

# Globular Clusters and the Horizontal Branch

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**Abstract.** An analysis of available Galactic globular cluster data on metallicity, ages, the distribution of stars on the horizontal branch and the distribution of the periods of RR0 Lyr variables showed that:

1. The latter two characteristics can be used for determining the Oosterhoff type.
2. The metallicities of the observed OoI and OoII clusters overlap in a narrow interval  $-1.65 < [\text{Fe}/\text{H}] < 1.52$ .
3. The OoII clusters are characterized by  $R-B < 0$ , a statistically significant relation ( $r=0.97$ ) between the relative number of B(BS) and V(VS) stars on the horizontal branch.
4. The OoI clusters divide into two groups:  $R-B < 0$  and  $R-B > 0$  with a relation between B and R ( $r=0.90$ ). The former clusters do not show a relation between VS and RS stars and the latter a relation between VS and BS stars on the horizontal branch.
5. The oldest clusters are characterized by BS close to 1 and the youngest by R close to 1.

**Key words.** globular clusters: horizontal branch structure:

## 1. Introduction

The existence of two types of globular clusters (GC) OoI and OoII was first noted by Oosterhoff (1941), the GC types being represented by different period-amplitude relations. However later Belserene (1954) showed that the RR Lyrae variables in  $\omega$  Cen, M5 and M3 are divided into two sequences and the clusters differ from each other in the relative population of the sequences. From an analysis of the OoII cluster NGC 5139 she found six variables belonging to OoI type clusters. In a detailed investigation of the OoI type cluster NGC 5272 Szeidl (1965) discovered six RRab stars belonging to OoII

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type clusters. Further studies revealed a considerable dispersion of points in the RRab period-amplitude diagrams of globular clusters. The mean period of RR0 (previous designation RRab, Clement et al., 2001) variables belonging to OoI GCs are characterized by  $0.5 < mP0 < 0.6$  and the OoII by  $mP0 > 0.6$  (Clement et al., 2001). The clusters differ in horizontal branch morphology. Clusters with  $R-B > 0$  belong to the OoI type GC (Kadla & Geraschenko, 1984). Using available observational data the mP0 classification is applied to clusters with the number of RR0 variables  $> 2$  and determined distribution of stars (B, V, R) on the horizontal branch.

## 2. Observational Data

In the present study we used data from the following two catalogues. The "Catalog of Parameters for Milky Way Globular Clusters" compiled by Harris (2003) which contains data for 150 GC, 148 of which have determined metallicities (exceptions BH 176 and 2MS-GC02). The data in the catalogue "Variable Stars in Globular Clusters" compiled by Clement et al. (2001) were summarized by the authors in tables 1 and 2.

The following characteristics of the HB were used for analysis:

mP0 - the mean period of RR0 variables;

nRR0 - the number of RR0 variables used for determining mP0;

B - the number of stars on the blue HB (BHB);

V - the number of RR Lyr variables;

R - the number of stars on the red HB (RHB);

HBR - the horizontal-branch ratio  $(B-R)/(B+V+R)$ ;

[Fe/H] - metallicity

The following were computed for individual clusters:  $(B+V+R) = S$ ,  $B/S = BS$ ,  $V/S = VS$ ,  $R/S = RS$  (the relative number of stars on the BHB, VHB and RHB).

Values of B, V and R with references to the investigators of the individual clusters are given in the papers by Lee et al. (LDZ, 1994, 83 GC, table 1), Preston et al. (PSB, 1991, 44 GC, table 4) and Brocato et al. (BBMP, 1996, 9 GC, table 2). The LDZ list includes 42 of the clusters in PSB and 8 in BBMP. The relative number of stars on the HB computed from the LDZ and PSB lists are in excellent agreement (fig.1). In the following L denotes LDZ, P - PSB and BR - BBMP.

$$BSP = -0.023 + 1.013BSL; n=42; r=0.99$$

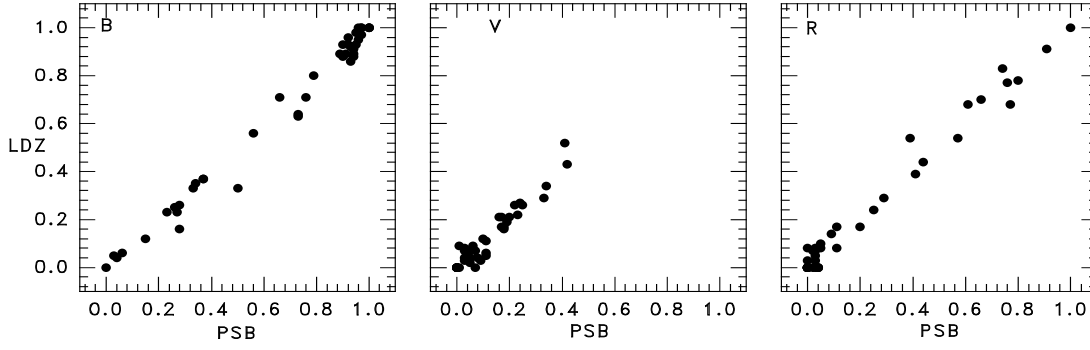
$$VSP = -0.002 + 1.048VSL; n=42; r=0.96$$

$$RSP = 0.010 + 0.999RSL; n=42; r=0.99$$

The relations determined from a similar comparison of the BBMP list have a lower correlation coefficient (r).

$$BSBR = -0.159 + 1.144BSL; n=9; r=0.94$$

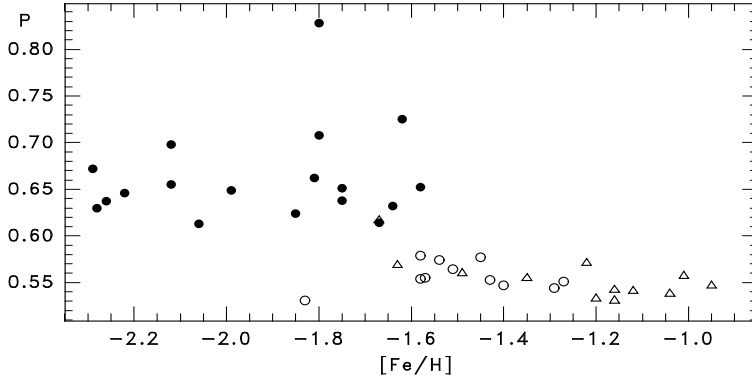
$$VSBR = 0.043 + 0.926VSL; n=9; r=0.85$$



**Fig. 1.** A comparison of the relative number of stars (BS, VS, RS) on the HB in the LDZ and PSB lists.

$$\text{RSBR} = 0.025 + 0.933\text{RSL}; n=9; r=0.82$$

There are altogether 72 clusters with determined B, V and R within the metallicity interval  $-2.29 < [\text{Fe}/\text{H}] < -0.90$ . The mP0 classification applied to GCs with  $n\text{RR0} > 2$  and  $[\text{Fe}/\text{H}] < -0.90$  indicates that the OoII GCs lie within the metallicity interval  $-2.29 < [\text{Fe}/\text{H}] < -1.58$  and the OoI  $-1.83 < [\text{Fe}/\text{H}] < -0.95$  (fig. 2). With the exception of NGC 4147 (-1.83) the two sequences overlap in the interval  $-1.65 < [\text{Fe}/\text{H}] < -1.57$  (fig.2). The maximum values for OoII clusters are -1.64, -1.62, -1.58 (mean -1.61). With the exception of NGC 4147 (-1.83) the minimum values for OoI GCs are -1.63, -1.59, -1.58 (mean -1.60). The mean period of RR0 variables and metallicity are plotted in fig. 2.



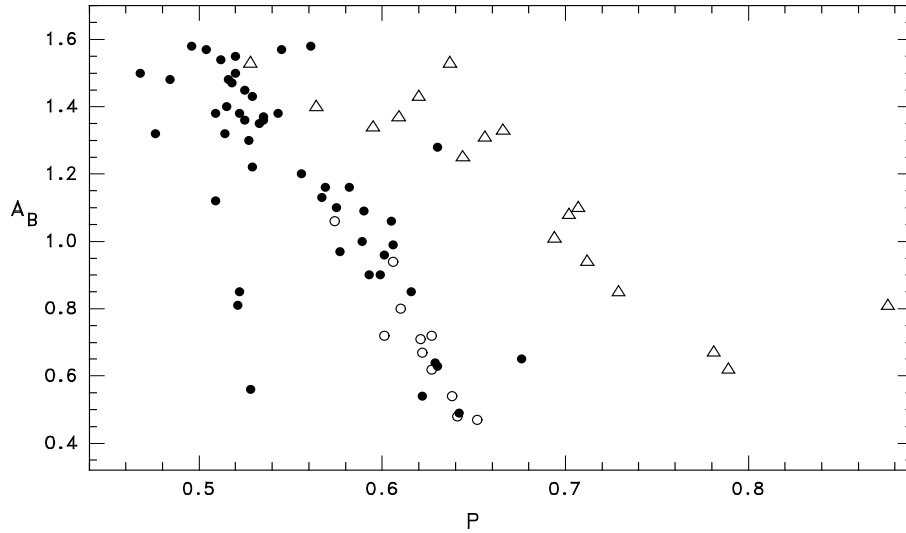
**Fig. 2.** Metallicity and the mean period of RR0 variables. ● - OoII type cluster. ○ - OoI with  $R - B < 0$ , △ - OoI with  $R - B > 0$ .

According to the catalogue Clement et al. (2001) RR0 variables have been discovered in 73 GCs (about one-half of the known GC) and for 54 (4 with  $[\text{Fe}/\text{H}] > -0.90$ ) of these have determined B and R .

### 3. OoII globular clusters

The adopted mP0 classification indicates that there are 19 OoII GC with  $n\text{RR0} > 2$  in the LDZ list, 15 in PSB and 2 in BBMP.  $R-B < 0$  for all the OoII type clusters. The cluster

Rup 106 with  $mP0 = 0.617$  is an exception. As noted by Clement et al. (2001) the P-A relation for the GC is similar to that of M3 (Kaluzny et al., 1995) and should be classified as OoI. It is also an exception as according to  $R-B > 0$  it belongs to OoI. The P-A relations for Rup 106, NGC 7089 (OoII) and NGC 3201 (OoI) with metallicities  $-1.67$ ,  $-1.62$  and  $-1.58$  respectively are plotted in fig 3. Evidently the upper value of  $mP0$  for OoI clusters should be increased to 0.613.

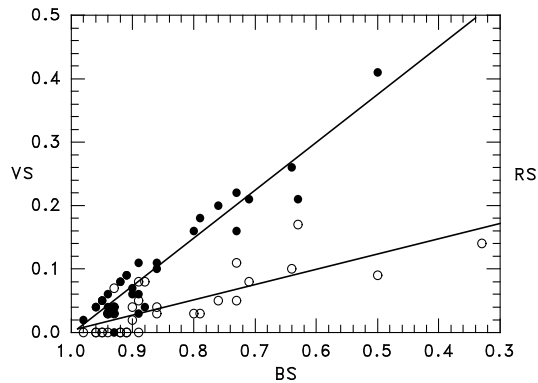


**Fig. 3.** The P-A relation for Rup 106 (○), NGC 7089 (△) and NGC 3201 (●)

Excluding Rup 106 the following relations derived for the OoII GC are shown in fig.4.

$$VS = 0.752 - 0.756BS = 0.754(1 - BS); n = 35; r = -0.97$$

$$RS = 0.245 - 0.240BS = 0.242(1 - BS); n = 35; r = -0.79$$



**Fig. 4.** The relation between RS and BS for the OoII clusters, ● - VS, ○ -RS.

Among the observed GCs the young cluster NGC 4590 has the largest value of  $VS = 0.41$  ( $RS = 0.09$ ). Note that the observed relative number of R stars in the OoII clusters does not exceed 0.17 and  $R-B < 0$  for all the OoII type clusters.

In the PSB list there are 43 GC with  $[Fe/H] < -0.90$ , and one (NGC 104) with  $[Fe/H] = -0.76$ . According to the adopted mP0 classification 23 belong to OoII and 17 to OoI. The 15 OoII GC with  $nRR0 > 2$  also show a strong correlation between VS and BS .

$$VS = 0.729 - 0.734BS = 0.731(1 - BS); n = 15; r = -0.98$$

$$RS = 0.264 - 0.259BS = 0.261(1 - BS); n = 15; r = -0.82$$

In the metallicity interval  $-1.57 < [Fe/H] < -1.51$  there are 3 OoII clusters with  $nRR0 < 3$  and two with a HB distribution which indicates that they belong to this group. If these clusters are taken into account the maximum metallicity average for the OoII GCs equals  $-1.52$ .

In the list compiled by (BBMP) there are 9 GC, 4 of which belong to OoII and 5 to OoI. However only two conform to the adopted at present criteria for OoII clusters. Values of mP0 for NGC 4372 and NGC 6218 have not been determined.

#### 4. OoI globular clusters

The OoII GCs are characterized by  $R - B < 0$ , while the OoI GCs include clusters with  $R - B < 0$  and  $R - B > 0$ . There are 21 OoI GCs with  $nRRO > 2$  and  $[Fe/H] < -0.95$  in the LDZ list, 15 in PSB and 3 in BBMP (table 1).

**Table 1.**

$R - B$	LDZ	PSB	BBMP
$R - B < 0$	10	6	3
$R - B > 0$	11	9	0

Only BS and RS of the considered clusters are correlated (fig 5).

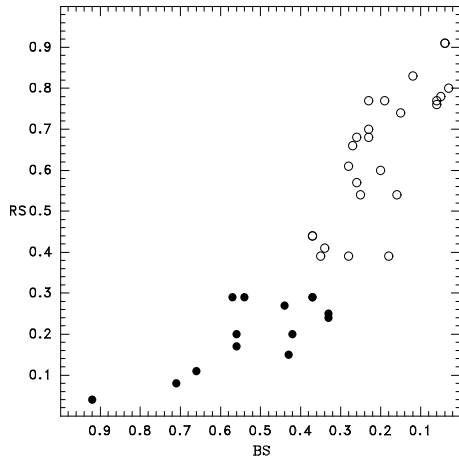
$$BSL = -0.676 - 0.745RSL; n = 21; r = -0.88$$

$$BSP = 0.693 - 0.772RSP; n = 15; r = -0.91$$

In the LDZ list there are also 14 GC with  $[Fe/H] > -0.90$ , which according to their B and R values (BS=0, RS=1) belong to OoI.

If the OoI GCs with  $R - B < 0$  and  $R - B > 0$  are considered separately a relationship between VS and RS is absent for the former and VS and BS for the latter.

Here we note that the data for NGC 6715 in the PSB list (BS-RS=0.21) differs from that given by Harris (HBR=0.83). If the latter is correct BS=0.90, VS=0.09, RS=0.01. (PSB data respectively 0.42, 0.37, 0.21). NGC 6715 is not in the LDZ list. There are several GC which fall out of the general scheme. Before reaching a final conclusion the data for such clusters should be checked.



**Fig. 5.** The relation between RS and BS for the OoI GC. ● - clusters with  $R - B < 0$ , ○ - clusters with  $R - B > 0$ .

## 5. Cluster Ages

The ages (BMA) of 65 GCs based on the relative ages determined by Buonanno et al. (1998) are given in the paper by Borkova & Marsakov (2000, BMA) who analysed the age lists published before 1999. Details on the method and lists used are given in their paper.

The latest homogeneous ages (SWA) for 55 GC were determined by Salaris & Weiss (2002, SWA). There are altogether 48 GC with determined ages both in SWA (column 4 table 4) and BMA. The distribution of stars on the HB has not been determined for four of these clusters (NGC 6652, IC 4499, Arp 2 and Terz 7). There is poor agreement between the two sets of age determinations:

$$\text{SWA} = 1.024 + 0.714\text{BMA}; r = 0,69; n = 48$$

The differences between the two sets of age estimates  $E(\text{Gyr}) = \text{BMA} - \text{SWA}$  are shown in fig. 6

The metallicity interval  $-1.85$  to  $-1.40$  stands out in that there are 20 clusters with  $E < 3$ . There is a much closer agreement if clusters with  $3 < E < 4.95$  and  $E > 3$  are considered separately

$$\text{SWA} = -6.253 + 1.176\text{BMA}; r = 0.94; 28; E > 3.$$

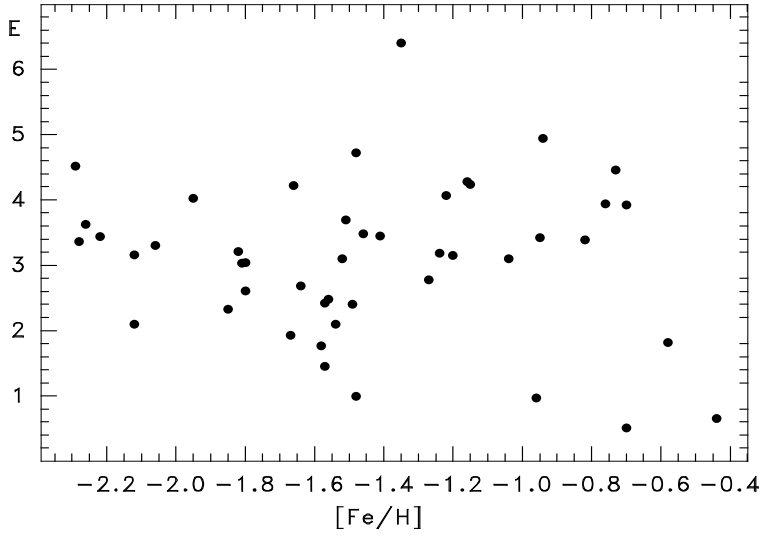
$$\text{SWA} = 1.949 + 0.720\text{BMA}; r = 0.93; 20; E < 3.$$

The number of clusters in each SWA age group are given in table 2 and fig. 7.

The numbers in brackets denote the number of clusters with  $[\text{Fe}/\text{H}] > -0.90$ . It follows that the youngest clusters belong to OoI with  $R - B > 0$  and the oldest to OoII. The young OoII clusters are the same age as the old OoI GC. The relation between BS and SWA for OoII clusters shows that BS increases with age.

$$\text{SWA} = 10.556 + 2.177\text{BS}; n = 19; r = 0.89$$

The data for BMA are given in table 3 and fig. 8.

**Fig. 6.**  $E(\text{Gyr}) = \text{BMA-SWA}$ **Table 2.**

SWA	OoI	OoI	OoII	Sum	OoI	OoI	OoII
	$R - B > 0$	$R - B < 0$			$R - B > 0$	$R - B < 0$	
6.4-10.6	12 +(6)	0	0	18	0.33	0.00	0.00
10.7-11.9	5	3	7	15	0.09	0.05	0.13
11.9-12.9	1	2	19	22	0.02	0.04	0.35
	18 +(6)	5	26	55	0.44	0.09	0.48

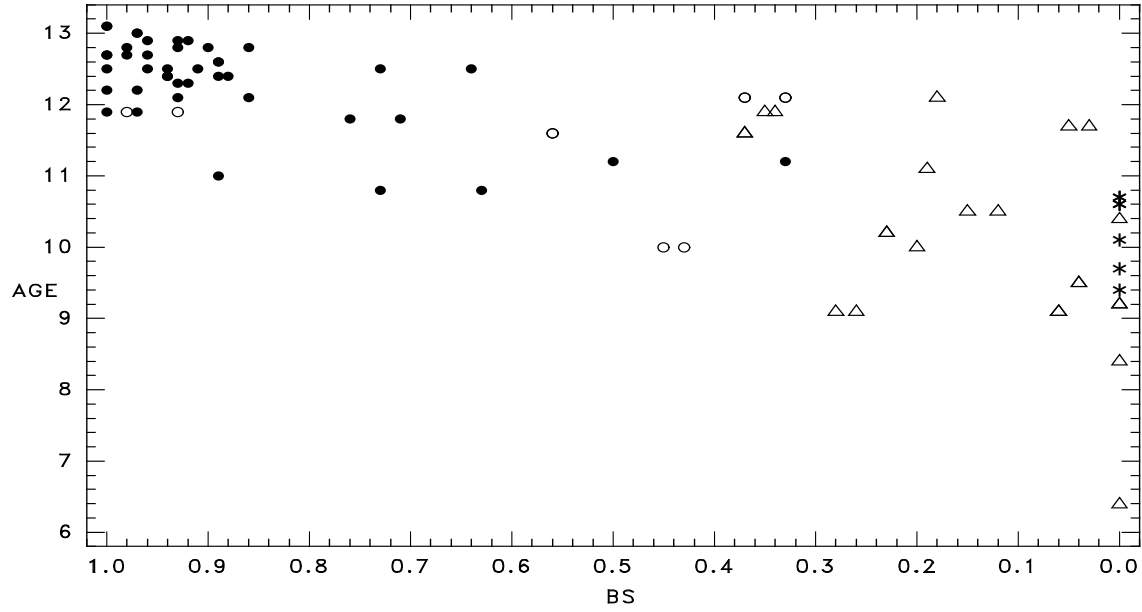
**Table 3.**

BMA	OoI	OoI	OoII	Sum	OoI	OoI	OoII
	$R - B > 0$	$R - B < 0$			$R - B > 0$	$R - B < 0$	
9.0-14.0	12+(6)	0	0	18	0.33	0.00	0.00
14.0-15.0	5	3	7	15	0.09	0.05	0.13
15.0-16.6	1	2	19	22	0.02	0.04	0.35
	19+(11)	9	25	64	0.47	0.14	0.39

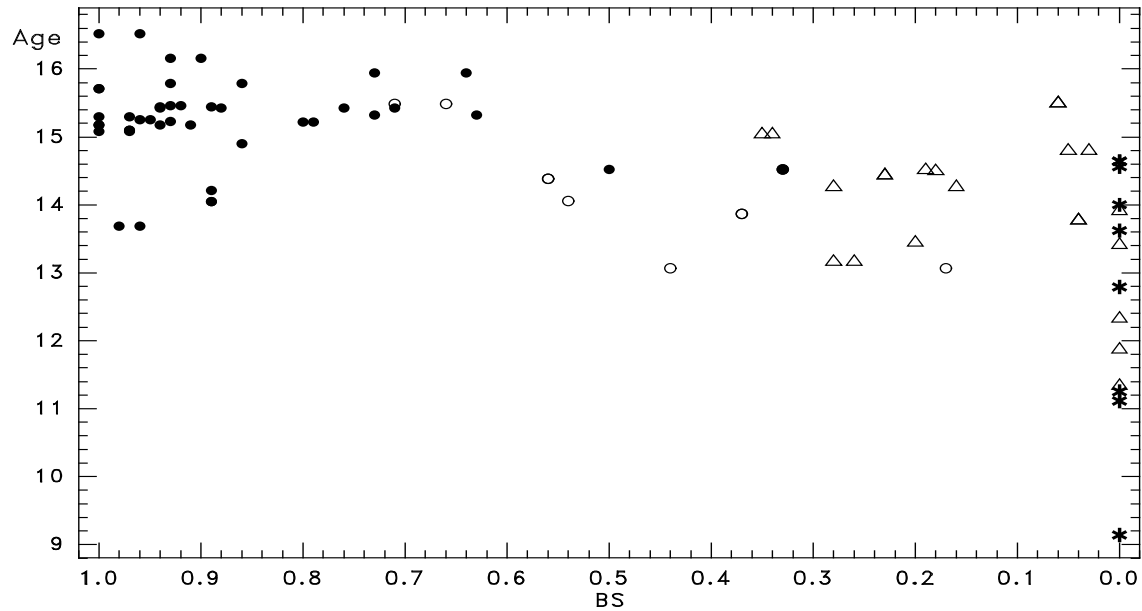
The cluster NGC 6626, age 19.1 (BMA), has not been included. According to  $mP0 = 0.577$ ,  $nRR0 = 8$ , it belongs to OoI. However with  $BS = 0.92$  and  $VS = 0.04$  it can be classified as OoII. The data used for analysis are given in table 4.

## 6. Conclusions

The  $mP0$  classification and the distribution of stars on the HB are indications of the Oo type. The Oosterhoff type clusters OoI are characterized by the mean period of RR0 variables  $0.5 < mP0 < 0.613$  and the type OoII by  $mP0 > 0.6$ . The  $mP0$  classification indicates that the OoII clusters lie within the metallicity interval  $-2.29 < [Fe/H] < -1.58$



**Fig. 7.** The relation between  $BS$  and SWA.  $\bullet$  - OoII type cluster.  $\circ$  - OoI with  $R - B < 0$ ,  $\triangle$  - OoI with  $R - B > 0$ ,  $*$  - clusters with  $[Fe/H] > -0.9$ .



**Fig. 8.** The relation between  $BS$  and BMA.  $\bullet$  - OoII type cluster.  $\circ$  - OoI with  $R - B < 0$ ,  $\triangle$  - OoI with  $R - B > 0$ ,  $*$  - clusters with  $[Fe/H] > -0.9$ .

and the OoI  $-1.83 < [Fe/H] < -0.95$ . With the exception of NGC 4147 ( $-1.83$ ) the two sequences overlap in the interval  $-1.65 < [Fe/H] < -1.57$  (table 1 and fig.2). The OoII GCs are characterized by  $R - B < 0$ , while the OoI GCs include clusters with  $R - B < 0$  and  $R - B > 0$ .

The BS and VS relation for the OoII clusters reveals a strong correlation between the two characteristics.



The oldest clusters belong to OoII with BS close to 1 and the youngest to OoI  $R-B > 0$  with RS=1. The characteristic R/B decreases with age.

The 14 clusters with  $[Fe/H] > -0.90$  and determined distribution of stars on the HB belong to OoI.

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Table 4.

Cl	FeH	SWAA	BMA	<i>B</i> SL	<i>V</i> SL	<i>R</i> SL	SumL	<i>B</i> SP	<i>V</i> SP	<i>R</i> SP	SumP	mP0	RR0
104	-0.76	10.7	14.64	0.00	0.00	1.00	77	0.00	0.00	1.00	336	0.737	1
288	-1.24	11.9	15.08	0.97	0.01	0.02	102	1.00	0.00	0.00	95	0.678	1
362	-1.16	9.5	13.78	0.04	0.05	0.91	78	0.04	0.04	0.91	92	0.542	7
Erid	-1.46	8.4	11.88	0.00	0.00	1.00	12						
1851	-1.22	9.1	13.17	0.28	0.11	0.61	103	0.26	0.06	0.68	96	0.571	21
1904	-1.57	12.6	14.05	0.89	0.11	0.00	35	0.89	0.11	0.00	35	0.685	2
2298	-1.85	12.9	15.23	0.93	0.07	0.00	15					0.649	1
2419	-2.12	12.8	14.90	0.86	0.11	0.03	107					0.655	24
2808	-1.15	10.2	14.44	0.23	0.01	0.77	265	0.23	0.09	0.68	56	0.539	1
Pal 3	-1.66	9.2	13.42	0.00	0.18	0.82	17						
3201	-1.58	12.1	13.87	0.37	0.34	0.29	176	0.37	0.34	0.29	176	0.554	72
Pal 4	-1.48	9.2	13.92	0.00	0.00	1.00	20						
4147	-1.83		15.49	0.66	0.23	0.11	62	0.71	0.22	0.08	51	0.531	4
4372	-2.09			1.00	0.00	0.00	76						
Rup 106	-1.67	10.4	12.33	0.00	0.18	0.82	50					0.617	13
4590	-2.06	11.2	14.52	0.50	0.41	0.09	44	0.33	0.52	0.14	21	0.613	13
4833	-1.80			0.95	0.05	0.00	175	0.93	0.04	0.03	180	0.708	7
5024	-1.99		15.22	0.79	0.18	0.03	176	0.80	0.16	0.03	188	0.649	29
5053	-2.29	10.8	15.32	0.73	0.16	0.11	44	0.63	0.21	0.17	48	0.672	5
5272	-1.57	12.1	14.52	0.33	0.42	0.25	226	0.33	0.43	0.24	240	0.555	145
5286	-1.67			0.91	0.09	0.00	35	0.89	0.03	0.08	36	0.614	8
5466	-2.22	12.5	15.94	0.73	0.22	0.05	77	0.64	0.26	0.10	80	0.646	13
5694	-1.86			1.00	0.00	0.00	30						
5824	-1.85			0.86	0.10	0.04	50					0.624	7
Pal 5	-1.43	10.0	13.45	0.20	0.20	0.60	20						
5897	-1.80	12.4	15.44	0.94	0.04	0.03	108	0.89	0.06	0.05	96	0.828	3
5904	-1.27	11.6	14.38	0.56	0.24	0.20	164	0.56	0.27	0.17	163	0.551	91
5927	-0.37		9.14	0.00	0.00	1.00	60						
5986	-1.58			0.95	0.05	0.00	56	0.98	0.02	0.00	50	0.652	7
Pal 14	-1.52			0.00	0.00	1.00	16						
6093	-1.75	12.9		0.92	0.08	0.00	37	0.96	0.04	0.00	45	0.651	4
6101	-1.82	11.0	14.21	0.89	0.06	0.05	83						
6121	-1.20	11.9	15.05	0.34	0.25	0.41	153	0.35	0.26	0.39	141	0.533	31
6144	-1.75			1.00	0.00	0.00	22						
6171	-1.04	11.7	14.80	0.03	0.17	0.80	89	0.05	0.17	0.78	99	0.538	15
6205	-1.54	13.0	15.10	0.97	0.03	0.00	113	0.97	0.03	0.00	106	0.750	1
6218	-1.48	12.7	13.69	0.96	0.00	0.04	73						
6229	-1.43		14.06	0.54	0.17	0.29	83					0.553	30
6235	-1.40			0.90	0.10	0.00	30	0.88	0.12	0.00	26	0.6	2
6254	-1.52	12.2	15.30	0.97	0.00	0.03	65	1.00	0.00	0.00	61		
Pal 15	-1.90			1.00	0.00	0.00	40						
6266	-1.29			0.57	0.14	0.29	110					0.544	62
6293	-1.92			0.90	0.10	0.00	41					0.6	2

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6341	-2.28	12.8	16.16	0.90	0.07	0.02	134	0.93	0.00	0.07	129	0.630	11
6342	-0.65			0.00	0.00	1.00	30						
6352	-0.70	9.7	13.62	0.00	0.00	1.00	30						
6362	-0.95	11.1	14.52	0.19	0.04	0.77	90					0.547	18
6366	-0.82	9.4	12.79	0.00	0.02	0.98	52					0.513	1
6397	-1.95	12.5	16.52	0.96	0.00	0.04	79	1.00	0.00	0.00	139		
6402	-1.39			0.65	0.35	0.00	97					0.564	39
6496	-0.64			0.00	0.00	1.00	35						
6535	-1.80	13.1	15.71	1.00	0.00	0.00	16	1.00	0.00	0.00	15		
6539	-0.66			0.00	0.00	1.00	30						
6541	-1.83			1.00	0.00	0.00	15	1.00	0.00	0.00	75		
6544	-1.56			1.00	0.00	0.00	38					0.570	1
6553	-0.21		14.00	0.00	0.00	1.00	47					0.526	2
6584	-1.49	12.1	14.50	0.18	0.42	0.39	38					0.560	34
6624	-0.44	10.6	11.25	0.00	0.00	1.00	22						
6626	-1.45		19.10	0.92	0.04	0.04	49	0.93	0.07	0.00	43	0.577	8
6637	-0.70	10.6	11.11	0.00	0.00	1.00	60						
6638	-0.99			0.26	0.17	0.57	23	0.25	0.21	0.54	24	0.666	1
6656	-1.64	12.5	15.18	0.94	0.06	0.00	117	0.91	0.09	0.00	99	0.632	10
Pal 8	-0.48			0.00	0.00	1.00	15						
6681	-1.51	11.9						0.93	0.07	0.00	15	0.564	1
6712	-1.01	10.5		0.15	0.11	0.74	94	0.12	0.05	0.83	118	0.557	7
6715	-1.58							0.42	0.37	0.20	59	0.579	55
6723	-1.12	11.6		0.37	0.19	0.44	106	0.37	0.19	0.44	106	0.541	23
6752	-1.56	12.7	15.18	1.00	0.00	0.00	211	1.00	0.00	0.00	196		
6760	-0.52			0.00	0.00	1.00	30						
6779	-1.94	12.8		0.98	0.02	0.00	62					0.906	1
6809	-1.81	12.4	15.43	0.94	0.03	0.03	102	0.88	0.04	0.08	215	0.662	4
6838	-0.73	10.1	14.56	0.00	0.00	1.00	32						
6864	-1.16			0.27	0.07	0.66	137	0.23	0.07	0.70	129	0.531	3
6934	-1.54	10.0		0.43	0.42	0.15	72					0.574	68
6981	-1.40		13.07	0.44	0.29	0.27	48					0.547	24
7006	-1.63		14.27	0.28	0.33	0.39	164	0.16	0.29	0.54	85	0.569	53
7078	-2.26	11.8	15.43	0.76	0.20	0.05	152	0.71	0.21	0.08	188	0.637	39
7089	-1.62		15.25	0.96	0.04	0.00	83	0.95	0.05	0.00	94	0.725	17
7099	-2.12	12.3	15.46	0.93	0.03	0.04	67	0.92	0.08	0.00	64	0.698	3
Pal 12	-0.94	6.4	11.34	0.00	0.00	1.00	7						
7492	-1.51	12.1	15.79	0.93	0.03	0.03	29	0.86	0.07	0.07	28	0.805	1

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