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STAR COMLEXES IN M33

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Abstract. The star complexes have a hierarchical structure in both space and time. A method for indentification of star complxes in M33 is applied. The average size of star clusters is from 11 to 20 pc, while the size of OB associations is ranged 60 - 100 pc. Several OB associations form a star complex with a mean dimension of 0.3 - 1 kpc. In this paper we apply correlation technique in order to compare different stellar populations in M33. Our results confirm the existence of a strong correlation between OB stars, HII regions, and WR stars which indicate the regions of massive star formation. There was confirmed a good correlation between RSGs and WR stars in spiral arms of M33. It can be expected that as the progenitors of WR stars are massive OB stars or RSGs with masses $\mathrm{M} \geq 20\mathrm{M}_{\odot}$. The massive RSGs as well WR stars probably originate from nearby sites of star formation. We consider this fact as a basis for selecting star complexes in M33. The aim of this paper is to pesent method for indentification of star complexes to be applied for other nearby galaxies.

1. INTRODUCTION

M33 is a nearby galaxy of Sc type with a suitable inclination between galactic disk and the celestial plane, to study the stellar associaton which form star compexes. In this galaxy 143 associations with a mean diameter 200 pc were isolated by Humphreys and Sandage (1980). Efremov (1995) considers the star complex as a slellar group of young stars formed together by fragmentation of a dense molecular cloud, which are initially structured owing to large scale gravitational instability. They consist of objects with total mases about $10^7 M_{\odot}$. The aim of the present paper is to propose a method for indentification of star complexes in M33, using observational data of HII regions which are excited by massive OB stars embedded in them. On the other side, WR stars are objects which are physically associated with HII regions. We suppose that OB, WR stars, and HII regions indicate the star complexes as regions of massive star formation. There was evidence of large scale groupings of RSGs and Cepheids not within OB associations but beyond them (Efremov, 1995). So the possible stellar populations of star complexes may be also red supergiants (RSGs) and Cepheids. Red supergiants (RSGs) in M33 were selected by Vassilev et al. (2002), observed in JHK passbands and published in 2MASS survey. The sample of RSGs was defined by the limit $K > 13$ mag. This criterion removes the brighter stars beacause they should belong to Milky Way background. The sample of RSGs contains 1650 stars selected by criterion $J - K > 1.1$ which are suitable for the purpose of the present

Table 1: General information on M33 galaxy

Center's coordinates (nucleus):
$R.A.(2000) = 23.462042°$
$Dec.(2000) = +30.6601944°$
Distance modulus: m-M = 24.52

paper. Observational data for coordinates of 905 Cepheids are from Mochejska et al. (2001). However the data of latter paper do not cover the total area of M33 since the observational data of Sandage (1983) are also used in the present study. The gas component and the stellar distribution of M33 are well studied. Catalogues of HII regions have been published and by Courtes et al. (1987) and in Ivanov et al. (1993) (hereafter IFM) a catalogue of 2112 OB stars was listed. A list of the Wolf-Rayet stars have been presented by Massey and Conti (1983) and Massey et al. (1987; 1995). Nowadays the number of WR stars in M33 amounts 168.

2. CORRELATION TECHNIQUE

In the present study we combine the surveys of OB stars, HII regions, and WR stars in order to compare the distributions of OB stars, HII regions, WR stars, RSGs and Cepheids in M33. On the other way we also use a correlation technique for comparison between the stellar populations in M33 proposed by Ivanov (1998). Let N1 stars of one population in M33 have surface density δ_1 while another population of N2 stars has a surface density δ_2. The two-dimensional angular distance between the stars of the k-th stellar couple is d_k as defined in the Appendix of Ivanov (1998). Supposing a random distribution of the stellar populations in the galaxy, the distance between the two stars of the k-th couple is exactly d_k, we define the probability (see Ivanov, 1998):

$$P_{12}(k) = [(1 - \exp(-\pi d_k^2 \delta_1)][(1 - \exp(-\pi d_k^2 \delta_2)], \quad (1)$$

a measure for associated stars. The real associated stars of two different populations form couples with $d_k \to 0$ and consequently $P_{12}(k) \to 0$. The couples of foreground stars have great neighbour distances d_k and $P_{12}(k) \to 1$. The quantity $P_{12}(k)$ gives the probability to find one star of population "1" and another star of population "2" within a radius equal to d_k in the case when both populations are randomly distributed. The probabilities $P_{12}(k) \approx 0$ can be used as a good characteristics for associated couples. The present criterion defines the upper and the lower limit of probability P_{min} and P_{max} which can be obtained from observational data. If $P_{12}(k) < P_{min}$, a couple of associated stars is selected. The number of "foreground couples" N_{bgr} we define as ones for which $P_{12}(k) > P_{max}$. Further in this Section we obtain $P_{min} = 0.05$ and $P_{max} = 0.95$. These quantities are generally accepted in the statistics. In case when the associated stars are selected by criterion $P_{12}(k) < 0.05$ the number of associated couples is indicated with N5. A stronger criterion for selecting the associated stars is imposed if the individual probabilities of the couples $P_{12}(k) < 0.01$ and the foreground couples are selected through $P_{12}(k) > 0.99$. Then

Table 2: Correlation parameters between stellar populations in M33. Column 1 gives the name of correlation parameters; column 2 between OB stars and HII regions; column 3 between HII regions WR stars; column 4 between RSGs and WR stars; column 5 between OB stars and WR stars; column 6 between Cepheids and WR stars; column 7 between RSGs and HII regions; column 8 between RSGs and Cepheids.

Correlation parameter	OB-HII	HII-WR	RSG - WR	WR - OB	Ceph- WR	RSG-HII	RSG-Ceph
R5	0.52	0.76	0.70	0.89	0.25	0.09	0.97
R1	0.38	0.54	0.43	0.74	0.14	0.04	0.83
RN5	2.2	7.4	16.3	91	0.74	0.12	135
RN1	1.7	5.5	10	26	0.40	0.06	114
Number of couples	748	140	140	140	140	748	147

the number of associated couples is denoted with N1. A simple way to evaluate the correlation between two populations is to obtain the percentage of associated objects

$$\mathrm{R5} = \mathrm{N5/N}; \qquad \mathrm{R1} = \mathrm{N1/N}. \tag{2}$$

The ratios R1 and R5 are very suitable measures for correlation between the stellar populations. If all stars between two populations are associated, then R5 = 1 or R1 = 1. In the opposite case there are no associated stars between the populations (R5 = 0 or R1 = 0). The ratios given by Eq. 2 are analogous to the conventional coefficient of correlation in the statistics. Another way to evaluate the correlation between two stellar populations is to calculate the ratio of the number of the associated objects to the expected number from random distribution:

$$\mathrm{RN5} = \mathrm{N5/N_{bgr}}; \qquad \mathrm{RN1} = \mathrm{N1/N_{bgr}}. \tag{3}$$

3. CORRELATION BETWEEN STELLAR POPULATIONS IN M33

The data presented in Table 2 can be interpreted as an evidence of tight correlations between WR stars, OB stars and HII regions. About 70 % of the OB stars are associated with the center of HII regions (however, RSGs and cepheids do not show any correlaton with HII regions. The lack of latter corrrelations is expected. Similar is the situation with a comparison between classical stellar asoociation of Humphreys and Sandage (1980) and RSGs, and cepheids. This fact was outlined in the paper ot IFM. About 60 % of associations are without RSGs. The correlation between HII regions, OB stars and WR stars is expected since the source for ionization of the gas in a HII regions are stars earlier than B2, which evolve to RSG. Hence a part of RSGs selected by present study should have a poor correlation with HII regions. We suppose that a fraction of the OB stars which excites the HII regions and belongs to stellar associations is not detected up to now because of the large extinction in the optical part of the spectrum (UBV photometry) of regions for stellar associations, and partly to the extinction in the spectral line H_α for HII regions. There is no correlation between RSGs and HII regions and between cepheids and WR stars. However taking into account that in Vassilev el al. (2002) were selected RSGs with masses 12 - 20

$M_{\odot}$, we found a strong correlation between RSGs and long period cepheids wih log $P > 1.0$. There is a good correlation beween short period ceipheids and RSGs. This fact shows that the star complex consists of sellar populations with a wide range of stellar masses. It is well known that long period cepheids have masses in the range of RSGs, selected by Vassilev et al. (2002). The correlations between stellar populations in M33 are given in Table 2. The evaluated correlation between RSGs and WR stars is also expected. The ratios R5 $\approx$ 0.7 given by Eq. 2 for WR stars and RN5 $\approx$ 16 given by Eq. 3 are high. These results may possibly indicate the existence of a tight correlation between RSGs and cepheids). This can be expected because the progenitors of WR stars are RSGs which have masses $\mathrm{M} \geq 20\mathrm{M}_{\odot}$. On the other hand, the massive RSGs as well as WR stars must originate from nearby sites of star formation. If a star compex is a huge group of clusters, OB associations, HII regions and high luminosity stars, as accepted by Efremov (1995), we have to search the star complexes in the regions of physically associated objects with high surface density comparing to surrouding objects.

4. STAR COMPLEXES IN M33

The clustering method for the identification the stellar groups is described in the paper of Ivanov (1996). The criterion proposes that the objects will be assigned to the one and the same group if they have statistically peak of surface density above the mean level of the neighber objects. In other words the surface density is the main property that can isolate the star complex from the surrounding objects. The data of Table 2 indicate that there are a real physical association between the OB star objects, HII regions and WR stars since we indentify the star complexes in this section as regions of physicaly associated objects with a peak density of 5 times above the surounding density of these objects. When the site of the density peak was defined, we take into account the surface density of additional objects as RSGs and Cepheids in the boundaries of star complexes. The Cepheids and RSGs do not show a considerable association to stellar groups in M33. Moreover, RSGs do not correlate with the main counterpart of star complexes of OB stars and HII regions. For this reason we do not expect many RSGs and Cepheids to belong to the same star complexes. However we found a lot of Cepheids and RSGs in some star complexes while they are in deficite in other ones. We suppose that the presence of these objects in some star complexes gives evidence for the connection between the RSGs and Cepheids through the stellar evolution prosses in parent molecular cloud.

Table 3: Star complexes in M33. Column 1 gives a running number of star complex according to the increasing right ascensions; columns 2 and 3 give the right ascensions and declinations for equoinox 2000.0; columns 4, 6, 8, 10 and 12 give the number of populations within the star complex; columns 5, 7, 9, 11 and 13 give the density of stars within the star complex compared to background stars. The number of cepheids in column 12 denoted with asterisk * is based on the data of Sandage (1983).

1	2	3	4	5	6	7	8	9	10	11	12	13
No	R.A.(2000)	Dec.(2000)	OB_N	OB_F	HII_N	HII_F	WR_N	WR_F	RSG_N	RSG_F	$Ceph_N$	$Ceph_F$
1	23.4297	30.4200	94	5.6	65	6.7	4	5.6	9	4.1	14 *	6.6
2	23.4300	30.3600	129	6.1	51	6.5	4	5.6	32	7.4	9 *	13.0
3	23.4303	30.6450	469	6.8	126	5.6	23	7.4	47	4.6	70	5.5
4	23.4332	30.5850	438	6.8	116	6.6	40	6.8	50	6.5	89	4.7
5	23.4332	30.6400	492	7.1	129	6.3	22	8.5	52	4.3	73	5.7
6	23.4340	30.3995	104	7.5	70	7.2	3	9.9	12	7.0	12 *	5.2
7	23.4370	30.5700	461	8.1	126	6.6	47	7.7	67	4.3	96	4.2
8	23.4375	30.3817	128	8.7	61	8.8	4	9.4	22	6.9	18 *	9.0
9	23.4376	30.4457	97	8.5	54	9.2	6	10.5	6	4.5	4	2.6
10	23.4380	30.6470	500	9.3	138	6.9	24	9.8	51	5.0	70	5.9
11	23.4387	30.5020	206	7.0	71	6.9	19	6.1	21	3.8	70	5.1
12	23.4389	30.7450	308	6.3	85	7.8	20	11.1	40	7.5	84	6.0
13	23.4391	30.8870	140	10.4	60	6.8	0	0.0	16	6.9	11*	6.7
14	23.4402	30.7950	267	6.7	93	7.8	8	6.8	14	4.4	55	6.3
15	23.4409	30.4400	97	7.6	55	9.4	5	7.7	5	4.6	9 *	11.2
16	23.4422	30.6467	5	10.4	138	7.7	25	9.9	52	5.2	73	6.0
17	23.4422	30.6800	478	6.6	133	7.3	38	9.5	54	5.3	47	5.7
18	23.4428	30.5250	315	8.3	105	9.4	30	8.3	40	6.3	104	4.6
19	23.4429	30.5560	451	7.8	124	7.5	48	7.0	57	4.4	112	4.3
20	23.4438	30.8020	241	6.9	96	8.1	7	9.7	13	4.6	54	6.2
21	23.4447	30.6400	513	9.8	134	8.2	23	10.7	54	4.9	77	6.0
22	23.4453	30.8667	142	9.6	60	8.8	0	0.0	19	8.4	12 *	9.1
23	23.4453	30.6050	461	6.2	125	7.4	34	6.1	45	6.7	78	4.8
24	23.4455	30.7150	309	6.9	112	6.6	38	6.2	45	6.2	75	6.1
25	23.4457	30.3775	130	9.0	57	9.1	4	8.1	24	6.2	11 *	9.1
26	23.4458	30.3450	110	8.6	42	6.0	3	20.2	29	5.5	8 *	25.1
27	23.4459	30.7560	339	8.4	93	8.0	21	11.9	36	6.5	99	5.2
28	23.4459	30.6895	389	6.8	124	7.2	34	12.1	55	5.0	56	5.0
28a	23.4465	30.7395	307	7.1	88	8.3	22	9.4	39	7.6	90	6.9
29	23.4468	30.5960	438	7.5	128	6.9	37	7.9	46	6.8	82	4.5
30	23.4480	30.8767	142	12.6	63	8.1	0	0.0	18	8.1	13 *	6.8
31	23.4483	30.6415	523	10.2	133	8.6	23	11.0	58	4.9	75	6.4
32	23.4499	30.7457	322	7.8	92	8.3	21	12.4	38	7.4	92	6.6
33	23.4502	30.5540	441	7.8	127	7.3	47	7.1	53	4.3	99	4.9
34	23.4511	30.6580	522	10.6	146	8.1	36	6.4	56	6.9	70	6.0
35	23.4511	30.7750	321	10.3	95	7.3	19	6.8	32	4.7	97	5.2
36	23.4512	30.5986	443	6.9	131	6.8	38	7.0	50	5.7	76	4.9
37	23.4535	30.7780	320	9.9	98	7.1	19	5.6	34	4.4	93	5.5
38	23.4535	30.6560	515	10.4	143	8.1	36	5.8	54	7.4	77	5.9
38a	23.4539	30.7795	318	9.6	99	7.0	19	5.6	34	4.4	87	5.8
39	23.4555	30.8875	143	12.1	61	7.8	0	0.0	15	6.6	11 *	7.8
40	23.4558	30.6300	532	7.0	135	7.3	25	6.6	51	4.5	91	5.2
41a	23.4559	30.5595	453	7.2	128	6.5	48	7.9	58	4.1	103	4.6

Table 3 (continued)

1	2	3	4	5	6	7	8	9	10	11	12	13
No	R.A.(2000)	Dec.(2000)	OB_N	OB_F	HII_N	HII_F	WR_N	WR_F	RSG_N	RSG_F	$Ceph_N$	$Ceph_F$
41	23.4579	30.7615	338	9.8	97	6.8	22	10.0	41	5.3	109	5.5
42	23.4600	30.9449	59	10.3	37	8.9	2	0.0	8	8.9	8 *	10.7
43	23.4604	30.5965	423	6.1	123	6.0	36	6.3	52	4.9	71	5.4
44	23.4607	30.6802	449	6.2	130	6.3	37	6.9	59	6.3	73	4.4
45	23.4607	31.0095	25	14.4	20	9.2	0	0.0	4	5.1	21*	6..4
46	23.4613	30.7775	317	8.8	94	6.2	18	5.3	36	5.0	99	5.6
47	23.4678	30.6875	360	5.4	110	5.4	30	6.3	58	5.4	68	4.2

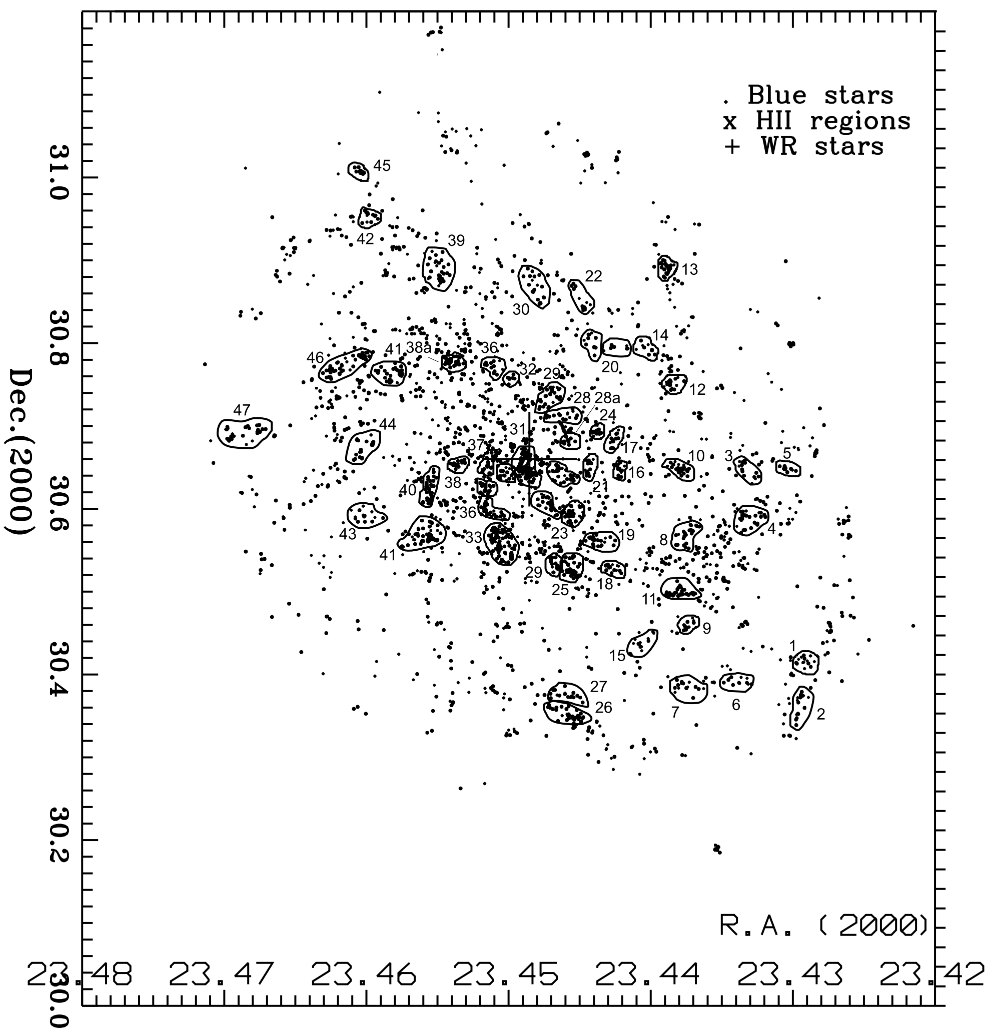

Figure 1: Star comlexes in M33.

5. DISCUSSION

The boundaries of star complexes using the peaks of surface density in OB, WR stars, and HII regions ditribution are defined in Fig 1. The coordinates of the center of complexes and surface densiy of the objects within star complex are given in Table 3. The complexes with numbers: 21, 23, 28, 29, 31, 33, 34, 36, 38, 40, 41a, 43 are located around the center of M33 (outlined by a large plus sign). They consist of lot of OB stars and bright HII objects. There is observational evidence that bright HII regions exibit a strong concentration of OB stars toward their centers. The coincidence of OB stars and HII regions in the same star compex is a good indicator for age estimation of the complex. We suppose that these star complexes indicate the extended central region of M33 with the youngest objects of the galaxy. At the same time these complexes have many WR stars. The pesence of WR stars in the central part of M33 indicate their star complexes as regions of massive star formation. On the other hand the star complexes with the numbers 4, 5, 8, 18, 25, 29, 33, 37, 41, 46, and 47 outline well the two main spiral arms. Their stellar population is different from that of star complexes in the central region of the galaxy M33. There is a good correlation between WR stars and RSGs in them. This fact is discussed by Georgiev and Ivanov (1997) who studied the ditribution of RSGs of IFM and WR stars as a function of galactocentric distance in M33. They suggested, by comparing the two distributions, that the RSGs with the masses higher than 30 $M_\odot$ would evolve to to WR stars, whereas the less massive should spend some part of their lives as RSGs. If our sample of RSGs have masses below this limit, in the range of $12-20M_\odot$, we expect to find WR stars and their progenitors RSGs at the same sites in the galaxy. The tight correlation between RSG and WR stars in Table 2 confirms their sugestion. This correlation speaks about the disposition of the two populations on the same or nearby sites in the galaxy while the stars disposed on remote regions in the galaxy have a negligible influence on our correlation parameters. The our sample of RSGs confines all regions of the galaxy. Then in the metal rich regions of star complexes, some RSGs would evolve to WR stars and may disapear. But in a less metal rich regions the progenitors may be in the stage of RSGs. So, the correlation between WR stars and RSGs occures in the region of chemical abundance as spiral arm regions. This fact explains because RSGs may exist or lack in some star complexes in Fig. 1. We can conclude from the stellar populations of star complexes in Table 3 that predictions of Maeder et al. (1980) for the influence of metalicity over the star's lifetime are confirmed by observations. The chemical composition in star complexes of M33 is better defined than in other galaxies. However, it should be taken into account the local imhomogenities in the abundance of heavy elements, which may explain the variation of the number of WR stars and RSGs from various star complexes. We combine the distributions of WR stars and RSGs in star complexes. Therefore, if some class of RSGs are protogenitors of WR stars we would have to compare the distribution of WR stars with diffferent samples of RSGs. So, the distribution of of WR stars should be compared with RSGs with different masses. Then we can obtain the sample of RSGs, which are probable progenitors of WR stars. Since, the distribution of WR stars is fixed we have a criterion to evaluate the masses of RSGs

Table 4: Regions of star complexes in M33. Column 1 gives the name of the region; column 2 the numbers of star complexes within the region; columns 3 the stellar population of the region.

Region No	Star complex No	Remark
center	21; 23; 28; 29; 31; 33; 34; 36; 38; 40; 41a; 43	OB + HII regions+WR
S1	4; 5; 8; 18; 25; 29; 33	OB +WR + RSG + Ceph
N1	16; 17;24; 27; 29; 32 36; 37 ; 41; 46; 47	OB + WR + RSG+ Ceph
North	13; 22; 30; 32; 42; 45	Without WR
South	1; 2; 6; 15; 25; 26	Without WR

in spiral arm complexes. The value of magnitude at which the distribution of the classes of the protogenitors and descendants coincide using data of Table 3, will show the mass of RSGs which evolve to WR stars. Then, taking into account data of Table 3 we conclude that RSGs in M33 with masses $15 - 20M_{\odot}$ evolve to WR stars.

Regions of star complexes may be considered as group of star complexes with violent star formation region.

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