	B2 V k	7.210	-0.071	-0.045
7	HD75724	B0.5 V	7.754	-0.075	-0.030
8	HD75821	O9.5 II	5.606	-0.103	-0.058
9	HD76341	O9 I	6.436	+0.030	+0.089
10	HD89137	O9.5 V	8.072	-0.058	+0.013

IR colours of stars of Table 2 of present paper with these late-type stars.

In Table 3 the data on near IR colours of several occasional early type stars from [17] are given. In Table 3 the following information is presented: the number for each star (column 1), the name of the stars (column 2), the spectra of the stars from [19] (column 3), the values of J from Vizier (column 4) and the values of near IR colours (columns 5 and 6) (from Vizier).

If we compare the data from Tables 2 and 3, it is obvious that the values for $J-H$ are mainly negative in both Tables (though the absolute quantities of negative values in Table 2 are larger than in Table 3). The values of $H-K$ are larger in Table 2 than in Table 3 (there are three negative values in Table 3). We can conclude that the stars of Table 2 are mainly early-type stars (similarities in $J-H$ in both Tables), but these stars (the stars of cluster RCW 38) have rather thick and cold circumstellar envelopes (or discs), because they have much larger values of $H-K$ than the occasional early type stars from Table 3.

Let us take the data of IR colours for O stars, connected with radial systems of dark globules. We choose occasional O type stars, connected with radial systems: HD 5005 and CD -47 4575 (both have spectral type O5 V). For these stars we have: 1. HD 5005, $J=7.796$, $J-H=0.003$, $H-K=0.01$, 2. CD -47 4575, $J=8.587$, $J-H=0.333$, $H-K=0.181$ (Vizier). The values of IR colours for these stars are rather close to zero, the same is taking place for occasional early type stars from Table 3.

8. *Conclusions*. There are two types of star-forming regions: with massive stars and with stars with middle and/or low mass stars. In this paper an interesting star-forming region with massive stars is investigated. That SFR is associated with an IR star cluster RCW 38 IR Cluster, which is invisible in optics, but well seen in 2MASS images. The observations carried out on SEST telescope (Cerro La Silla, Chile) revealed interesting structures and phenomena connected with that object. ^{12}CO (1-0) observations showed the existence of several molecular clouds, two of which are associated with the investigated cluster. Cloud 1 is a large cloud with a depression, in which the cluster might be embedded (it is not excluded the possibility that the depression was formed by the young bright stars of RCW 38 cluster). Cloud 2 is a bar-shaped or disc-shaped cloud, which is rotating around the axis of rotation with an angular velocity $4.6 \cdot 10^{-14} s^{-1}$, so it is a rather fast rotator. A red-shifted molecular outflow in SE direction from RCW 38 (with velocity ~+5.6 km/s) is investigated. That outflow is perpendicular to the elongation of cloud 2.

The SIMBA observations show the existence of a bright central source, coinciding with the object RCW 38, and two almost perpendicular extensions. The extension in SW-NE direction coincides with the molecular cloud 2 both in coordinates and in shape (we can presume that this extension is also rotating like the cloud 2). The absence of emission in ^{12}CO, where the second extension of SIMBA image is located (the SE-NW one), can be explained as an absence of ^{12}CO gas mixed with dust in that extension.

It is not excluded that the shape of ^{12}CO and SIMBA images are due to the existence of a strong magnetic field in the clouds. Such a strong magnetic field was discovered by OH Zeeman measurements of one of the clouds belonging to the complex, in which the clouds 1 and 2 are also included (the strength of that magnetic field was estimated as $38 \pm 3 \mu G$). A water maser is also associated with RCW 38 cluster [5].

We have chosen nine stars from the central part of the cluster RCW 38 (to investigate the population of that cluster). The near IR colours of 7 stars correspond to the early type stars, having thick cold envelopes (or discs).

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ИССЛЕДОВАНИЕ НЕОБЫЧНОГО ИНФРАКРАСНОГО ЗВЕЗДНОГО СКОПЛЕНИЯ И ОБЛАСТИ ЗВЕЗДООБРАЗОВАНИЯ "RCW 38 IR CLUSTER"

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Исследовано инфракрасное звездное скопление RCW 38 IR Cluster, которое также является областью звездообразования для массивных звезд. Приводятся данные наблюдений на телескопе SEST (Ла Силья, Чили) на 2.6-мм ^{12}CO и с SIMBA на 1.2-мм. ^{12}CO наблюдения выявили наличие нескольких молекулярных облаков, два из которых (облака 1 и 2) связаны с объектом RCW 38 IR Cluster. Облако 1 является большим массивным облаком, имеющим депрессию, в которой расположен исследуемый объект. Не исключено, что депрессия образована звездным ветром и/или излучением молодых ярких звезд, принадлежащих звездному скоплению RCW 38 IR Cluster. Обнаружено также вращение облака 2 вокруг оси, имеющей направление ЮВ-СЗ, с угловой скоростью $\omega = 4.6 \cdot 10^{-14} c^{-1}$. В ЮВ направлении от объекта обнаружено красное

истечение со скоростью +5.6 км/с. Это истечение перпендикулярно вытянутости облака 2. Исследуемое скопление ассоциируется с ИК точечным источником IRAS 08573-4718, который имеет ИК-цвета, типичные для непроэволюционировавшего, скрытого (в облаке) звездного объекта. Скопление также связано с мазером воды. SIMBA изображение показывает наличие центрального яркого сгущения, совпадающего с самим скоплением, и двух отростков. Один из этих отростков (имеющий направление ЮЗ-СВ) по координатам и форме совпадает с облаком 2, так что не исключено, что и этот отросток вращается подобно облаку 2. В непосредственном окружении этих отростков имеются сгущения, напоминающие объекты Х-А.

Ключевые слова: *область звездообразования:вращение молекулярных облаков* .

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