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PHOTOMETRIC AND SPECTROSCOPIC STUDY OF SHAKHBAZIAN COMPACT GALAXY GROUPS SHCG 104, SHCG 120, SHCG 223, AND SHCG 245

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RESUMEN

Los grupos compactos de galaxias Shakhbazian son las configuraciones más densas que se conocen. Hace algunos años iniciamos un estudio fotométrico y espectroscópico de estos grupos. En este artículo presentamos los resultados de la investigación en los grupos ShCG 104, ShCG 120, ShCG 243 y ShCG 245. Presentamos los corrimientos al rojo de las galaxias miembro, los resultados de la fotometría R, las curvas de brillo superficial-radio efectivo, las masas estimadas, las luminosidades y las razones masa-luminosidad de los grupos, además de algunos parámetros dinámicos como la dispersión de velocidad radial y el tiempo de cruce. Los ShCGs estudiados consisten principalmente de galaxias elípticas y lenticulares. Se muestra que algunas galaxias en estos grupos están en proceso de interacción.

ABSTRACT

We present the results of the detailed photometric and spectroscopic study of Shakhbazian compact galaxy groups ShCG 104, ShCG 120, ShCG 223 and ShCG 245. The redshifts of member galaxies, the results of photometry in R band, the surface-brightness profiles, the curves of isophotal twisting and Fourier parameter a_4 are presented. We determined the mass, the luminosity, the mass-to-luminosity ratio, the radial velocity dispersion and the crossing time of groups. Also the morphological types of member galaxies are determined. It is shown that some galaxies in groups are in the process of interaction.

Key Words: **GALAXIES: CLUSTERS: INDIVIDUAL (SHCG 104, SHCG 120, SHCG 223, SHCG 245) — GALAXIES: INTERACTIONS — GALAXIES: PHOTOMETRY**

1. INTRODUCTION

A few years ago we commenced detailed photometric and spectroscopic studies of Shakhbazian compact galaxy groups (ShCGs). The groups have a prolate spheroid, “cigar”-like space configuration (Oleak et al. 1995). Compact groups are good laboratories for studying the processes of interaction and merging which are very likely in their very dense environment. Due to the small number of members of CGs in comparison to galaxy clusters, the analysis of different stages of interaction and merging is much easier here. ShCGs were selected by visual inspection of the POSS prints as dense groups of compact and mainly red galaxies, the images of many of which often were hard to distinguish from those of stars. Thus, some of the supposed members of groups could likely be stars. Follow-up spectral observations of about 40 ShCGs presented in Tiersch et al. (1996, 1999, 2002 Paper 1), Tovmassian et al. (2003a Paper 2, 2003b Paper 3, 2004 Paper 4, 2005a Paper 5, 2005b Paper 6, 2006 Paper 7) showed, however, that only a few of the assumed members of ShCGs are stars. Moreover, some objects in the area of groups which were assumed to be stars, turned out to be galaxies. Hence, the great majority of the assumed members of groups are indeed galaxies. Our photometric observations made with high angular resolution showed that the majority of the group members

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TABLE 1

GROUP COORDINATES AND GALACTIC EXTINCTION

ShCG	α $h\ m\ s$ (2000)	δ $\circ\ '\ ''$ (2000)	Q_R [mag]
104	09 27 14.9	+52 58 49	0.035
120	11 04 27.7	+35 52 45	0.000
223	14 49 48.6	+29 10 34	0.098
245	12 22 49.5	+31 56 46	0.008

TABLE 2

RADIAL VELOCITIES OF INDIVIDUAL GALAXIES

g	ShCG 104 v km s^{-1}	ShCG 120 v km s^{-1}	ShCG 223 v km s^{-1}	ShCG 245 v km s^{-1}
1	53070	21420	25190	18450
2	62040	20130	24650	18410
3	62340 e	21450	25040	18260
4	-	21060	23720	-
5	49980	21120	24680	-
6	50130	20700	25520	-
7	-	-	25520	19220
8		21000	-	19520
9			-	-
10			25190	-
11			24890	-
13			24890	-

are ordinary E/S0 galaxies, seen as very compact on the POSS images.

In this paper we present the results of the spectroscopic and photometric study of four more groups: ShCG 104, ShCG 120, ShCG 223, and ShCG 245.

2. OBSERVATIONS AND RESULTS

The coordinates of the centers of studied groups and the galactic extinction Q_B (Schlegel, Finkbeiner, & Davis 1998) are given in Table 1.

The details of the spectroscopic and photometric observations of ShCGs are presented in Papers 1-7. Spectroscopic observations of five galaxies in ShCG 104 were made with the 6-m telescope of the Special Astrophysical Observatory, RAS, Russia, on February 28, 2004. The Long Slit Spectrograph was used in the observations. The spectrograph has a resolution 11-12 Å. The wavelength range is 4800 - 8600 Å. The exposure time was 1200 s. Galaxies 2, 3 and 5 were observed also with the 2.1-m telescope of the Guillermo Haro Observatory in Cananea, México, operated by National Institute of Astrophysics, Optics and Electronics, in February 2004. The Faint Object Spectrograph and Camera (Zickgraf et al. 1997) with dispersion 8.5 Å/pixel in the spectral range 4000-9000 Å was used. The exposure time was 3600 s. The same telescope and equipment were used in observations of ShCG 120 (October 1996), ShCG 223 (October 1998) and ShCG 245 (March 1996). Redshifts of ten galaxies of the group ShCG 223 and of three galaxies in ShCG 245 were measured also by Kodaira et al. (1990). The redshifts determined by us and by Kodaira et al. (1990) agree with each other within the errors of measurement. The accuracy of the radial velocity (RV) measurements is $\sim 40 - 60$ km s^{-1}. For some faint objects the accuracy may reach 200 km s^{-1}. The measured RVs were corrected for solar motion. The RVs of the observed galaxies are presented in Table 2.

Photometric observations were made in the R band with the 1.5-m telescope of the National Astronomical Observatory in San Pedro Mártir, México, in March 1998 at seeing better than $2''$. The TEK CCD detector with a 1024×1024 array of 24×24 μm pixels has been used in observations. The obtained images were corrected to flat fields using the twilight images of blank sky areas (Christian et al. 1985).

The images of the studied groups are presented in the left panels of Figures 1-4. The isophotes of the observed galaxies are presented in the right-hand panels. The latter are chosen arbitrarily for revealing possible signs of interaction between galaxies. The galaxy identification numbers are from Stoll, Tiersch, & Braun (1996a, 1996b), Stoll, Tiersch, & Cordis, 1996c). Magnitudes were calibrated in the Kron-Cousins photometric system. The star cluster NGC 4147 served as a standard. The reduction of the photometric data was done with the MIDAS program. The magnitudes of galaxies in R were estimated within the contour of the surface brightness $\mu = 26\overset{m}{.}5/\mathrm{arcsec}^2$, though in some cases a limit generally lower than this was reached. The overlapping halos of images of galaxies were separated by extrapolation of the fitted ellipses in the non-overlapped parts down to the mentioned limiting surface brightness. The diameters, D, and the axial ratios, b/a, were determined by the same contour. For a galaxy embedded in a common halo the diameter was estimated by extrapolation of the surface brightness

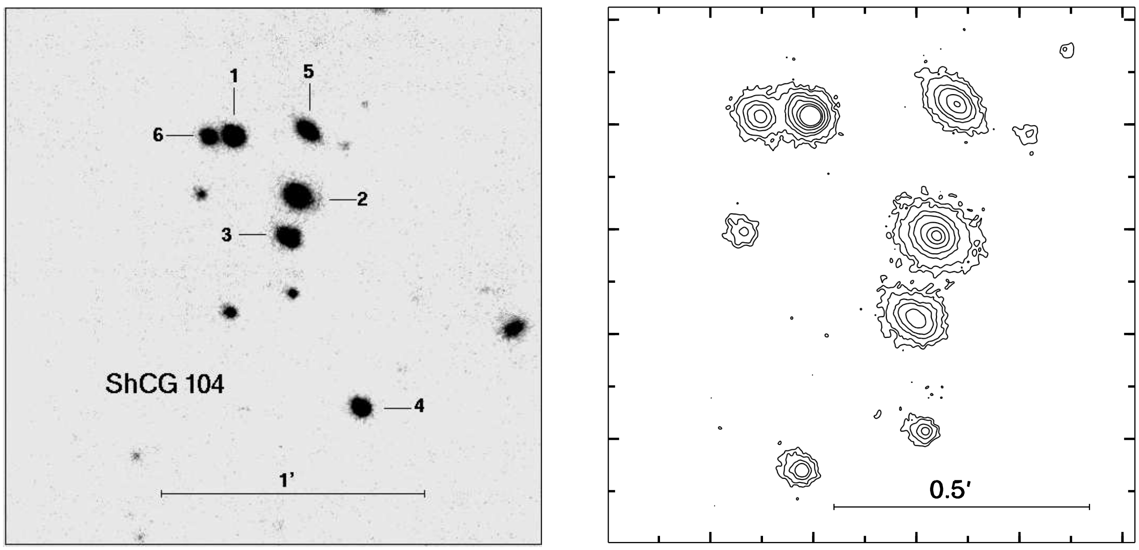

Fig. 1. The image of ShCG 104 in R (left) and the isophotal contour plots of galaxies (right). North is up, east to the left.

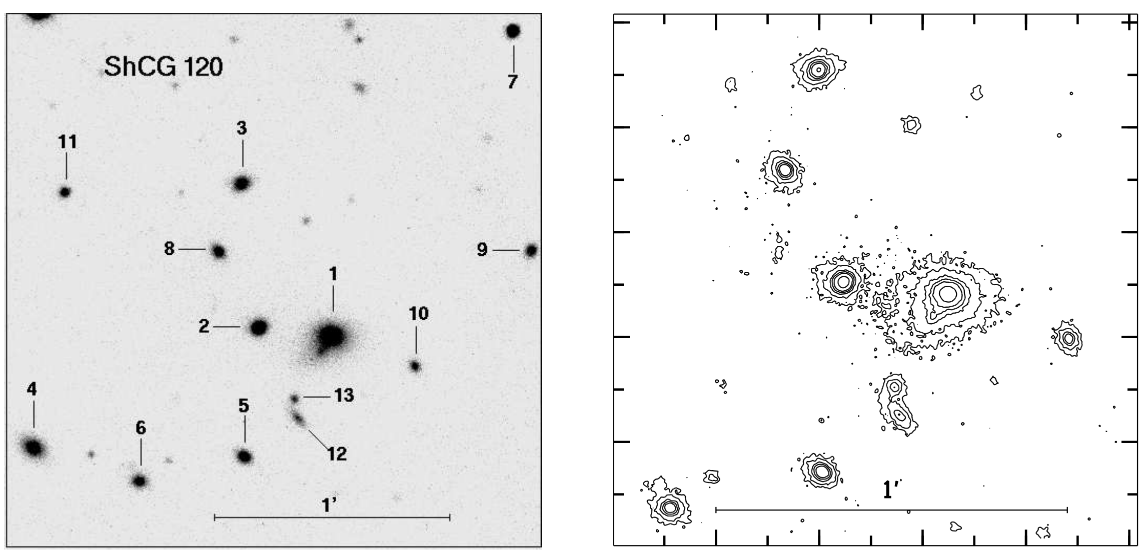

Fig. 2. The image of ShCG 120 in R (left) and the isophotal contour plots of galaxies (right). North is up, east to the left.

profile down to the same limit. The measured integrated isophotal magnitudes were corrected for the extinction Q_R within our Galaxy (column 4 of Table 1). The observed groups are relatively nearby, therefore the K correction was neglected. The estimated accuracy of magnitudes of isolated images is about $0.^{m}06$. The error may be higher in the case of overlapping halos.

We draw the graphs of the surface brightness, μ in R, versus semi-major axis, a (Figures 5-8) generally up to $\mu = 26.^{m}5/\mathrm{arcsec}^2$. If a faint galaxy is embedded in the halo of a brighter one, then we get a reliable surface brightness only down to the value determined by the halo of the neighbouring galaxy.

Interacting galaxies may have distorted forms, bridges and tails, as it has been demonstrated by numerical simulations (e.g. Barnes 1985, 1989, 1990; Hernquist, Katz, & Weinberg 1995; Mihos 1995). However, not always such signs are obvious. Note that ShCGs contain a high fraction of early type

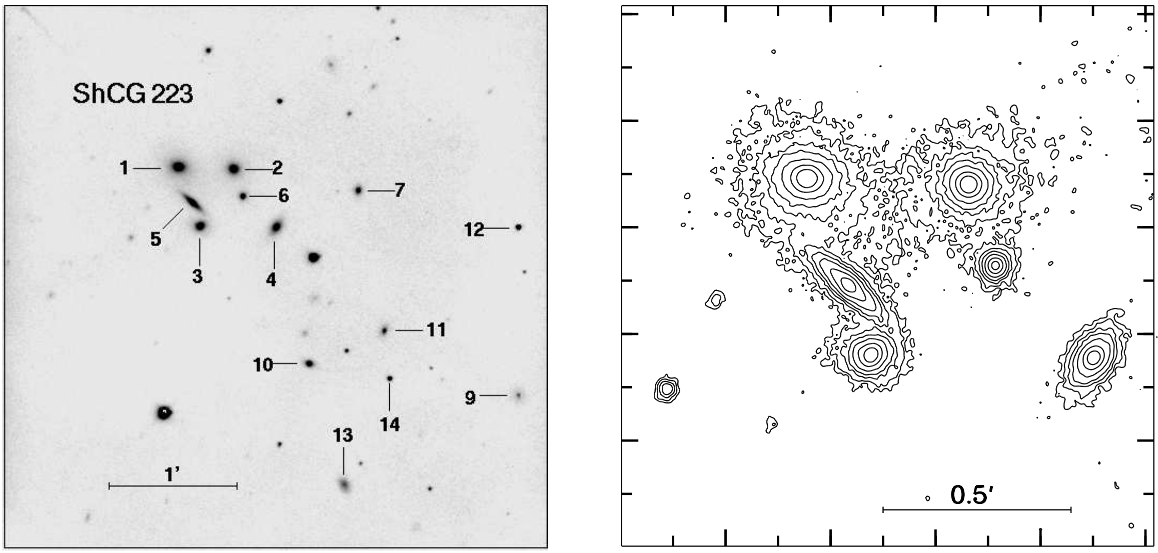

Fig. 3. The image of ShCG 120 in R (left) and the isophotal contour plots of galaxies (right). North is up, east to the left.

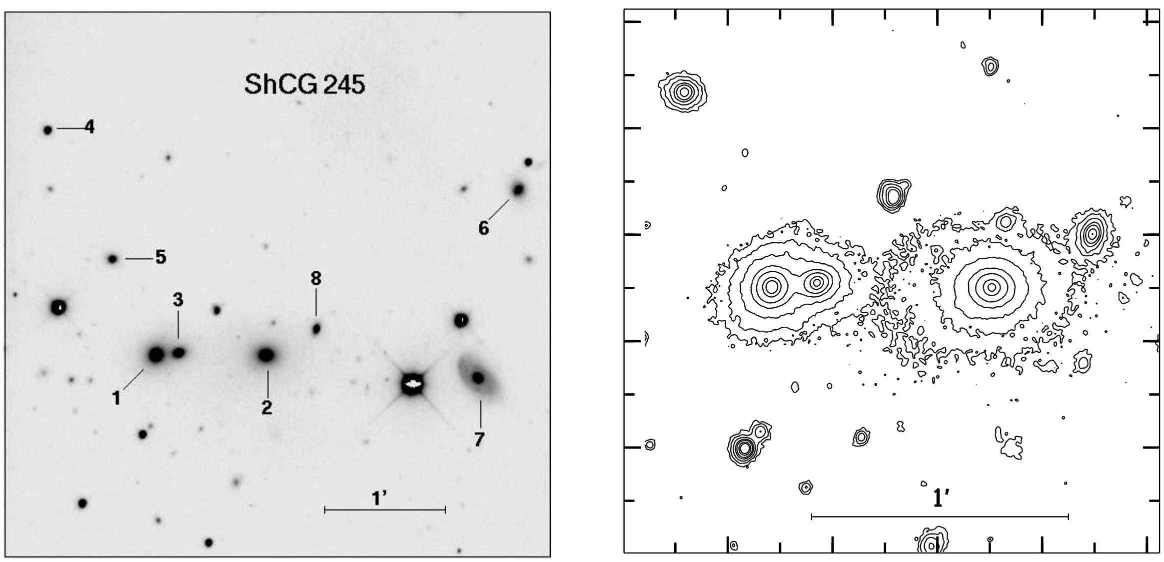

Fig. 4. The image of ShCG 245 in R (left) and the isophotal contour plots of galaxies (right). North is up, east to the left.

(E/S0) galaxies, which could be formed in groups as the result of interaction and merging of spiral galaxies (Toomre & Toomre 1972, Tovmassian, Plionis & Andernach 2004). Such gas poor galaxies are not expected to produce prominent tidal features during interaction. Interaction between galaxies may result also in dynamically heated enlarged envelopes (Barnes 1989; Schindler & Müller 1993). To identify traces of galaxy interaction when they are not otherwise obvious we inspected contour plots to check for the presence of enlarged external isophotes. This is the same method we have successfully used in our previous papers. Several galaxies with enlarged halos have been detected in ShCGs (e.g. ShCG 154, Paper 1, ShCG 361, ShCG 362, Paper 4). In comparison to isophotes of galaxies of about the same brightness,

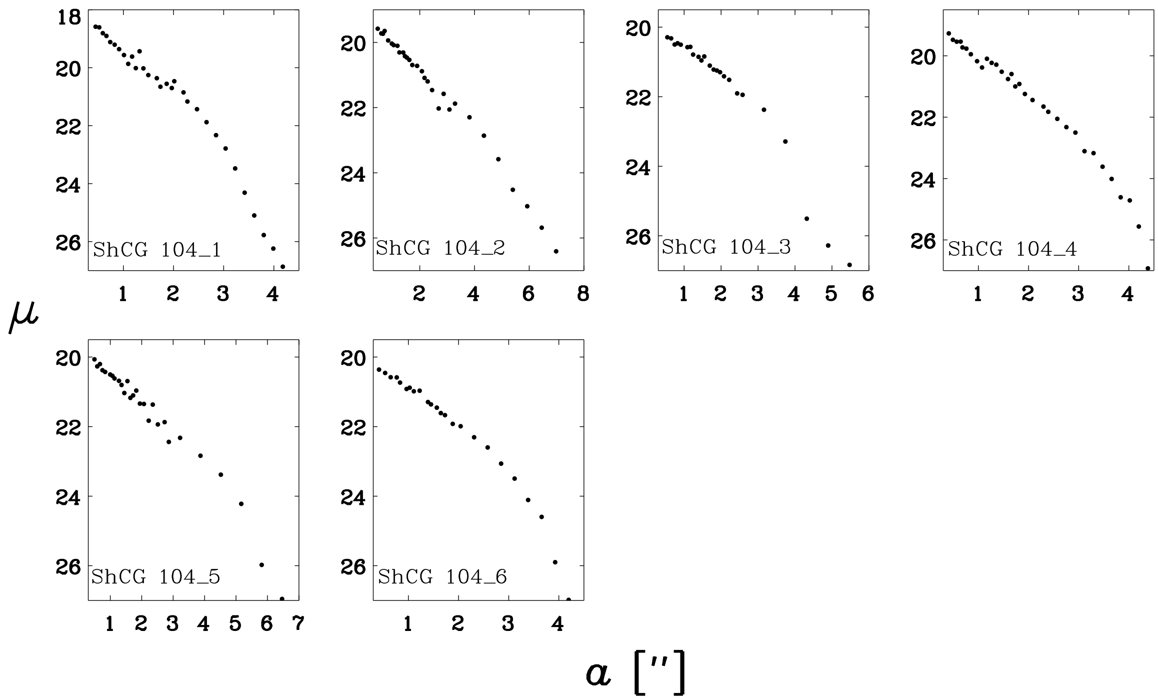

Fig. 5. The surface brightness profiles, μ, vs. effective radius, $r_{eff}^{1/4}$, in R for galaxies in ShCG 104.

the outer isophotes of the mentioned galaxies are appreciably far from each other, and their overall sizes are larger.

In absence of obvious signs of interaction the processes of possible interaction could be revealed by the study of the curves of isophotal twisting and of the Fourier parameter a_4. Kormendy (1982) and di Tullio (1979) considered the twisting of the isophotes as a sign of mutual tidal perturbations or galaxy collisions. Bender & Möllenhoff (1987) mentioned that the boxiness most likely originates from merging or tidal disruptions of companion galaxies. If a_4 is negative, the isophotes of the galaxy are called "box-like", and if a_4 is positive, the isophotes are "disk-like" (Bender 1988). Though, according to Lima Neto & Combes (1995), Bettoni & Fasano (1993, 1995), and Fasano & Bettoni (1994), they are not strictly correlated with interaction and merging processes. Moreover, Naab & Burkert (2003) showed that the merger outcome might have disk-like isophotes. We constructed the curves of the isophotal twisting and the curves of the Fourier parameter a_4 of galaxies in the studied four ShCGs. These curves are presented in Figures 9-12. The position angle (PA) is estimated by the MIDAS subroutine FIT/ELL3 by fitting ellipses to the isophotes. PA is very sensitive against disturbances, and for this reason in most cases we measure it mainly in the inner parts of galaxies within $\approx 2''$, which is comparable to the seeing during observations[6]. However, since galaxies, including their central regions, have an ellipsoidal structure, the scatter caused by the atmosphere will somewhat enlarge, or make a little smoother, the image, but the structure of the ellipsoid will remain unchanged. Hence, the measured PA is reliable.

We determined the morphological types of galaxies first by inspection of large scale direct images. Then we inspected the surface brightness profiles (Figures 5-8).

The results of the photometry of member galaxies in ShCG 104, ShCG 120, ShCG 223, ShCG 245 are presented in Table 3 in which the following information is given. Column 1: the galaxy identification number; Column 2: the magnitude in $R_{26.5}$; Column 3: the colour $R - K_{\rm total}$ for galaxies observed by 2MASS (Jarrett et al. 2000), and http://www.ipac.caltech.edu/2mass); Column 4: the axial ratio b/a; Column 5: the diameter of the galaxy; Column 6: the morphological type.

[6]The angular resolution of the used TEK-CCD is $0.328''$/pxl.

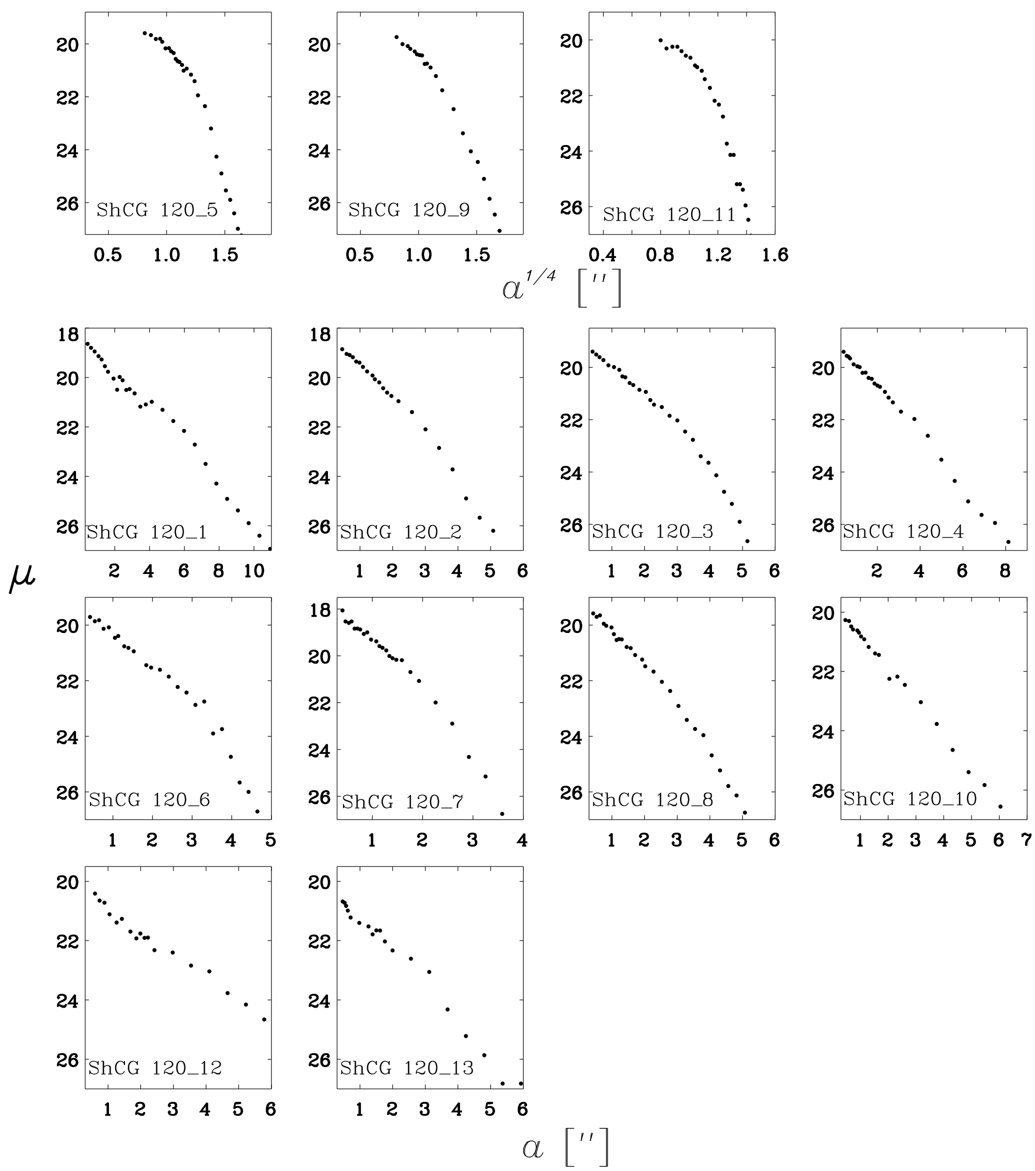

Fig. 6. Same as Figure 5 for galaxies in ShCG 120.

3. DISCUSSION

A galaxy is assumed to be a member of a CG, if its RV differs from that of the RV of the group by no more than ≈ 1000 km s^{-1}. Twenty five out of 27 galaxies with determined redshifts in the studied four groups have concordant RVs. Only two objects (Nos. 2 and 3 in ShCG 104) are background galaxies. Integrated isophotal magnitudes in the R band were determined for 35 member galaxies and also for two background galaxies.

The distances to the groups and the photometry of their member galaxies were used to deduce their physical parameters, according to the formulae adopted in Paper 1. These parameters are presented in Table 4 as follows. Line 1: the mean redshift z (weighted by masses of member galaxies); Line 2: the length a of the group ($H_0 = 74$ km s^{-1} Mpc^{-1}) determined by the two group members with largest mutual separation; Line 3: the radial velocity dispersion, RVD (weighted by the masses of the galaxies); Line 4: the virial radius, R_{vir}, of the group (weighted by the masses of galaxies); Line 5: the virial mass, $\mathcal{M}_{vir}$; Line 6: the luminosity L of the group in solar units; Line 7: the mass-to-luminosity ratio in solar units, $\mathcal{M}_\odot/L_\odot$; and Line 8: the crossing time, τ_c.

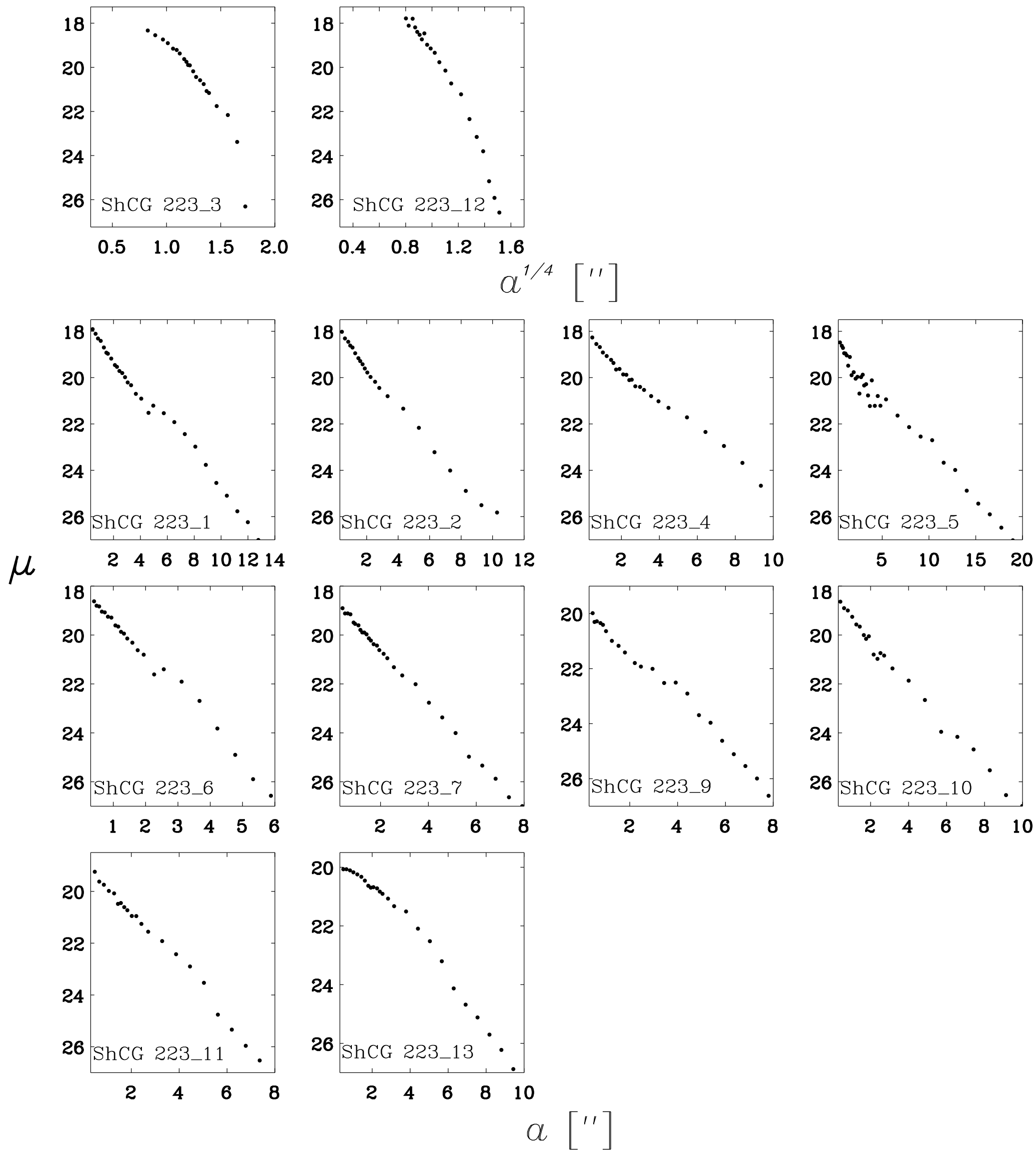

Fig. 7. Same as Figure 5 for galaxies in ShCG 223.

For systems with a small number of members the weighting by masses of some parameters is important, because the differences between weighted and unweighted RVDs may reach in such cases a factor of ≈ 2.

The main properties of the four individual groups are described below.

ShCG 104. We obtained spectra of five out of six objects in ShCG 104 (Stoll et al. 1996a). Three of them, galaxies 1, 5 and 6 compose a dense triplet of concordant redshift galaxies. The pair of background galaxies 2 and 3 are located about 150 Mpc farther. Isophotes (the right-hand panel of Figure 1) do not show any signs of interaction between members of the triplet. In contrast, the background galaxies 2 and 3 may be interacting. The projected distance on the sky between these two galaxies is about 40 kpc. Note that the halos of both these galaxies are significantly enlarged. Galaxy 3 has a strong Hα emission line in its spectrum. It is also a radio source (FIRST J092713.5+5258432) and probably an infrared source (IRAS Z09236+5311). Though galaxy 3 is an emission-line one, its image does not show any signs of spiral arms. According to the $\mu - a$ curve (Figure 5), it is rather of S0 type. The $\mu - a$ curves

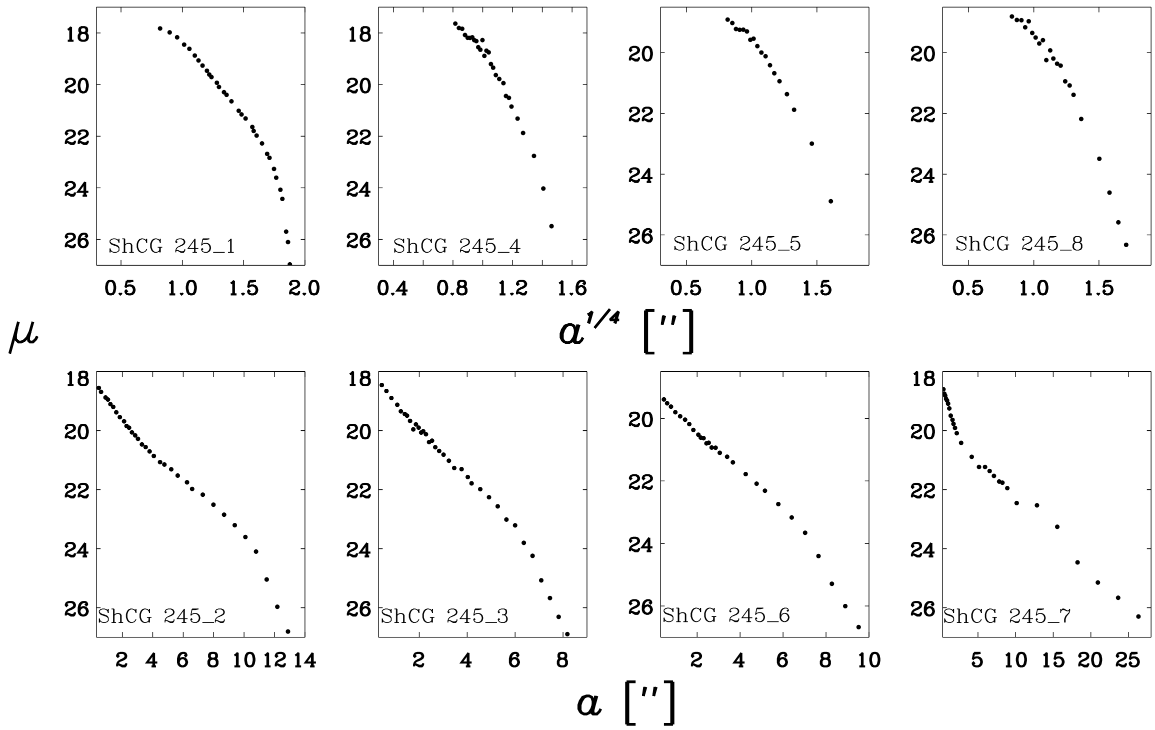

Fig. 8. Same as Figure 5 for galaxies in ShCG 245.

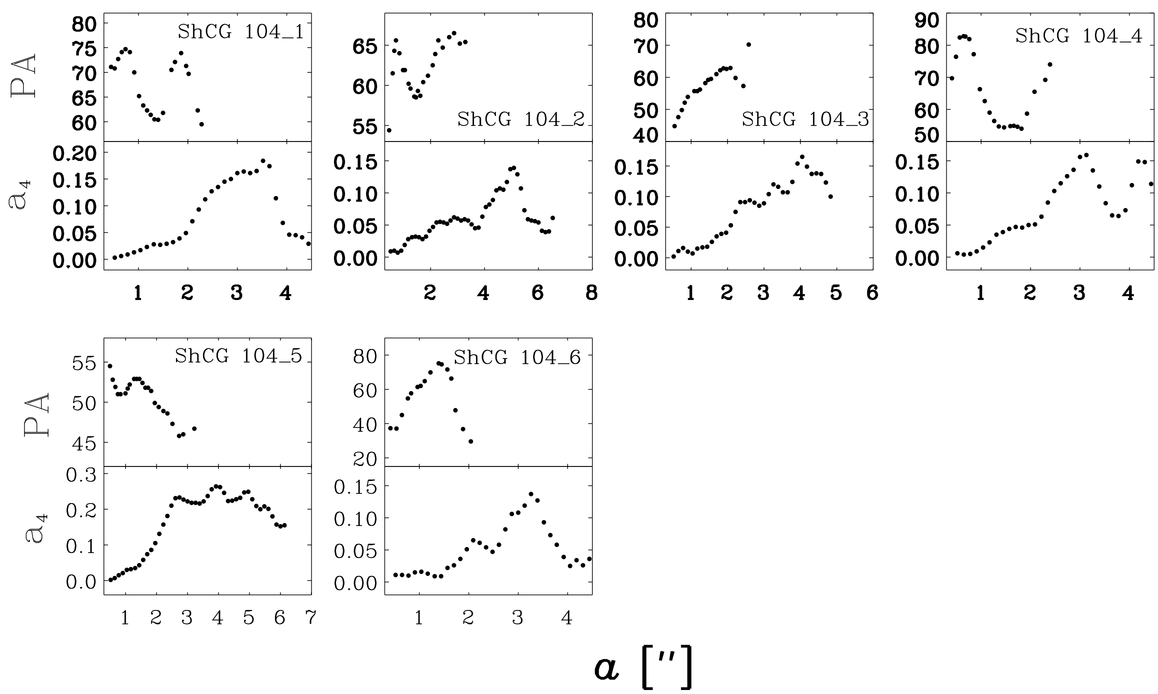

Fig. 9. The position angle, PA, and the Fourier coefficient, a_4, vs. semi-major axis a for the galaxies in ShCG 104.

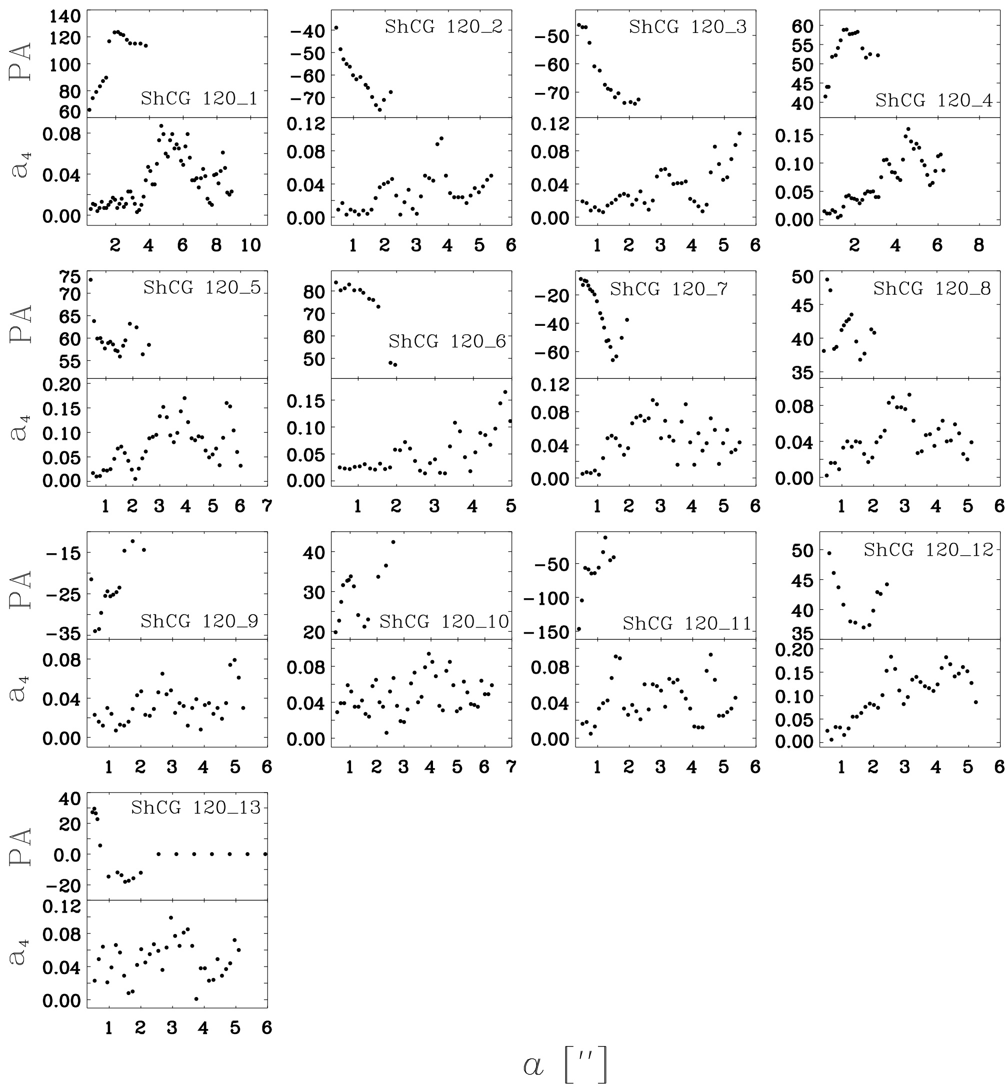

Fig. 10. Same as Figure 9 for the galaxies in ShCG 120.

show that all the other galaxies in the area but one, No. 5, are also of E/S0 or S0 type.

ShCG 120. Redshifts are measured for seven galaxies of this group of thirteen members (Stoll et al. 1996b). The position of the group coincides with that of the poor cluster A 1151 (richness group 0). It belongs to clusters of distance group 6 (Abell 1958). The redshift of ShCG 120, 0.0705, is at the lower limit of the wide redshift range (0.07 - 0.2) spanned by Abell clusters of this distance group. Many faint galaxies are observed in the area of the group, and we assume that the group is projected over a more distant cluster. On the other hand, the group has a relatively high RVD of about 460 km s^{-1}. Though there are some groups with similarly high velocity dispersion, such high RVD is more characteristic of a cluster. Therefore, we suggest that the group might be the central part of the cluster A 1151.

A sufficiently enlarged halo of galaxy 1 (see the isophotes on the right-hand panel of Figure 2) might be considered as a sign that this galaxy is gravitationally interacting with another object. We suggest that a small galaxy to the south-east of it may be merging with it. To prove the suggestion one should determine the redhift of the small galaxy. Galaxy 2 also seems to be interacting with galaxy 1. Other galaxies of the group are located relatively far from each other and no signs of interaction between them are evident. Almost all galaxies of the group are of early type, E or S0 (see Figure 6). Only two objects

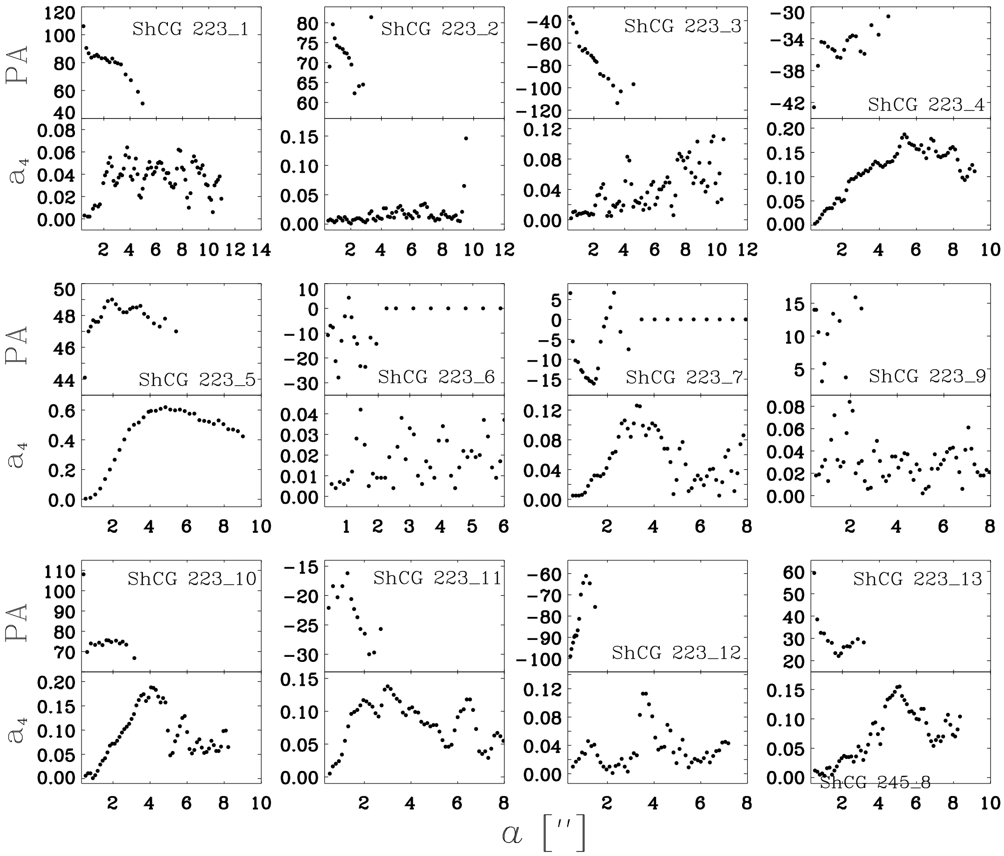

Fig. 11. Same as Figure 9 for the galaxies in ShCG 223.

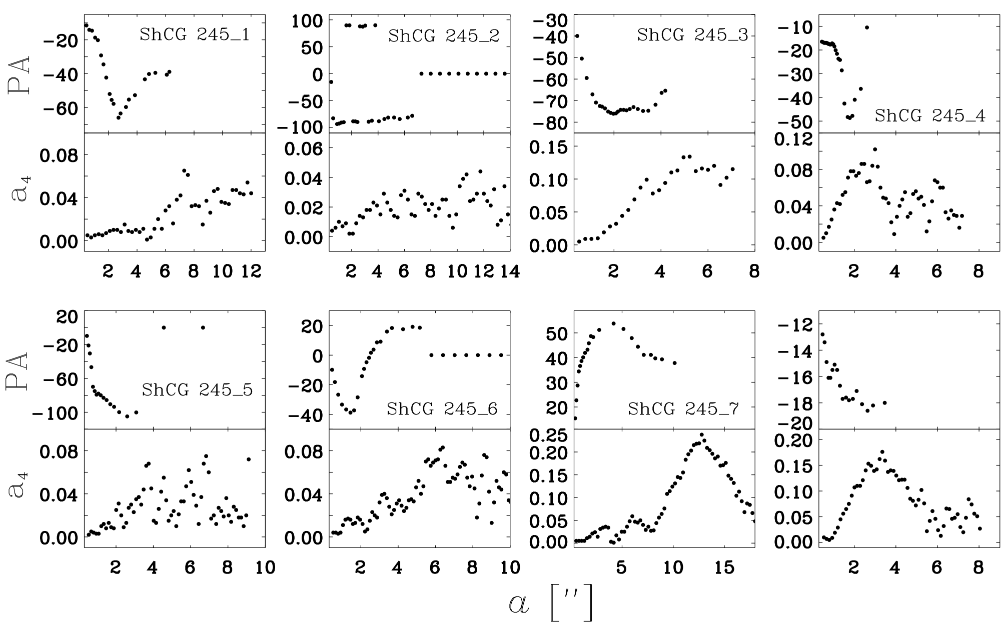

Fig. 12. Same as Figure 9 for the galaxies in ShCG 245.

TABLE 3

PHOTOMETRIC PARAMETERS OF INDIVIDUAL GALAXIES

Gal	R	$R-K_t$	b/a	$D['']$	Type
		ShCG 104			
1	16.82	-	0.9	9	S0
2*	17.12	2.89	0.8	15	S0
3*	17.68	-	0.7	12	S0
4	17.46		0.8	9	E/S0
5	17.85	-	0.6	10	S0
6	18.23	-	0.9	8	E/S0
		ShCG 120			
1	15.74	-	0.8	23	S0
2	16.86	-	0.9	12	E/S0
3	17.31	-	0.8	11	S0
4	17.04	-	0.7	19	E/S0
5	17.53	-	0.8	15	E
6	17.79	-	0.8	10	E/S0
7	16.85	-	0.9	8	E/S0
8	17.67	-	0.8	11	E/S0
9	17.85	-	0.9	17	E
10	18.25	-	0.8	13	E/S0
11	18.22	-	0.9	9	E
12	18.29	-	0.5	19	S
13	18.75	-	0.8	17	S
		ShCG 223			
1	15.15	3.33	0.8	27	E/S0
2	15.56	3.03	0.9	25	E/S0
3	15.78	-	0.8	18	E/S0
4	15.89	2.59	0.7	21	S
5	16.00	3.31	0.3	38	S
6	16.79	3.14	0.9	14	S0
7	16.61	2.28	0.8	17	S0
9	17.43	-	0.8	17	S
10	16.60	3.43	0.8	22	S
11	17.19	-	0.7	17	S0
12	16.76	-	0.9	10	E/S0
13	16.84	-	0.7	20	S0
		ShCG 245			
1	15.00	3.18	0.9	25	E
2	15.25	3.48	0.9	29	S0
3	16.00	-	0.8	16	S0
4	16.23	-	0.8	10	E
5	16.78	3.12	0.9	13	E
6	16.37	2.90	0.8	23	S0
7	15.01	2.79	0.7	63	S
8	16.73	3.11	0.7	17	E

*Background galaxy.

TABLE 4

GROUP PHYSICAL PARAMETERS

Parameter	ShCG 104	ShCG 120	ShCG 223	ShCG 245
z	0.1675	0.0705	0.0826	0.0628
a [kpc]	200	210	295	315
RVD [km s^{-1}]	137	464	460	437
R_{vir} [kpc]	25	46	55	59
$\mathcal{M}_{vir}$ [$10^{11}\mathcal{M}_\odot$]	5.2	107.5	127.3	123.1
L [$10^{11}/L_\odot$]	2.2	1.5	5.9	3.4
$\mathcal{M}/L$ [$\mathcal{M}_\odot/L_\odot$]	2.4	71.4	21.3	36.4
τ_c [10^6 years]	76	40	49	55

in the area, Nos. 12 and 13, are spiral galaxies. Redshifts of these two faintest galaxies are not known and their membership to the group is not certain.

ShCG 223. The original group consists of 14 members (Stoll et al. 1996c). We, and also Kodaira et al. (1990), measured redshifts of ten galaxies. They all have concordant redshifts (Table 2). The isophotes (the right-hand panel of Figure 3) show that galaxies 1 and 2 of the group are certainly interacting with each other. Galaxy 3 probably is also involved in the interaction. Meanwhile, two other galaxies, Nos. 5 and 6, located in close proximity on the sky to galaxies 1-3 do not demonstrate any signs of interaction. We assume that these two members of the group are projected over the interacting pair (or triplet). Inspection of the image of the group (Figure 3) and of $\mu - a$ curves (Figure 7) show that its five members, Nos. 4, 5, 9, 10 and 13 are spiral galaxies. Such a high number of spiral galaxies shows that the group is a relatively young one. According to the image, object 14 seems to be a star.

ShCG 245. Eight members of this group (Stoll et al. 1996c) are located in a relatively narrow strip oriented E-W. We obtained spectra of five objects. Three of them were observed also by Kodaira et al. (1990). All five galaxies have concordant redshifts with a radial velocity dispersion of 437 km s^{-1}. Galaxies 1, 2 and 3 of this group are interacting with each other (see the right panel of Figure 4). The faint object north of galaxy 2 seems also to be involved in interaction. It may even be merging with galaxy 2. Galaxies 5 and 8, which are near to this interacting triplet, are projected on the sky near to the latter. Except for galaxy 7, all galaxies of the group are of E or S0 type (Figure 8). Galaxy 7 is a spiral (Figures 4 and 8).

4. CONCLUSIONS

In this paper we present the results of the study of four ShCGs: ShCG 104, ShCG 120, ShCG 223, and ShCG 245. We measured redshifts of 27 galaxies in these four ShCGs. Twenty-five of them have concordant redshifts in corresponding groups. Integrated isophotal magnitudes in R band were measured for 35 member galaxies. Surface brightness isophotes showed that in all four groups there are interacting galaxies. By means of curves $\mu - a^{1/4}$ and $\mu - a$ we determined morphological types of those galaxies, the spiral arms of which are not apparent on prime images. No one of the studies galaxies has a box-like isophotes. They all are disk-like.

Up to now we have studied in total 44 ShCGs (the present paper; Papers 1-7; Tiersch et al. 1996, 1999). Physical parameters of the studied groups span a wide range of values. Note that CGs are mostly dynamically bound parts of larger systems (Tovmassian & Chavushyan 2000, Tovmassian; Plionis, & Torres-Papaqui 2006). Therefore, the deduced physical parameters must be considered as provisional. RVDs of the studied sample of 44 groups are within 88.5 km s^{-1} (ShCG 74W) and 667.1 km s^{-1} (ShCG 360) with a mean value of 330.0 ± 170.0 km s^{-1}. The mean RVD of ShCGs is comparable to that of HCGs and loose groups (LGs) (Hickson et al. 1992; Geller & Huchra 1983), and is much smaller than that of rich galaxy clusters, the typical value for which is ~ 1000 km s^{-1} (Zabludoff, Huchra, & Geller 1990). Mass-to-luminosity ratios span even a wider range of values than RVDs. They vary from 2 (ShCG 371) to 480 (ShCG 298) with a mean of 64.8 ± 85.5. The same relates to crossing times, they vary from 2 Myrs for ShCG 19 to 190 Myrs for ShCG 254. The mean crossing time is 90 ± 64 Myrs. It is much smaller than the Hubble age, ≈ 12.6 Gyrs (Alcaniz & Lima 2001). Hence, member galaxies have made many revolutions within the corresponding group and have had many chances for interaction and merging. Therefore, processes of interaction and merging should be common in very dense environments of ShCGs. Indeed, we found interacting galaxies with bridges, tidal tails, enlarged halos in the overhelming majority of the studied groups.

Interaction may result in formation of E and S0 type galaxies (i.e. Toomre & Toomre 1972). Tovmassian et al. (2004) showed that E/S0 galaxies in groups are formed mainly by merging of two spiral galaxies of about the same luminosity. The relative number of E/S0 galaxies in ShCGs is $\approx 70\%$. In HCGs the content of E/S0 galaxies is smaller, about 50% (Hickson, Kindl, & Auman 1989). If the early-type fraction of galaxies in groups is to be considered as an indicator of dynamical evolution, the higher fraction of early-type galaxies in ShCGs with respect to HCGs suggests that ShCGs are more evolved than HCGs. As a result of interaction the ram pressure may push out interstellar gas from gas-rich galaxies which, being heated, will emit in X-rays (Paper 1).

Elliptical and lenticular galaxies in the studied groups are mostly very red, $B - V \approx 1$ or even higher. By colour they are comparable to the reddest galaxies of RC2 and RC3 (Buta et al. 1995). In spite of the high number of interacting galaxies, FIR emission was detected only in a small number of them (Tovmassian et al. 1998). Most galaxies in ShCGs are gas poor early type galaxies, therefore interactions between them may not result in starburst and accompaning FIR emission. FIR emission may occur when rare spiral galaxies are involved in an interaction. Note also that Shakhbazian groups are on average ≈ 3 times farther than HCGs (Tovmassian, Martinez, & Tiersch 1999) and the possible FIR emission may not be detectable. We plan to present a more comprehensive discussion of the physical and dynamical properties of ShCGs after completion of the reductions of observational data of a couple of dozens more ShCGs.

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