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CEPHEID COMPLEXES OF THE MILKY WAY

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Abstract. A method for identification of Cepheid complexes in Milky Way is applied. Based on the search algorithm and the data of Cepheids (Berdnikov et al. 2000) were found 18 Cepheid complexes of Milky Way with space (3D) density 5.0σ density peak with an excess of about ten objects. The data for OB, WR stars, open clusters, stellar associations, and HII regions were used too. These objects have a hierarchical structure in space. The results show the existence of a correlation between OB associations, HII regions, and WR stars that trace the regions of massive star formation. Probably stellar associations, HII regions and open clusters from nearby sites of star formation form regions of 1kpc centered in the Cepheid complexes. We consider this fact as a ground for identification of 18 Cepheid complexes in the Milky Way.

1. INTRODUCTION

Efremov (1995) defines the star complex as a stellar group of young stars formed together through fragmentation of a dense molecular cloud due to large-scale gravitational instability. A star complex consists of different stellar objects with total mass of about $10^7 M_\odot$. The aim of the present paper is to propose a method for identification of Cepheid complexes in embedded massive OB stars that ionize the gas in HII regions. On the other side, HII regions are physically associated with young star clusters. We suppose those stellar associations; HII regions and young star clusters indicate massive star formation in the star complexes. There is evidence that Cepheids build up large-scale groups as star complexes (Efremov 1995). They are members of star complexes. Based on the search algorithm in the Sect. 2 and the data of Cepheids (Berdnikov et al. 2000) were found 18 Cepheid complexes of the Milky Way in Sect. 3 using space (3D) density 5.0σ density peak with an excess of about ten objects. The results on stellar content of star complexes were discussed in Sect. 4.

2. CEPHEID DISTANCES IN THE MILKY WAY

Berdnikov's (2000) Cepheids were positionally matched to sources from 2MASS catalog (see http://irsa.ipac.caltech.edu). Coordinate matching was done using 3" radius and colour index $J - K_s \leq 1$. The near infrared wavelengths JH*Ks* photometry is also useful to identify Cepheids in the Milky Way towards the regions as star complexes in high extinction. We derive the period-luminosity relation for 54 Classical Cepheids with distances from Ngeow and Kanbur (2004) which agrees at $\approx 1.44\,\sigma$ level with Hipparcos geometic distances and $\sigma \pm 0.1 mag$ in $M_{K\,s}$.

$$M_{Ks} = -2.30 - 3.44\log(P); \tag{1}$$

Using the mean colour excesses for galactic Cepheids from Laney and Stobie (1993) we obtain

$$(J - Ks)_o = 0.46 + 0.149(\log(P-1) - 0.005; \tag{2}$$

and then for 334 Cepheids with JHK_s of 2MASS photometry we have

$$E_{J-K} = (J - Ks) - (J - Ks)_o; \tag{3}$$

and from Dutra and Bica (2001) follows

$$A_K = 0.67 E_{J-K} \tag{4}$$

then

$$(K\,s)_o = K\,s - A_K; \tag{5}$$

and in the end distances for 334 stars in kpc were obtained

$$R = 10^{0.2(K\,s)o - M_{K\,s}) + 1} / 1000; \tag{6}$$

The most of Cepheids (304) coincide with the stars of Berdnikov et al. (2000). The dispersion between the two sets of distances is around 0.6 kpc. Compared the distances from 2MASS in this section with Berdnikov's el al. (2000), the data of distances from Berdnikov are more suitable for Cepheid distribution of the Milky Way.

3. SEARCH ALGORITHM FOR CEPHEID COMPLEXES IN THE MILKY WAY

The method is based on the apparent stellar surface density to search for Cepheid peaks. Let a set of N irregularly spaced Cepheids occurs in the field of the Galaxy. The space angles between all 455 Cepheids in the catalog of Berdnikov el al. (2000)

$$d_{i,j} = (\sin(y_i)\sin(y_j) + \cos(y_i)\cos(y_j)\cos(x_i - x_j) \quad i,j = 1\ldots N, \quad i \neq j, \tag{7}$$

were obtained, where the coordinates right ascension (x_i) and declination (y_i) and angle (d_{ij}) between the stars are in degree, N= 455. Then the nearest neighbor angles

$$\mathrm{d_l = \min\{d_{ij}\}, \quad l = 1,2,\ldots N,} \tag{8}$$

for each Cepheids was obtained. The mean neighbor angle of Cepheids, which form a group, is

$$\mathrm{< d >= \frac{1}{N-1}\sum d_l.} \tag{9}$$

The mean neighbor angle of group is a good characteristic for stellar surface density (δ) in a candidate Cepheid group and is given by equation (see Ivanov, 1996)

$$\mathrm{< d >= \frac{1}{2\delta^{1/2}}.} \tag{10}$$

4. CEPHEID COMPLEXES OF THE MILKY WAY

First, we obtain a surface density (2D) peaks above 5σ the background distribution in preliminary. We have to select Cepheid candidate for complexes with density 5σ deviation above the background Cepheids of the Milky Way. The criterion in Sect. 2 proposes that the Cepheids will be assigned to one candidate Cepheid complex if they form a group with density (δ) peak obtained by equation 10 with 5.0 σ deviation above the background of Cepheids and have an excess of $\approx$ 5 – 10 stars. This first step is helpful to obtain the density peaks in surface (2D) density 5σ above the background. In this way were found 31 Cepheid group. The second step was to combine 2D density peak with a space density peak taking into account the distance to Cepheids in a cone angle $d_{i,j}$ on sky of the group obtained by equation 7. Varying the low and the high distance limits within the space angle are then found Cepheid space concentrations in the 31preliminary 2D cluster center. Usually were defined the various numbers of Cepheids within a space volume while was obtained the possible maximum 3D density of the Cepheid group. In this way we received Cepheid groups with space density peak > 5σ deviation above the neighboring Cepheids in space. These density centers we call Cepheid complexes. The success of procedure to convert 2D density into 3D density depend on accuracy of the Cepheid distances and the distances of luminous and OB stars of Humphreys and McElroy (1984). We accepted the distances of Cepheids from the catalog of Berdnikov et al. (2000) where are data for 455 Cepheids but a part of them, 151 Cepheids, are concentrated in 18 Cepheid complexes which are outlined on galactic plane in Fig. 1.

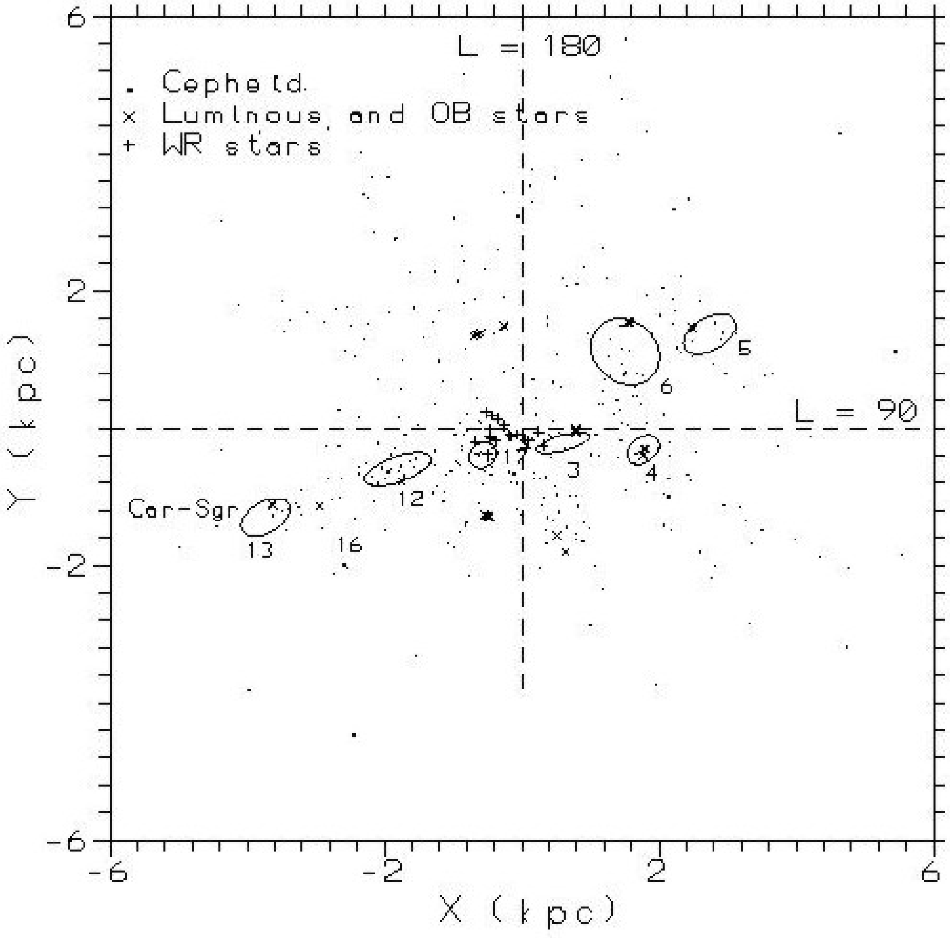

Figure 1:

The main parameters of Cepheid complexes are given in Table 1. There are two large regions of the Milky Way, which contain several Cepheid complexes. These largest regions are identical with the spiral arm Car-Sgr that consists of Cepheid complexes with numbers from 12 to 18. The spiral arm Per-Cas contains complexes from 5 to 7. The possible Cygnus arm is outlined by complexes with numbers 3 and 4. The position of Cepheid complexes 4 and 17 is not clear. Cepheid complex 4 may be a part of Perseus arm, while that of No 17 belongs to Car-Sgr.

Table 1: Stelllar distribution in Cepheid complexes

CC	L	B	$d_{\odot}(kpc)$	$\overline{P}$	σ	*Diam.*	N_{ceph}	N_{OB}	$N_{SN\,R}$	d_{α}
1	23.26	-0.08	0.65	8.4	4.3	0.639	11	2	-	18.2
2	28.03	-0.02	1.69	7.7	3.4	0.528	14	1	-	10.2
3	68.38	-0.06	0.66	5.7	1.4	0.581	10	-	3	21.7
4	86.85	-0.01	1.79	7.8	0.5	0.733	20	13	4	9.8
5	116.59	0.00	3.07	6.5	1.6	0.639	27	-	8	5.6
6	125.96	-0.02	1.89	5.8	1.2	0.799	27	1	3	9.1
7	163.77	0.03	1.99	8.2	1.4	0.643	6	1	1	12.1
8	205.76	0.00	1.40	5.1	0.7	0.515	6	-	1	16.4
9	206.82	0.02	2.24	4.1	0.8	0.704	10	-	-	10.2
10	240.84	0.03	3.38	11.8	8.4	0.684	9	-	-	8.5
11	267.34	-0.08	1.09	10.1	9.3	0.867	29	2	6	21.5
12	286.38	-0.02	1.96	10.4	8.9	0.499	20	2	1	8.9
13	289.04	0.01	3.97	7.6	4.8	0.436	9	1	-	4.3
14	293.32	-0.01	1.58	7.8	8.5	0.551	20	1	1	11.1
15	294.87	-0.04	1.05	6.2	1.5	0.330	11	1	-	11.0
16	297.22	-0.03	3.09	8.0	2.0	0.387	7	-	-	6.9
17	310.59	-0.04	0.61	5.9	0.8	0.486	18	-	-	20.5
18	328.9	-0.03	1.54	8.4	1.4	0.554	7	-	2	14.9

The contents of the table are as follows:
Column 2 -3 give the galactic coordinates of the center of the group
Column 4 gives the mean distance to the center of group in kpc obtained by Cepheids
Column 5 gives the mean period of Cepheids in Cepheid complex
Column 6 gives the effecive diameter of the complex in kpc.
Column 7 gives the number of Cepheids
Column 8 gives the number of Luminous and OB stars of Humphreys and McElroy (1984)
Column 9 gives the number of WR stars from Hiparcous catalog
Column 10 gives the number of SNR from Guseinov et al. (2003, 2004a,b)
Column 11 gives cone angle in degree on sky around the center of cepheid complex

The similarity of mean periods of Cepheids in complexes can be seen in Table 1. The mean Cepheid period reflects the nearby ages of different complexes in the Milky Way. We believe that Cepheid complexes contain other stellar objects. The effective diameter of complexes were accepted equivalent to the space volume occupied by Cepheids. We found other stellar objects around the centers of Cepheid complexes. We ound also 83 luminous and OB stars of Humphreys and McElroy (1984) within the volume occupied by Cepheid complexes. There is a good coincidence between Cepheid and luminous OB stars of Humphreys and McElroy (1984). We found many other objects in Cepheid complexes. Columns from 7 to 9 in Table 1 gives the number of the related objects to Cepheid complexes. There are also 13 stellar associations, 6 open clusters from Linga (1995), and 6 HII regions of Blitz et al. (1982), We found 18 WR stars from van der Hucht (2001) catalog but their distances are based on Hiparcos catalog. Most of objets, indicators of massive star formation, belonging to Cepheid complexes. In this way Cepheid complexes in Table 1 become the centers of real star complexes.

5. DISCUSSION

5.1. The distance accuracy of WR stars in the star complexes

The OB, WR stars, HII regions and SNR were searched within the Cepheid complex boundaries. However the belonging of these objects to the Cepheid complexes put the question of different distance accuracy of the related objects. Especially the distance accuracy of stars of Humphreys and McElroy (1984) compared with Cepheid distance is good. Cepheid distances coincide with that given in Hiparcos catalog. Hiparcos trigonometric parallaxes were used for deriving the period-luminosity relation for classical Cepheids (Feast and Catchpole, 1997). They used 26 Cepheids with the greatest weight parallaxes which are close to the Sun at ≈ 0.5 – 1 kpc. We have searched Hiparcos stars in the regions of the star complexes in Table 1. We were found 247 OB stars in the Hiparcos catalog within 17 of the Cepheid complexes in the Table 1. The most of them, about 80 per cent of stars, fall in four nearby star complexes with numbers 1, 4, 11 and 18. These four Cepheid complexes are nearby ≈ 0.6 kpc from the Sun. These stars have good determined parallaxes with a mean error of 1.5 mas. We confirm the conclusion of Feast and Catchpole (1997) that Cepheid distances at ≈ 0.6 kpc are in good accordance with Hiparcous data. However the more remote stars than > 1 kpc have higher errors and they were not found in more distant star complexes. There is the best coincidence between Cepheid and Hiparcos distances, obtained as trigonometric parallaxes up to 0.6 kpc. The OB, WR stars, SNR and HII regions were searched within the Cepheid complex boundaries. However the belonging of these objects to the Cepheid complexes depends on distance accuracy of OB, WR stars and HII regions comparing with Cepheid distances. The data of luminous and OB stars from Humphreys and McElroy (1984) show a good agreement with Cepheid distances. However the data only of 41 WR stars from catalog of van der

Hucht (2001) were found in Hiparcous catalog: web interface http://visier.u-strasburg.fr/ VisieR On-line Data Catalog: I/239/hip/. The 18 WR stars in Table 1 were found in star complexes nearer than 0.6 kpc. The photometry distances of van der Hucht (2001) do not show any correlation with Hiparcous distances. There are not any WR stars within the Cepheids complexes. The accuracy of photometic distances to WR stars is a problem now. The distances of 18 WR stars found in four Cepheid complexes in Table 1are from Hiparcous catalog.

5.2. The CMD of luminous and OB stars in regions of star complexes

The star complex usually consists of several OB associations and open clusters, HII regions, Cepheids, WR stars and SNR. The high density of the respective objects with similar ages delineates the complexes. Coordinates of open clusters, OB associations, Cepheids and WR stars may single the star complexes in Fig. 1. Each complex in Table 1 contains about 5 -10 Cepheids. The mean effective diameter of complexes is $\approx$ 600 pc. The periods of Cepheids are similar in the same star complex. This is important result connected with the similarity of ages of members in the star complexes. Bastian et al. (2007) consider the largest scale of star forming in the local spiral galaxy M33 extension regions of 1 kpc in size which are twice bigger than the size of star complexes. They call these regions spiral arm pieces. We found 788 luminous and OB stars of Humphreys and McElroy (1984) around the centers of Cepheid complexes in a twice-bigger diameter than the diameter of Cepheid complex given in column 6 of Table 1. This large number of luminous and OB stars in the regions of Cepheid complexes confirm the existence of a scale of 1kpc centered in the Cepheid complexes. The CMD of stars in the regions, which are around Cepheid complexes, are shown in Fig. 2.

In these regions dominate massive stars with masses from 9 to 20 $M_{\odot}$. The main concentration of massive stars shown of Fig. 2 fall in regions around Cepheid complexes with CC No 4, 5 and 12 in Table 1. They are really spiral arm pieces, as Elmegreen and Efremov (1998) were suggested, of well known spiral arms Car-Sgr, Per-Cas and Cygnus, denoted in Fig. 1. Comparing Cepheid complexes of Milky Way with star complexes in M33 galaxy we conclude that the main difference is the deficit of WR stars in the complexes of Milky Way. It is due to uncertainty of WR distances in the catalog of van der Hucht (2001) comparing with Hiparcous parallaxes. However there are concentrations of WR stars from catalog of van der Hucht (2001) in regions around Cepheid complexes with No 1, 3, 11 and 17 in Table 1 if we take into account only their position on the sky. We believe that the deficit of WR stars in Milky Way complexes is not real. It is due, probably to uncertainty of WR distances in the catalog of van der Hucht (2001) comparing with Hiparcous parallaxes. However there are concentrations of WR stars from catalog of van der Hucht (2001) in the regions of main spiral arm in the Milky Way on the sky. They are regions from spiral arm pieces in the spiral arm Car-Sgr as Elmegreen and Efremov (1998) were emphasized. The data in the present paper show that young clusters, OB associations and high luminosity stars

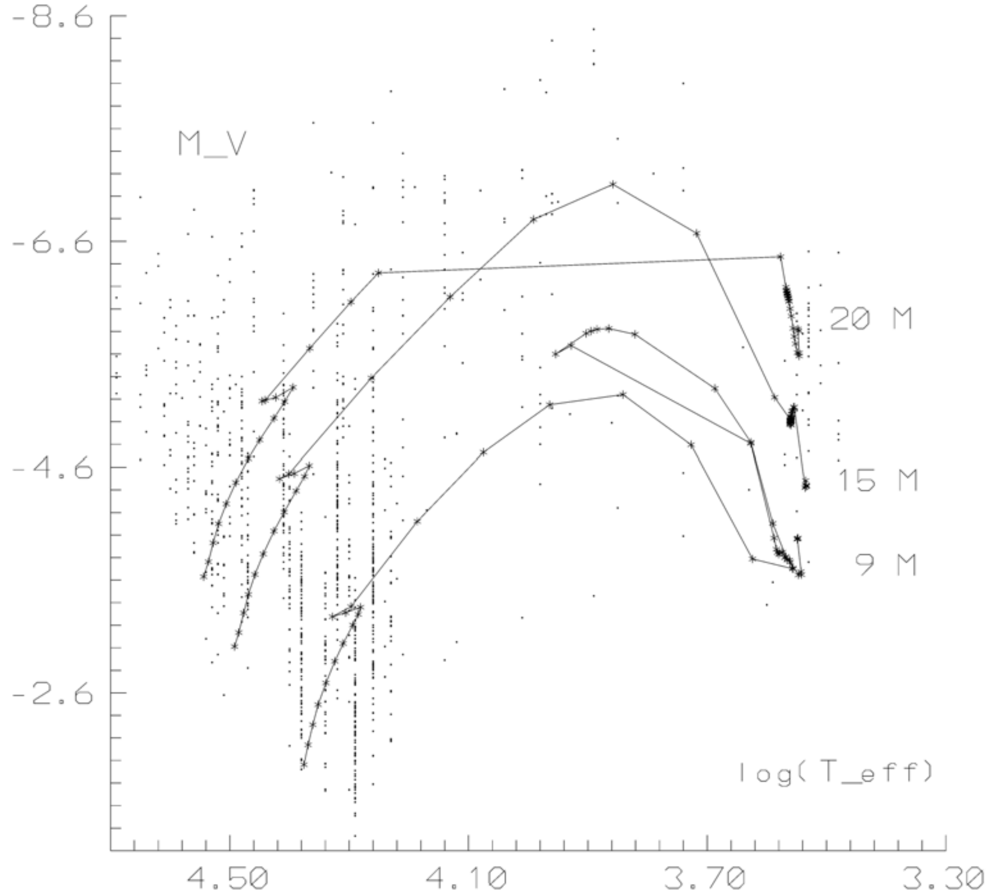

Figure 2:

with huge Cepheid complexes outline the Car-Sgr arm which is at ≈ 4 kp*c* long from the Sun as can be seen from Table 1. This result is an observational test for hierarchy of stars in formation in the Milky Way.

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