Space distribution and clustering of 345 Cepheids in the Milky Way from 2MASS data

Georgi R. Ivanov
Department of Astronomy, University of Sofia
gr_ivanov@phys.uni-sofia.bg
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Abstract. JHK_S photometry from the 2MASS survey is used for investigation of the distribution of Milky Way Cepheids. The diameter and thickness of the explored region of the Milky Way disk is about 10 kpc and about 1 kpc, respectively. This paper presents: 1) recalibrated period-luminosity relation in the K_S band, based on 29 well studied Cepheids, 2) reestimated distances for 345 Cepheids, 3)a method for detecting dense groups of Cepheids in 3D space and 4) 18 newly revealed large Cepheid groups. It is found that the characteristic size of the largest groups is about 700 pc. Many other young objects are found around the centers of the Cepheid groups: OB stars, WR stars, associations, open clusters, HII regions. It is concluded that the Cepheid groups are good indicators of the locations and sizes of the star forming complexes.
Key words: Cepheids, period-luminosity relation, star complexes

Пространствено разпределение и клъстеризация на 345 цефеиди от Млечния път по 2MASS данни

Георги Р. Иванов

Фотометрия в системата JHK_S от обзора 2MASS е използвана за изследване на разпределението на цефеиди от Млечния път. Диаметърът и дебелината на разглежданата околност от диска на Млечния път са съответно около 10 кпс и около 1 кпс. В тази работа са представени: 1) прекалибрирана зависимост период-светимост в K_S лъчи, базирана на 29 добре изучени цефеиди, 2) преоценени разстояния до 345 цефеиди, 3) метод за отделяне на плътни групи от цефеиди в тримерното пространство и 4) 18 новоизявени големи цефеидни групи. Намерено е, че характерният размер на най-големите групи е около 700 пс. Множество други млади обекти са намирени около центровете на цефеидните групи: OB звезди, WR звезди, асоциации, разсеяни купове, HII области. Заключено е, че цефеидните групи са добри индикатори на положението и размерите на звездо-образуващите комплекси.

Introduction

The dust extinction in the JHK_S bands of the 2MASS photometry is about 10 times lower then in the optical bands. This fact facilitates the investigation of highly reddened objects, such as many of the Cepheids in Milky Way (MW) plane.

The largest star complexes in the MW consist of various kinds of objects with total mass about $10^7 M_\odot$ and their study is very important for understanding the structure and evolution of the MW galaxy. There is evidence that the Cepheids form large-scale groups, being subsystems of the star complexes (Efremov 1995, Elmegreen & Efremov 1996). Therefore, having good distances to the Cepheids, one can investigate the MW star complexes indicated by the Cepheid groups.

The period-luminosity relation (PLR) of the Cepheids is commonly used tool for estimating their distances and investigations of the MW structure. The near-infrared PLR of the Cepheids has been calibrated a few times in the last decade (Laney & Stobie, 1993; Feast & Catchpole, 1997; Ngeow & Kanbur, 2004). However, the use of 2MASS photometry system involves recalibration of this PLRs.

Usually, only one or two random-phase observations are available in the 2MASS catalogue. But due to the amplitude decreasing with the wavelength increasing, as shown by Soszynski et al. (2005), the 2MASS magnitudes and colours of the Cepheids must be close to their mean values within $\sigma = \pm 0.2$ mag. Therefore, the expected additional increase of the scatter of the PLR must be small. Moreover, the approximate geometric parameters of the Cepheid groups will be determined well enough because of the use of numerous Cepheids, despite of the larger individual distance errors.

This paper presents: 1) a recalibrated near-infrared PLR in K_S band, based on 29 well studied Cepheids, 2) reestimated distances for 345 Cepheids, 3) a method for detecting dense groups of Cepheids in 3D space, and 4) 18 newly revealed Cepheid groups as indicators of star forming complexes. The stellar content of the complexes is discussed briefly in the last section.

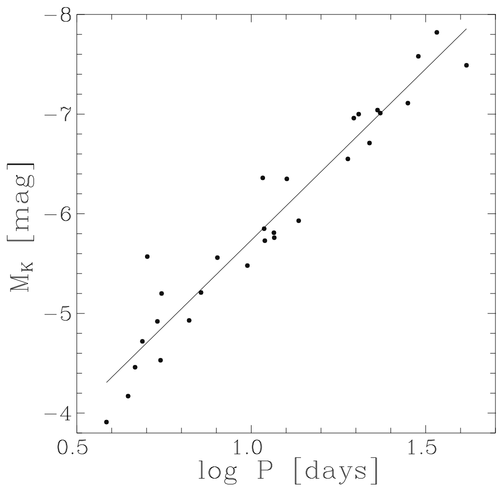

Fig. 1. The period-luminosity relation for 29 classical Cepheids in K_S band, derived here.

1 Period-luminosity relation and distances to the Cepheids

The 2MASS photometry was used for identification of MW Cepheids towards regions containig star complexes in high extinction. The respective objects of the catalogue of Berdnikov et al. (2000), containing BVRI data for 455 Cepheids, were positionally matched to the sources in the 2MASS catalogue (see http://irsa.ipac.caltech.edu). Coordinate matching was done within radius of 3" and colour index $J - K_s \leq 1$. By this way 345 Cepheids were identified among the 2MASS data and used further.

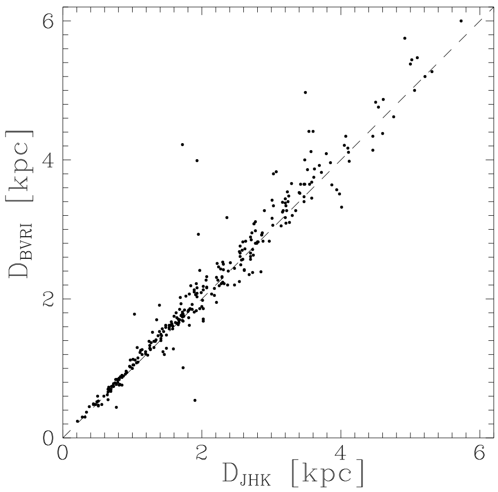

Fig. 2. Comparison between the distances of 345 Cepheids derived in this study and in the BVRI study of Berdnikov et al. (2000). The dashed line is the 45^o line.

Using the mean colour excesses for the Galactic Cepheids from Laney & Stobie (1993) we obtain

$$(J - K_s)_o = 0.46 + 0.149(logP - 1) - 0.005; \tag{1}$$

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

$$E_{J-K} = (J - K_s) - (J - K_s)_o. \tag{2}$$

With the data of Dutra & Bica (2001) we can write

$$A_K = 0.67E_{J-K} \tag{3}$$

and then

$$(K_s)_o = K_s - A_K \tag{4}$$

We used the distances to the Cepheids from Ngeow & Kanbur (2004). They agree at $\sim 1.44\ \sigma$ level with the Hipparcos geometric distances. After this the PLR in the K_s band for 29 Cepheids with standard error ± 0.1 mag was derived:

$$M_{Ks} = -2.30 - 3.44logP. \tag{5}$$

Figure 1 shows the PLR in the 2MASS K_s band.

Finally, the distances for 345 Cepheids in kpc were calculated as

$$R[kpc] = 10^{0.2((K_s)_o - M_{K_s})+1}/1000. \tag{6}$$

Figure 2 shows comparison between the distances derived in this work and the distances of Berdnikov et al. (2000). About 5% of the objects strongly deviate from the bisector in Fig.2. They were not used further.

2 The method for detecting of Cepheid groups in 3D space

The star complexes are groups with high stellar density. Therefore, the mutual distances between the stars in the complexes would be substantially smaller than those of the background stars. This fact lies at the base of the special "agglomerative" algorithm, proposed by Battinelli (1991) as "Path Linkage Criterion" (PLC) (see below).

An improved technique for identification of star complexes, based on the PLC, was proposed by Ivanov (1996), as follows. First, numerous candidates for Cepheid groups are extracted by the PLC. Second, each candidate for a Cepheid group becomes recognized as real group if its space density exceeds the mean density of its vicinity by at least 5 times.

For the processing of the collected data the rectangular coordinates x, y and z of the Cepheids (in kpc) must be derived. Then the Euclidean distance between each pair of points $(i, j = 1, ..., N)$ are calculated as follows:

$$d_{i,j} = [(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2]^{1/2}. \tag{7}$$

The distance between i-th point and its nearest neighbour point plays important role in this technique. Let us note it as

$$\mathrm{d_I = min\{d_{ij}\}; I = 1, 2, ..., N; j \neq i.} \tag{8}$$

The application of the PLC to N points (here in the 3D space) contains a few steps as follows.

1) We get arbitrary point, i.e. the point No.1 in our list and find (through (7) and (8))the distance d_1 from it to the closest other point.

2) We replace this closest point to be No.2 in our list and find the distance d_2 from it to the closest other point, excluding point No.1.

3) We replace this closest point to be No.3 in our list and find the distance d_3 from it to the closest other point, excluding the points No.1 and No.2.

4) We continue the process till we gain No.(N-1) as the closest to the point with No.(N-2) and the respective distance d_{N-1} from it to the last point with No.N.

By this manner we derive the chain of distances $d_1, ..., d_I, ..., d_{N-1}$, which define a path passing through all the points. The regions with high concentration of short distances in the chain correspond to the regions with high density of the points in the 3D space.

The second stage of the PLC is application of a searching distance d_S to extract regions of the chain containing at least L neighbour distances with $d < d_S$, i.e. at least L+1 points. Therefore, two distant points may belong to one group if we can move from one to another with a step that is always less than d_S. Further we extract all such points as members of one group.

However, this is not the final group yet.

It is obvious that the PLC is able to detect both compact and filamentary groups of stars. Filamentary young stellar groups may be the result of an star formation provoked by ionization stellar winds, SNs, etc. Therefore, the PLC has important advantage in respect to other methods that can not detect filamentary roups (Battinelli 1991).

However, by increasing d_S we increase the variety of the extracted groups. To avoid this disadvantage of the PLC and to extract the most concentrated groups we introduce density estimations.

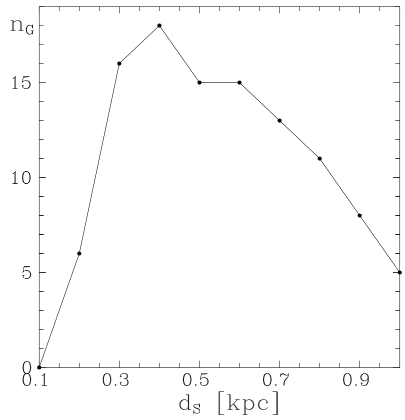

Fig. 3. Dependence of the number of the revealed Cepheid groups n_G on the search distance size d_S.

In the third stage of the method we derive the average stellar density in a spheroidal layers centered on the centers of the revealed groups and having volumes 3 times larger than the volumes of the candidate groups. To avoid overlapping of the layers and neighbour groups the inside diameter of the layer is chosen to be 2.2 times larger than the size of the group.

It is difficult to derive the space density δ of the group, because its space volume is poorly defined. However, we may assume Poisson distribution of the points, i.e. mutual independence of the presence of the points in their place. Let us consider a group with K close points (Cepheids), extracted by the PLC. Then the value of density δ may be estimated through the average minimal neighbour distance in the group

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

as shown by Ventsel & Ovcharov (1973):

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

In this way we select groups whose density is at least 5 times higher than the density of the vicinity. Depending on the searching distance d_S, these groups have various densities and numbers of stars. The smallest groups are the dense OB associations that have at least 3 Cepheids sizes sizes about 20 pc. The largest groups have sizes about 1 kpc compatible with the giant molecular clouds. Generally, we apply the described method for searching groups with at least 6 members (L=5) and changing d_S we find various numbers of groups n_G.

Figure 3 shows the dependence of the number of the detached groups n_G on d_S in our case. According to Battinelli (1991) we choose a searching distance d_S that corresponds to the maximum number of groups as the characteristic size of hierarchy. This distance corresponds to the largest hierarchy of star forming complexes.

Here we find that the maximum number of selected groups corresponds to a search distance d_S of 0.4 kpc, which gives a characteristic size of the largest groups of Cepheids of about 700 pc.

Table 1. Parameters and population of the revealed Cepheid groups

CC	L	B	$d_\odot(kpc)$	$\bar{P}$	σ	$Diam.$	N_{ceph}	N_{OB}	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	9.8
5	116.59	0.00	3.07	6.5	1.6	0.639	27	-	5.6
6	125.96	-0.02	1.89	5.8	1.2	0.799	27	1	9.1
7	163.77	0.03	1.99	8.2	1.4	0.643	6	1	12.1
8	205.76	0.00	1.40	5.1	0.7	0.515	6	-	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	21.5
12	286.38	-0.02	1.96	10.4	8.9	0.499	20	2	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	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	-	14.9

The contents of the table are as follows:
Column 2-3: Galactic coordinates of the center of the group;
Column 4: mean distance to the center of the group, in kpc;
Column 5: mean period of Cepheids in the group, in days;
Column 6: standard deviation of the mean period;
Column 7: effective diameter of the complex, in kpc;
Column 8: number of Cepheids in th group;
Column 9: number of luminous and OB stars from Humphreys and McElroy (1984);
Column 10: angular size of the group, in degrees.

3 The Cepheid complexes and their stellar content

Applying the described objective technique we found that 345 MW Cepheids form 18 Cepheid complexes (CCs). The main parameters of the CCs, as well as the data about their content of OB and WR stars are collected in Table 1.

The distances of the CCs to the Galactic plane and the equivalent diameters of the CCs (the diameters of spheres whose volumes are equivalent to the volumes of the CCs) show that the investigated Cepheids are distributed in the Milky Way disk, inside an elliptical volume with a thickness of about 1 kpc and diameter of about 10 kpc.

Many other stellar objects can be found around the centers of the CCs. There is a good coincidence between high space density of Cepheids and the 83 luminous OB stars listed by Humphreys & McElroy (1984), as well as 18 WR stars. Inside the CCs there are also 13 stellar associations, 6 open clusters from Linga (1995) and 6 HII regions from Blitz et al. (1982). Since almost all indicators of active star formation can be found inside and close to the CCs, these formations seem to be kernels of real star forming complexes.

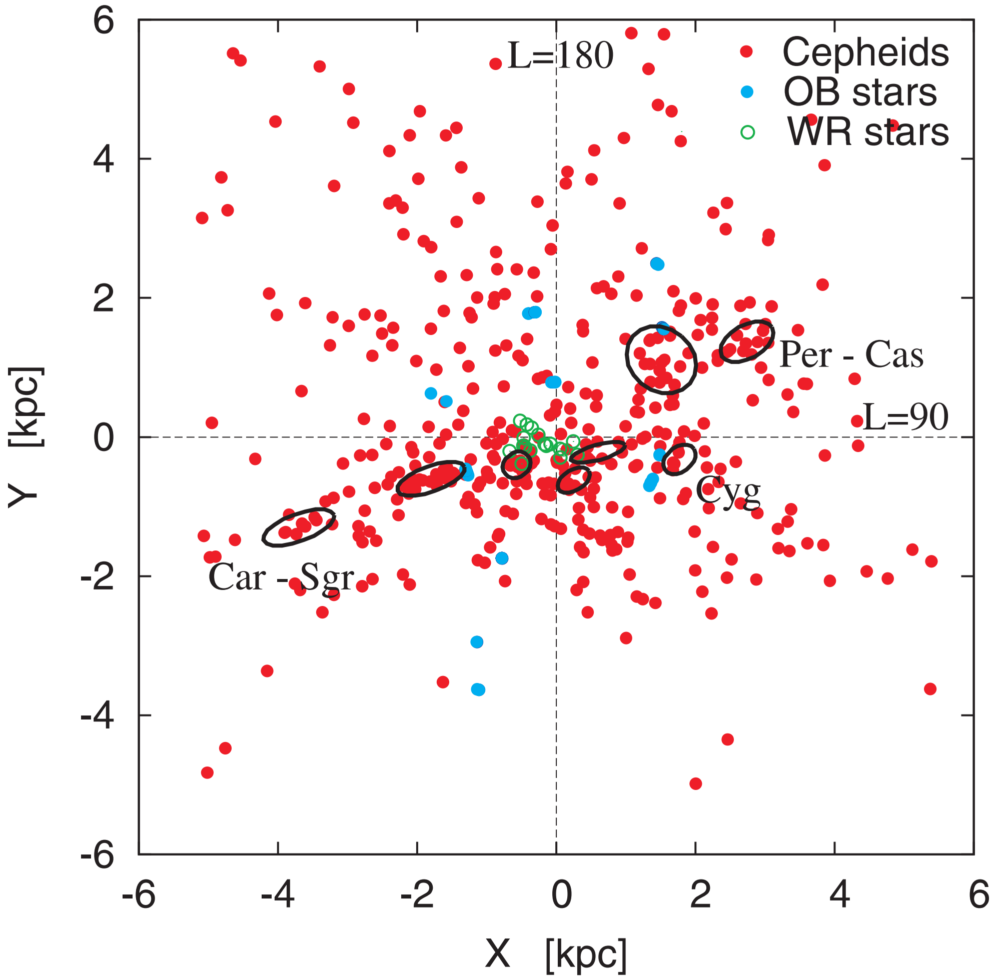

Fig. 4. Distribution of Cepheids, OB stars, WR stars and the Cepheid complexes in the Solar vicinity, projected on the Milky Way plane.

Figure 4 shows the distribution of Cepheids, OB stars and WR stars in projection on the MW plane. The projections of 8 large CCs among the MW spiral arms are shown with ellipses. They trace well the local spiral arms Carina-Sagittarius, Perseus-Cassiopeia and Cygnus.

The results lead to the conclusion that the Cepheid groups are good indicators of the location and size of the star forming complexes in the Milky Way.

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Fig. 5.