GALAXY EVOLUTION IN THE ENVIRONMENT OF RDCS J1252.9-2927 AT z ~ 1.24 (I)

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Abstract. For the study of the galaxy evolution in the environment of the cluster RDCS J1252.9-2927, at high redshift z ~ 1.24, we used the catalogs of Demarco et al. (2007) and Tanaka et al. (2009). We analyzed the 2D-large scale distribution of galaxies in the field of RDCS J1252.9-2927, and the role of galaxy-galaxy interactions in the modification of color and morphology of galaxy pairs. Combining optical-NIR photometric data, morphological data, and ACS/HST archival images, the analysis of photometric and morphological properties of galaxies in pairs is completely performed. The presence of Extremely Red Galaxies (ERGs) in the Catalog of Demarco et al. (2007) is revealed too.

Key words: galaxy groups and clusters – galaxy-galaxy interactions – galaxy pairs.

1. INTRODUCTION

One of the most studied issues in the actual astronomy is represented by the formation and evolution of structures in the Universe. From the initial density fluctuations of the Universe filamentary structures grow, being distributed all over the Universe and constituting the cosmic web. Clusters of galaxies are often present at crossroads of filaments, and they should develop as a result of the hierarchical assembly of galaxies present along filaments (e.g. Demarco et al. 2005; Tanaka et al. 2006; Demarco et al. 2010).

It is already stated that the best natural laboratories for the study of galaxy evolution are represented by galaxy clusters and the surrounding regions. A wide range of environments are present here, from the dense core to the low density field.

The number of galaxy clusters at high redshifts ($z > 1$) is still poor and our knowledge on the galaxy population in these clusters are limited (e.g. Stanford et al. 2006; Lidman et al. 2008; Mei et al. 2009; Hilton et al. 2009). But there is a continuous progress in searching of clusters in the X-ray and optical/mid-infrared surveys (e.g. Fassbender et al. 2011, Nastasi et al. 2011, Suhada et al. 2011). The results of observational campaigns spanning several years, represented mainly by spectroscopic and photometrical data, are necessary to confirm the galaxy cluster candidates as real gravitationally bound systems and to determine their redshifts.

Our study is focused on RDCS J1252.9–2927 environment, one of the highest redshift X-ray clusters, at z = 1.237, that was discovered in ROSAT Deep Cluster Survey (Rosati et al. 2004).

According to Rosati et al. (2004), the total mass of the cluster inside a 0.5 Mpc radius is estimated as $M(<0.5Mpc) = (1.9 \pm 0.3) \times 10^{14} M_{Sun}$, in the cosmological model $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$. In the same cosmological model, Lombardi et al. (2005) determined the total mass inside a 1 Mpc radius to be $M(<1Mpc) = (8 \pm 0.3) \times 10^{14} M_{Sun}$. In this cosmological model, at the cluster redshift, a linear size of 0.5 Mpc corresponds to 1' on the sky (i.e. 8.3 kpc corresponds to 1" on the sky).

The images obtained with the Advanced Camera for Surveys (ACS) on the *Hubble Space Telescope (HST)* in the F775W and F850LP bandpasses were reported by Blakeslee et al. (2003). The authors revealed a tight colour-magnitude relation (CMR) of early-type galaxies belonging to this cluster. Due to the special resolution of ACS, it was possible to determine in the core of the cluster a central pair of galaxies with signs of dynamical interaction, surrounded by a large early-type galaxy population.

In addition to the optical *HST* imaging, Lidman et al. (2004), Toft et al. (2004), and Strazzullo et al. (2006) obtained the ground-based near-IR imaging of RDCS J1252.9–2927 environment, underlying a clear near-IR color-magnitude relation CMR. The luminosity function of the cluster galaxies was analyzed too, and a shallower slope than the value measured at similar restframe wavelength in clusters in the local universe was revealed.

Demarco et al. (2007) obtained detailed dynamical and spectrophotometric information on galaxies in this high redshift cluster, providing an in-depth view of structure formation at this epoch.

The investigation of this cluster was extended by Tanaka et al. (2009). These authors obtained wide-field imaging observations of the X-ray luminous cluster RDCS J1252.9-2927. This cluster underlines several galaxy groups that seem to be embedded in filamentary structure extending from the cluster core. In order to establish if these galaxies are physically associated to the cluster, the spectroscopic study of the galaxies have been performed by Tanaka et al. (2009), using GMOS on Gemini-South and FORS2 on VLT. The authors concluded that three groups contain galaxies at the cluster redshift, being probably bound to the cluster. The presence of such a filamentary structure as traced by galaxy groups at z > 1 was for the first time confirmed.

For our study we combine:

- the catalog of Demarco et al. (2007), with optical-NIR photometric data, redshifts, and morphology for galaxies in a 36 arcmin^2 field;

- the catalog of Tanaka et al. (2009), with $(V, R, i_{775}, z_{850}, K)$ optical-NIR photometric data and redshifts for 126 galaxies (in a 25 arcmin x 35 arcmin field);

- Hubble Space Telescope / Advanced Camera for Surveys archival images (from Hubble Space Telescope Archive at Canadian Astronomy Data Centre).

In the sequel we analyze the distribution of galaxies in the field of RDCS J1252.9-2927, taking into account their spectroscopic redshifts and morphology. The role of color-color and color –magnitude diagrams in the characterization of Extremely Red Objects is discussed too. The photometric and morphological properties of galaxies in pairs and groups in the RDCS J1252.9–2927 environment are also determined. We especially consider the role of galaxy-galaxy interactions in triggering the star formation, and strong modification of galaxy morphologies and colors.

2. DISTRIBUTION OF GALAXIES - THE DEMARCO ET AL. CATALOGUE

The catalog of Demarco et al. (2007) provides $(B, V, R, i_{775}, z_{850}, J, K)$ optical-NIR photometric data, redshifts and morphology for the galaxies in a 36 arcmin^2 field.

In the cosmological model $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, at the cluster redshift of $z = 1.237$, a linear size of 0.5 Mpc corresponds to 1' on the sky .

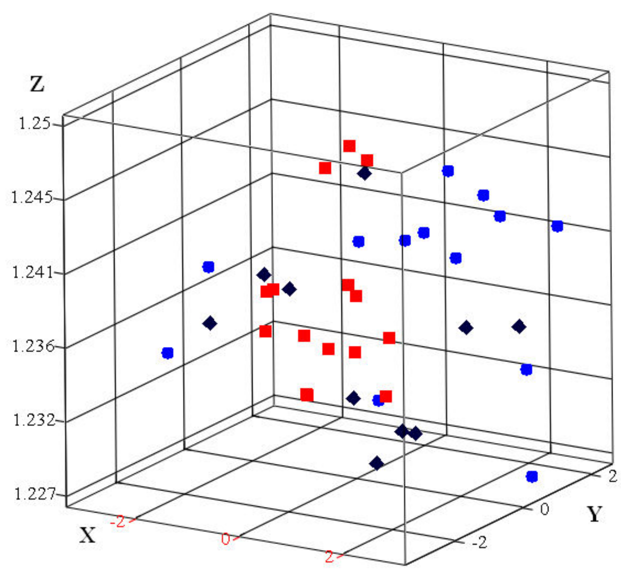

Fig. 1 – The 3D distribution of galaxies as function of morphology in the field of RDCS J1252.9-2927 (squares – E; diamonds – S0/Sa; dots – Sb/Irr).

For the 38 spectroscopically confirmed cluster member, with redshifts $1.2273 < z < 1.2475$, the photometric catalog contains:

- (B,V,R) (B,V,R) ground - based optical data obtained with VLT/FORS2 (ESO Very Large Telescope);
- (i_{775}, z_{850}) – band photometry from HST/ACS (Hubble Space Telescope / Advanced Camera for Surveys);
- (J,K) near-IR data from ground - based VLT/ ISAAC.

The magnitudes are in the AB system (Oke 1974), being corrected for Galactic extinction.

Also, these 38 galaxies are classified according to the morphological T-type (de Vaucouleurs et al. 1976), as determined by Postman et al. (2005): E elliptical galaxies ($-5 \le T \le -3$); S0 lenticular galaxies ($-2 \le T \le 0$); S spiral and Irr irregular galaxies ($1 \le T \le 10$).

Demarco et al. (2007) determined the redshifts for 189 field galaxies in the RDCS J1252.9–2927 cluster environment.

In Fig. 1 we present the 3D distribution of galaxies, as function of morphology, for the studied field, with (X, Y) = galaxies position (in arcmin) and Z = spectroscopic redshifts.

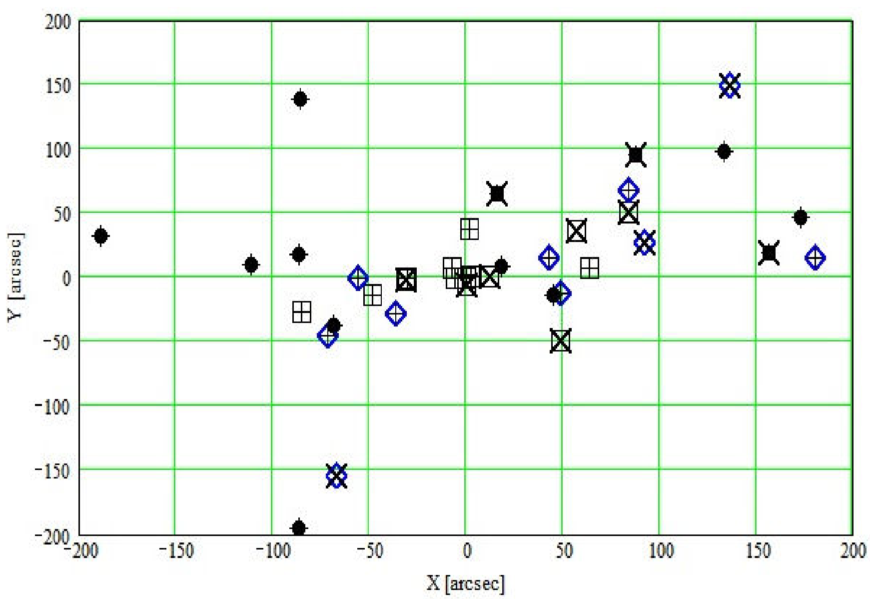

Fig. 2 – The 2D distribution of galaxies as function of morphology
in the field of RDCS J1252.9-2927 (squares – E; diamonds – S0/Sa; dots – Sb/Irr).

For the field of RDCS J1252.9-2927, we group the galaxies into three classes function of their morphology, the symbols being as follows: squares = E galaxies (15 galaxies); diamonds = S0/Sa galaxies (10 galaxies); circles =Sb/ Irr galaxies (11 galaxies); and 2 galaxies without morphology.

In Fig.2 we show the 2D distribution of galaxies, the symbols being the same as in Fig.1. The central brightest galaxy BCG1 (ID 291 $\alpha_{J2000} = 12^h 52^m 54.41^s$, $\delta_{J2000} = 29^0 27'17.7''$, $z = 1.2343$, K =17.321) is a passive early-type galaxy, and belongs to a pair of galaxies together with BCG3 (ID 289, $z = 1.2378$, K = 17.641). The two galaxies are separated by 1.”8 (~ 15 kpc). Another brightest cluster galaxy is BCG2 (ID 247, $z = 1.2351$, K =17.631). BCG1 is closely located near the position of the X-ray center: $\alpha_{J2000} = 12^h 52^m 54.4^s$, $\delta_{J2000} = 29^0 27'17.5''$ (Rosati et al. 2004).

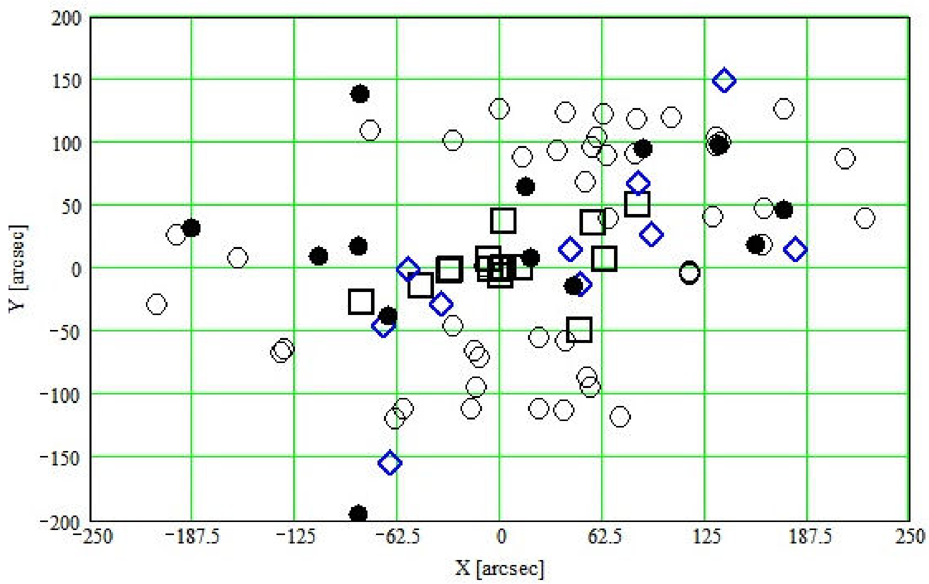

Fig. 3 – The 2D distribution of galaxies cluster as function of morphology, and the field galaxies in the redshift range 1< z< 1.3 (squares – E; diamonds – S0/Sa; dots – Sb/Irr;.circles – field galaxies) .

The presence of red passive elliptical galaxies around this central pair of galaxies is clearly visible (see Fig. 1 and Fig. 2). These elliptical and lenticular galaxies are positioned in the central region of the cluster, at a radius of 0.5 Mpc.

On the existing symbols in Fig.2, we superimposed additional symbols for the two substructures of the analyzed cluster: (X) – for the galaxies with redshifts

$1.22 < z < 1.24$, and (+) – for the galaxies with $1.24 \le z < 1.25$. The distribution of galaxies cluster is elongated in the east-west direction (i.e. from the right to the left direction in Fig.2), as a result of a possible merger of these two substructures (see also Fig. 2 and Fig.3).

In Fig.3 we represent the 2D distribution of the 38 spectroscopical confirmed cluster members and the field galaxies with redshifts in the range $1 < z < 1.3$. The hypothesis of filamentary structures that grow and feed the two substructures of the RDCS J1252.9-2927 cluster can be asserted.

3. COLOR-COLOR DISTRIBUTION FUNCTION OF GALAXIES MORPHOLOGY

The extreme properties such as very red optical to near-infrared colors [$(V-I) \ge 3.5$, $(R-K) \ge 5$, $(I-K) \ge 4$, $(J-K) \ge 1.75$] and moderately faint near-infrared magnitudes ($K \approx 17.5-20$) are characteristic for *Extremely Red Objects* (EROs).

The selection criteria of the passively evolving elliptical galaxies by means of red optical and near-infrared colors have been originally used to the identification of galaxies clusters at $z \ge 1$.

As the 4000 Å break falls between *R*- (or *I*-, *J*-) band and *K* band, at $z \ge 1$ these old passively-evolving galaxies should be characterized by red optical-NIR colors, representing redder colors than most galactic stars and field galaxies.

The red colors of ERGs population are consistent with two classes of galaxies:

a) old passively evolving elliptical galaxies at $z \ge 1$;

b) high-redshift dusty starburst galaxies, characterized by high star-formation rates, or AGN reddened by strong dust extinction.

In order to address this issue, we transform the photometry from the AB system to the Vega system according to the following formula:

$$B_{Vega} = B_{AB} + 0.088;\ V_{Vega} = V_{AB} - 0.052;\ R_{Vega} = R_{AB} - 0.244;$$
$$i_{755\,Vega} = i_{755\,AB} - 0.401;\ z_{850\,Vega} = z_{850\,AB} - 0.569;\ J_{s,Vega} = J_{s,AB} - 0.968;$$
$$K_{s,Vega} = K_{s,AB} - 1.899 .$$

The $(R-K)-(J-K)$ color-color diagram of galaxies function of morphology is presented in Fig. 4 (left panel), where the clustering of E/S0/Sa galaxies in specific colors ranges is conspicuous.

The presence of a large population of Extremely Red Objects EROs in the Catalog of Demarco et al. (2007) is revealed by the $(R-K)-(J-K)$ color-color diagram, where the old cluster galaxies present colors in the ranges $1.7 \le (J-K) < 2$

and $5 \leq (R-K) < 6.2$. The galaxy with $(J-K) \sim 2.2$ represents the confirmed cluster AGN (ID 174), this one being the reddest galaxy in this color-color diagram.

The second color-color diagram $(V-i_{775})-(i_{775}-z_{850})$ (Fig. 4 right panel) is useful for the selection of Balmer/4000A break galaxies and star-forming galaxies (applying the selection criteria $0.4 < i_{775}-z_{850} < 0.85$; $0.2 < V - i_{775} < 1.25$; $2.4(i_{775}-z_{850})-1.12 < V-i_{775} < 7(i_{775}-z_{850})-2.3$ for the cluster members with emission line [O II] ($\lambda 3727$)).

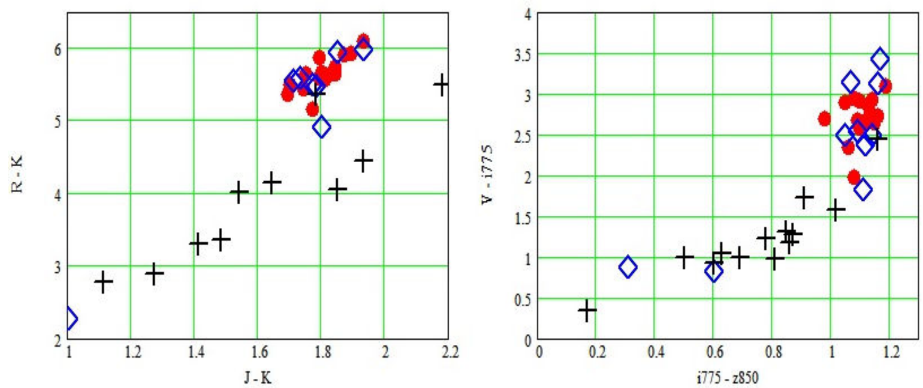

Fig. 4 – The $(R-K)-(J-K)$ color-color diagrams of galaxies function of morphology (left panel); the $(V-i775)-(i775-z850)$ color-color diagram function of morphology (right panel): circles – E; diamonds – S0/Sa; crosses – Sb/Irr

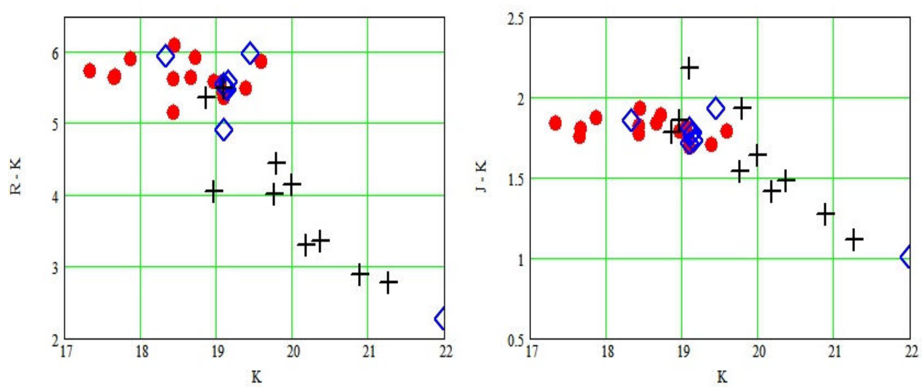

Fig. 5 – The $(R-K)-K$ color-magnitude diagram of galaxies function of morphology (left panel); the $(J-K)-K$ color-magnitude diagram function of morphology (right panel): circles – E; diamonds – S0/Sa; crosses – Sb/Irr

The two population of passive and star-forming galaxies are well delimited in the $(R-K)-(J-K)$ and $(V-i_{775})-(i_{775}-z_{850})$ color-color diagrams. Although the galaxies ID 6301 and ID 3159 are S0/Sa type, they present bluer optical-NIR colors as a result of an increased star formation rate due to possible interactions/mergers.

The Fig. 5 shows the $(R-K)-K$ and $(J-K)-K$ colour-magnitude diagrams, where the E and S0/Sa galaxies have colors in the specific range of the old passively evolving galaxies at $z \geq 1$, and the red sequence is well delimited in both diagrams.

4. INTERACTIONS EFFECTSON COLOR AND MORPHOLOGY OF GALAXIES

According to Lin et al. (2007), Patton et al. (2011), the projected physical separation $10\,\mathrm{h}^{-1}\,\mathrm{kpc} < \Delta r_{\mathrm{proj}} < r_{\max}$ (with $r_{\max} \in \{30, 50, 100\}\,\mathrm{h}^{-1}\,\mathrm{kpc}$), and rest-frame line-of-sight velocity difference $|\Delta v| \leq 500\,\mathrm{km/s}$ can uniquely identify the galaxy pairs.

Because in the case of RDCS J1252.9-2927 we have the spectroscopic redshift, the galaxy pairs are determined using the following thresholds:

(1) Projected relative distance: $r_{\max} \leq 100\,\mathrm{h}^{-1}$ kpc ;

(2) Relative magnitude: $|\Delta K| \leq 1.75\,\mathrm{mag}$.

Fig. 6 presents the invert color composite of the HST/ACS ((i_{775}, z_{850}) bands) and deep VLT/ ISAAC *(J + Ks* band) images, covering a field of 4 arcmin^2 around the cluster center (N is up; E is to the right).

The image is from http://www.spacetelescope.org/images/heic0313d/.

In order to analyze the existing galaxy pairs from the central region, we delimited this one with a square.

The analyzed pairs are presented in Fig.7, where the 2D distribution of galaxies and pairs of galaxies as function of ACS/HST morphology (right panel), is compared with the central region from Fig. 6 (central square image). The symbols are the same as in Fig. 2, for the right panel of Fig.7.

We determined 11 galaxies in: one group, 2 mixed pairs (i.e., an elliptical/lenticular galaxy + a spiral or irregular galaxy), and one *dry merger* (i.e. major mergers between galaxies without presence of gas, such as E/S0 galaxies). The group contains 5 E/S0 galaxies, presenting dry mergers too.

In Table 1 are presented the photometric and morphological characteristics of the galaxies in the studied pairs.

We observe that the galaxies in pairs present obvious features of interactions, with signs of morphological disturbance and bluer colors, as characteristics of interactions/mergers that trigger star formation activity.

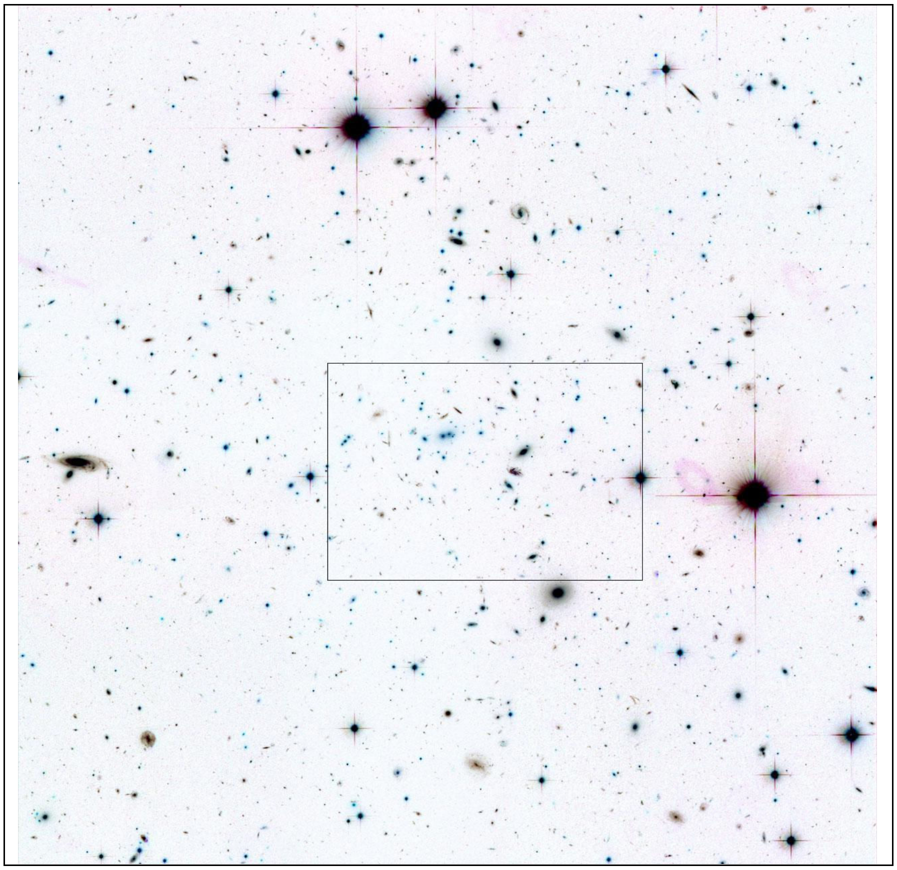

Fig. 6 – The invert color composite of the HST/ACS ((i_{775}, z_{850}) bands) and deep VLT/ ISAAC *(J + Ks* band) images, covering a field of 4 arcmin^2 around the cluster center (N is up; E is to the right).

Fig. 8 presents the $(R - K) - (J - K)$ color-color diagram (left panel), and the ($V - i775$) – ($i775 - z850$) color-color diagram (right panel) of the galaxies in the studied pairs. The galaxies are represented with circles (5 E in the group), squares and dots (for the mixed pairs); crosses – "dry merger".

From these diagrams one observes that the ($V - i775$) color of the Irr galaxies in the two mixed pairs is evident bluer than the color of their E/S0 companions, while the E/S0 galaxies in pairs present comparable colors.

Table 1. Galaxies pairs properties

ID	z	K_{Vega}	Type	(R – K)	(J - K)	(V -i)	Pair
291(BCG1)	1.2343	17.321	-5	5.745	1.841	2.689	Dry mergers
289(BCG3)	1.2378	17.641	-5	5.675	1.801	2.839	
304	1.2384	17.851	-5	5.905	1.871	2.929	
338	1.2312	19.031	-5	5.575	1.811	2.679	
282	1.2472	18.701	-5	5.935	1.891	2.659	
313	1.2455	18.421	-5	6.105	1.931	3.089	Mixed pair
339	1.2274	18.951	8	4.055	1.851	0.979	
294	1.2455	18.411	-5	5.625	1.821	2.579	Dry merger
310	1.2342	18.461	-5	5.645	1.841	2.349	
248	1.2322	19.781	8	4.445	1.931	1.309	Mixed pair
265	1.2358	19.121	-2	5.475	1.781	2.499	

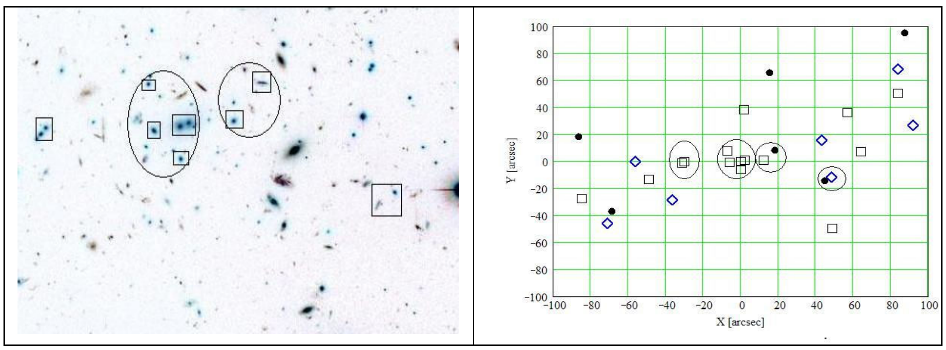

Fig. 7 – The 2D distribution of galaxies and galaxy pairs function of morphology (right panel); The composite image of the central region (left panel).

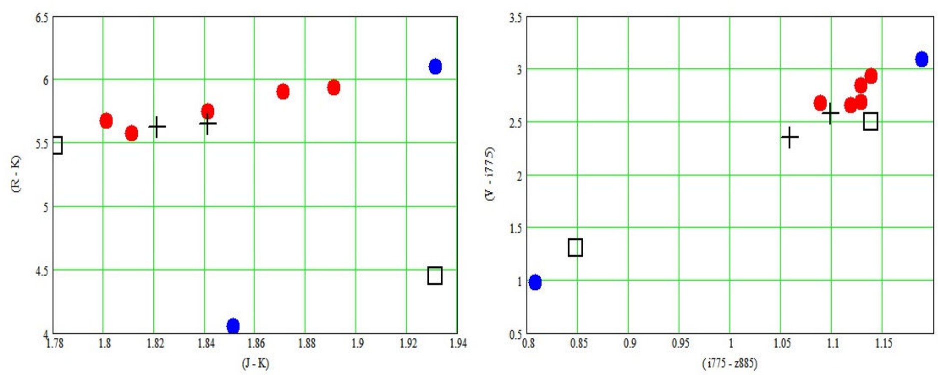

Fig. 8 – The (*R* – *K*) – (*J* – *K*) and (*V* – *i775*) – (*i775* – *z850*) color-color diagrams of galaxies in pairs

5. CONCLUSIONS

In this paper, based on Demarco et al. (2007) catalog and archival ACS/HST images, we analyze the 3D-distribution of galaxies in the field of RDCS J1252.9-2927, and the role of galaxy-galaxy interactions in the modification of color and morphology of galaxy pairs.

Our analysis revealed that RDCS J1252.9–2927 cluster is still in the process of forming, presenting filamentary and clumpy structures.

The galaxy pairs sample was obtained with a strong pair isolation criterion in terms of the apparent angular separation and rest-frame line-of-sight velocity difference. The on-going interactions present evident morphological signs, such as distorted morphologies, for the mixed selected pairs. Also, galaxies in mixed pairs present bluer colors, as a result of increased star formation rate due to the close interactions and mergers.

Combining optical-NIR photometric data, morphological data, redshifts and ACS/HST archival images, the analysis of photometric and morphological properties of galaxies in pairs was completely performed.

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