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STAR FORMATION REGIONS IN LDN 1667

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A group of three star formation regions in the dark cloud LDN 1667 is examined. All three of these regions contain Trapezium type systems. ^{12}C(1-0) observations are made of the part of the molecular cloud LDN 1667 associated with one of the star formation regions. Three molecular clouds were detected, one of which (the main cloud) has a red and a blue outflow. Three stars from the star formation regions are found to have annular nebulae and one star has a conical nebula. The dark cloud LDN 1667 is associated with a radial system of dark globules which is formed by the star HD 57061.

Keywords: *molecular clouds: molecular outflows: star formation regions*

1. Introduction

There are two types of star formation regions [1]: (1) regions in which massive stars are formed and (2) regions in which stars of low and intermediate mass are formed. In this article we examine three star formation regions of the second type which lie in the dark cloud LDN 1667. Some stars in the three star formation regions are Trapezium type systems. Ambartsumyan [2] pointed out the importance of Trapezium type systems for the evolution of stars. ^{12}CO(1-0) observations have been made of a part of the molecular cloud LDN 1667 that is associated with one of the star formation regions. A radial system of dark globules is also associated with the dark cloud.

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2. Star formation regions

We shall examine three star formation regions. They all lie in the same molecular cloud (LDN 1667).

1. We found this region ourselves and it is not included in any of the standard catalogs. Its coordinates are $\alpha(2000) = 7^h22^m09^s.4$, $\delta(2000) = -25^o44'14''$ (see Fig. 1). Star formation region (SFR) 1 consists of five stars which form a Trapezium type system and a star with a nebula in the form of a cone (Fig. 1). Data on the stars from SFR 1 are listed in Table 1 (data from Ref. 3). In this table the first five stars are the stars of the trapezium, star No. 6 is a star with a conical nebula. The first column of the table gives the numbers of the stars, the second and third columns give the coordinates of the stars, and columns 4-9, the stellar magnitudes and colors of the stars.

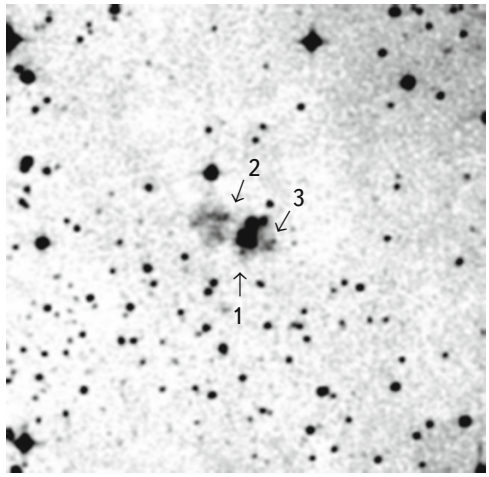

Fig. 1. DSS2 R image of the region containing SFR 1. (1) SFR 1, (2) stars with a nebula in the form of a cone, (3) annular nebula. North is upward and east to the left. The size of the image is 6'×6'.

TABLE 1. Data on the Stars Associated with Star Formation Region 1

N	α(2000)	δ(2000)	*B*	*B - V*	*B - R*	*J*	*J - H*	*H - K*
1	$07^h24^m12^s.14$	-25°49'56".5	17.53	-	1.64	14.143	1.389	0.679
2	07 24 12.62	-25 50 06.8	16.76	1.07	1.77	12.392	0.875	0.719
3	07 24 12.76	-25 49 57.9	13.01	-	2.29	14.493	-0.136	1.344
4	07 24 13.13	-25 50 03.1	-	-	-	15.870	0.941	0.858
5	07 24 13.18	-25 50 10.42	15.93	1.25	0.27	12.254	1.160	1.009
6	07 24 14.53	-25 49 54.8	18.46	-	1.78	-	-	-

As can be seen in Fig. 1, star 1 is coupled to an annular nebula. Table 1 shows that the *B-R* magnitudes for stars 1, 2, and 6 are very close.

2. This SFR lies in the same cloud as the previous one. This region contains six stars which form a Trapezium type system (this trapezium is in the form of a chain, see Fig. 2). Of these six stars, one is coupled to the annular nebula CLN 108 [4] (star 3 of Table 2). The table lists data on the stars in the trapezium (the first six stars), which are close to the star with a conical nebula (star 7, Fig. 2). The first column of the table gives the numbers of the stars, the second and third columns, the coordinates of the stars, and columns 4-9, the colors of the stars.

3. This SFR lies in the same cloud as regions 1 and 2. This region contains five stars which form a Trapezium system (this system is in the form of a chain, see Fig. 3). Data on the stars in the trapezium are listed in Table 3.

TABLE 2. Data on the Stars Associated with Star Formation Region 2

N	α(2000)	δ(2000)	*B*	*B - V*	*B - R*	*J*	*J - H*	*H - K*
1	$07^h24^m15^s.19$	$-25^o55'07''.7$	-	-	-	15.28	1.078	0.584
2	07 24 15.52	-25 55 03.6	16.02	-	-1.6	12.519	1.185	0.487
3	07 24 16.09	-25 54 48.9	14.87	0.52	4.65	11.732	0.414	0.287
4	07 24 16.29	-25 54 53.8	-	-	-	14.674	1.015	0.341
5	07 24 15.56	-25 54 40.2	15.61	0.13	2.16	13.625	0.566	0.153
6	07 24 17.21	-25 54 41.0	-	-	-	15.750	0.726	0.352
7	07 24 06.54	-25 54 21.7	13.81	0.42	0.73	12.132	0.396	0.075

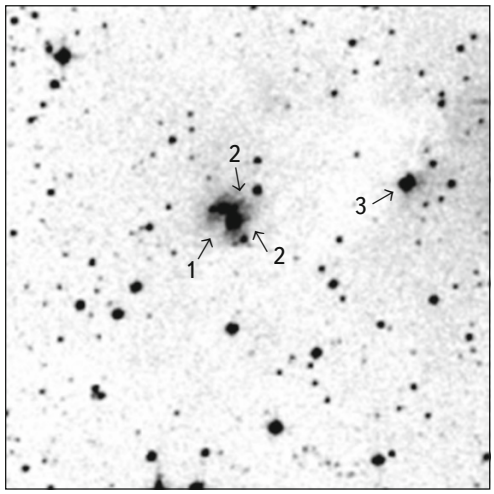

Fig. 2. DSS2 R image of the region containing SFR 2. (1) SFR 2, (2) annular nebula, (3) star with a nebula in the form of a ring (star 7 from Table 2). North is upward and east to the left. The size of the image is 6'×6'.

TABLE 3. Data on the Stars Associated with Star Formation Region 3

N	α(2000)	δ(2000)	*B*	*B - V*	*B - R*	*J*	*J - H*	*H - K*
1	$07^h23^m57^s.65$	-25°53'51".4	11.01	0.882	1.42	8.336	0.516	0.127
2	07 23 57.87	-25 53 36.3	15.13	0.30	3.71	12.153	0.413	0.301
3	07 23 58.53	-25 53 26.64	-	-	-	14.663	1.296	1.422
4	07 23 59.71	-25 53 16.78	-	-	-	11.616	-0.017	-0.005
5	07 24 00.07	-25 53 21.39	10.018	-0.074	0.00	10.113	-0.069	-0.01

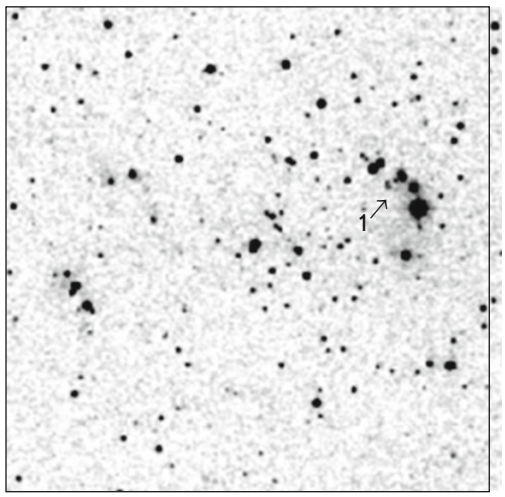

Fig. 3. 2MASS K image of the region containing SFR 3. (1) SFR 3. North is upward and east to the left. The size of the image is 6'×6'.

The first column of Table 3 gives the numbers of the stars, the second and third columns, the coordinates of the stars, and columns 4-9, the colors of the stars.

The table shows that star 3 has a quite large value of *B-R*, still larger than B-R for star 3 of Table 2. Veri [5] has analyzed data on the colors *B-V, B-R, J-H*, and *H-K* for stars in various spectral classes. Such large values of *B-R* are encountered in a few class K stars. For these class K stars, the data on the colors *B-V, J-H*, and *H-K* are similar to those for the two stars mentioned above.

3. Radial system of dark globules

A type I radial system of dark globules is associated with the dark cloud (see Fig. 4). The globules in this

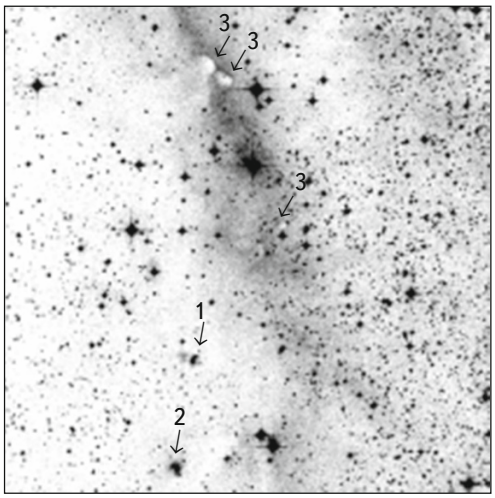

Fig. 4. DSS2 R image of the radial system of dark globules. (1) SFR 1; (2) SFR 2; (3) globules of the radial system. North is upward and east to the left. The size of the image is 20'×20'.

system have bright rims consisting of ionized hydrogen. The globules were formed by star HD 57061, which is of spectral class O9Ib. We now estimate the distance to this star. From Ref. 6, we have M_V = - $6^m.1$ and $(B-V)_0$ = - $0^m.25$ for the star O9Ib. For the star O9Ib Vizier gives V = $4^m.396$ and $B-V$ = - $0^m.159$. This yields E_{B-V} = $(B-V)$ - $(B-V)_0$ = $0^m.091$ and A_V = $3.3E_{B-V}$ = $0^m.3$. We obtain a distance modulus of $10^m.2$, which yields a distance of 1.1 kpc. This means the molecular cloud and the observed star formation regions must be at this distance. As proposed in Ref. 7, with time a type I radial system converts to a type II radial system in which the central star is of a yet later type and can no longer ionize the HII region and the rim. It is possible to estimate the time over which the HII and rims will radiate (i.e., the recombination time). For this, we use Sobolev's formula [8] for the emission time of an ionized cloud after the ionization sources are shut off, $t^* = 1/(n_e \cdot \Sigma C_i)$ (the sum over i is taken here from 2 to " and $n_e n^+ C_i$ is the rate at which electrons are captured by ions to the i-th level per cm^3 per s; at temperatures on the order of 10000 K $\Sigma C_i \sim 10^{-13}$ for hydrogen [8]). For $n_e \sim 10^2$ cm^{-3} [9], we have $t^* \sim 3200$ years, so that the emission takes place very rapidly. After emission, the radial system decays owing to the differential rotation of the galaxy [7].

4. ^{12}CO(1-0) observations of star formation region 1

^{12}CO(1-0) observations made in Chile of southern objects have been quite productive: discovery of molecular outflows and rotation of molecular clouds [10,11]. ^{12}CO(1-0) observations of the part of the cloud LDN 1667 associated with SFR 1 were made on August 30, 2003 with the 15-m (Sweden-ESO submillimeter telescope, SEST)

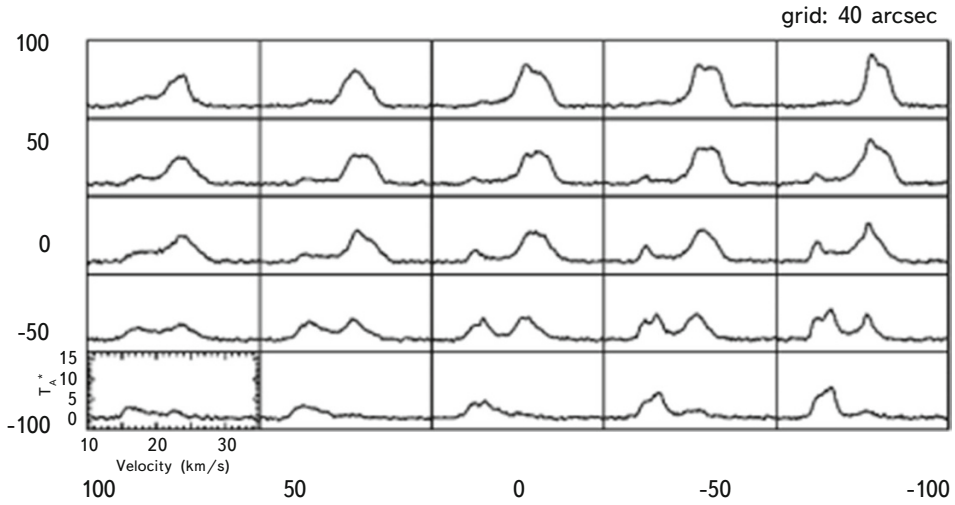

Fig. 5. ^{12}CO(1-0) spectra of part of the cloud around SFR 1.

TABLE 4. ^{12}CO(1-0) Velocity Distribution in Part of the Molecular Cloud Around SFR 1

---		-	+		-	+		-	+		---	+		---
15.9	17.8	24.07	15.9	17.4	23.7	---	---	23.7	---	---	23.9	---	---	23.9
---		-	+		---	+		---	+		---	+		-
15.9	17.8	23.7	16.3	17.8	23.9	16.1	-	23.9	16.1	---	23.9	15.9	18.0	23.7
---		-	+		---	+		---	+		---	+		-
15.9	18.2	23.5	15.9	17.8	24.1	16.3	---	24.3	16.1	---	23.9	15.9	18.0	23.5
---		---	---		---	+		---	+		-	+		-
15.9	17.6	23.5	16.3	17.4	23.7	16.1	17.6	23.3	16.1	17.8	23.7	15.9	18.0	23.3
---		---	---		---	---		---	+		---	+		-
15.9	17.8	23.0	16.3	17.4	23.7	16.1	17.8	23.3	16.1	18.0	23.7	15.9	18.0	23.2

telescope at La Silla, Chile. The directional diagram of the antenna at 115 GHz is ~45° and the beam efficiency is 0.70. Positions in the direction of the source were observed with an interval of 40" in a frequency modulation regime with a frequency spread of 10 MHz. During the observations the telescope was equipped with an SIS detector and a high-resolution acousto-optical spectrometer (1000 channels and a velocity resolution of 0.112 km/s). These observations were made with the late Prof. Jorge Mayem (National Observatory of Chile, Santiago, Chile).

Figure 5 shows some ^{12}CO(1-0) observations of the part of the cloud around SFR 1. This figure can be used to determine the velocity distribution in that region. The cells in Table 4 (which list the radial velocities in

km/s) correspond to the frames of Fig. 5. Since both red and blue outflows are present, the red outflow is indicated by a "+" sign and the blue, by a "-" sign.

Table 4 shows that there are three clouds in this region: the main cloud with a velocity of about 23.70 km/s, a second cloud with a velocity of 17.78 km/s, and a third, with a velocity of 16.11 km/s. The red and blue outflows belong to the main cloud. The red outflow has a velocity in the range 24.63-28.33 km/s or +0.93 to +4.63 km/s relative to the main cloud. The blue outflow has a velocity in the range 20.18-23.15 km/s relative to the main cloud or -3.52 to -0.55 km/s relative to the main cloud. For a better representation of the distribution of the clouds in this region, Table 5 lists the antenna temperatures of the emission from these clouds. The cells in this table correspond to the frames in Fig. 5. The antenna temperatures are given in units of 0.33 K. In each cell the antenna temperature of the blue outflow is given on the left in the top row and that of the red, on the right. In the second row, the antenna temperature for the third cloud is given on the left, for the second cloud in the middle, and for the main cloud on the right.

Table 5 shows that the red outflow occupies the north-west part of the observed region, while the blue outflow occupies the north-east and western parts. These outflows were formed by one or two stars from the star formation region, perhaps the stars associated with the nebulae mentioned above.

5. Conclusion

Three star formation regions in a single molecular cloud (LDN 1667) have been examined. These star formation regions consist of stars that form Trapezium type systems (two of these are in the form of a chain). ^{12}CO(1-0) observations of the part of the cloud associated with one of these star formation regions reveal the existence of

TABLE 5. Distribution of the Antenna Temperature Along the Part of the Cloud LDN 1667 Associated with SFR 1

5		---	2		3	---		8	---		11	---		9
8	---	22	6	---	27	3	---	29	3	---	30	---	---	37
4		---	---		8	---		13	---		9	5		8
8	---	20	4	---	21	5	---	21	7	---	26	6	---	32
2		---	---		4	---		6	---		4	2		2
10	---	22	6	---	23	9	---	21	12	---	22	15	5	29
---		---	---		---	---		5	2		2	2		2
9	---	12	14	---	15	12	9	15	10	11	19	13	12	18
---		---	---		---	---		---	---		---	---		---
9	---	6	10	6	5	10	6	3	6	10	7	11	10	7

three molecular clouds in this region: the main cloud with a velocity of 23.70 km/s and two others with velocities of 17.78 and 16.11 km/s. All three star formation regions are associated with the main cloud. A red outflow with a velocity of 0.93-4.63 km/s relative to the velocity of the main cloud and a blue outflow with velocities of -3.53 to -0.55 km/s relative to the main flow have been discovered. Of the stars in the star formation region, three are associated with annular nebulae and one star is associated with a conical nebula. The main molecular cloud is associated with a radial system of dark globules. This radial system was formed by the star HD 57061.

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