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THE INNER STRUCTURE OF GALAXY CLUSTERS IN THE TRIPLETS

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ABSTRACT. The inner structure of galaxy clusters is determined by the interaction of baryon matter with the surrounding structures and the influence of the underlying dark matter. For the search of the results of such interaction, we select the 18 triplets (11 elongated and 7 rounded ones) of galaxy clusters from the triplets founded in the PF Catalogue of Galaxy Clusters and Groups (Panko & Flin). The shape of the all founded triplets vary from practically regular triangle to straight chain, i.e., the ellipticity of the best-fitted ellipse of the triplets ranged from 0.12 to 0.92. We select the triplets with ellipticities in the range 0.8 – 1.0 as the first subset and with the ellipticities in the range 0.1 – 0.4 as the second one.

The comparison the results obtained for two subsets allowed to conclude the elongated triplets arise along the filament. Binggeli effect was detected in a major part of clusters. In the linear substructure L11 in PF 0369–7499 galaxies show also perpendicular alignment in contrast to other galaxies of this cluster. We suppose the substructures in the galaxy clusters of our data set must be connected with the influence of other triplet members.

Keywords: galaxy clusters: morphology: inner structure; galaxies: orientations; data analysis

АНОТАЦІЯ. Внутрішня структура скупчень галактик визначається взаємодією баріонної матерії з навколишніми структурами та впливом підстилаючої темної матерії. Для пошуку результатів такої взаємодії ми обрали 18 триплетів (11 витягнутих і 7 округлих) скупчень галактик із списку триплетів, що було знайдено у Каталозі скупчень і груп галактик PF (Panko & Flin,2006). Форма всіх триплетів, що було знайдено, варіюється від майже правильного трикутника до практично прямого ланцюжка, тобто еліптичність найкращого еліпсу для триплетів скупчень галактик знаходиться у межах від 0,12 до 0,92. Ми обрали триплети скупчень з еліптичностями в діапазоні 0,8 – 1,0 в якості першого набору даних та з еліптичностями в діапазоні 0,1 – 0,4 в якості другого набору.

Порівняння результатів, отриманих для двох наборів, дозволило дійти до висновку, що витягнуті триплети виникають уздовж філаменту, що збігається з ідеєю еволюції елементів великомасштабної структури Всесвіту. Ефект Бінггелі був виявлений у більшої частини скупчень. Особливо розглянуто PF 0369–7499, що має дуже вузьку лінійну підструктуру L11. Галактики у лінійній підструктурі цього скупчення показують перпендикулярне вирівнювання відносно напряму на найближчого сусіда, на відміну від інших галактик цього скупчення. Ми припускаємо, що підструктури в скупченнях галактик нашого набору даних мають бути пов'язані з впливом інших членів триплету.

Ключові слова: скупчення галактик: морфологія: внутрішня структура; галактики: орієнтація; аналіз даних.

1. Introduction

The different elements of the Large Scale Structure of Universe (LSS) evolve in the interaction with surround. From the base theoretical works like Silk (1968), Peebles (1969), Peebles & Yu (1970), Zeldovich (1970), and latest it is considered the LSS elements as co-evolved objects. The fluctuations of the gravitational field and Hubble flow produce the different kinds of LSS elements, namely, $3D$ contraction gives spherical or ellipsoidal structures, $2D$ leads to filaments, and the walls are formed due to $1D$ contraction. Some additional overdense regions in the filaments can evolve to groups of small galaxy clusters which form elongated higher-level structures having two, three and more galaxy clusters. In another case – in the walls higher-level structures can obtain rounded shapes. The triplets of galaxy clusters can be good examples of both the first and second cases of the contraction, and must be reflected in the inner structure of the galaxy clusters belonging to corresponding type of the triplet.

Our approach takes into consideration the result of the modern observations (Wen et al., 2009, Dietrich et al., 2012, Parekh et al., 2020) as well as numerical simulations from the first (Klypin & Shandarin, 1983) to latest (Springel et al., 2005, Vogelsberger et al., 2014, Artale et al., 2017, Cui et al., 2018, Tomoaki et al., 2021), where the massive gravitational bounded objects, galaxy clusters can arise on the cross of filaments or the cross of filament and wall. We suppose the footprints of such interactions we can detect as substructures in the galaxy clusters for all components, namely DM, hot gas and galaxies. The correspondence of the DM, hot intracluster gas and galaxies distribution in galaxy clusters was studied (for example, Dietrich et al., 2012) and it was shown the difference in the distributions of the cluster components arises in the collisions (Markevitch et al., 2004). The features of the distribution of galaxies give us good image for other components – hot gas and DM for non-collided, but for evolved clusters.

Our previous studies were directed to the detection of substructures in galaxy clusters in fields with different densities, from the richest regions (Panko et al., 2021) to isolated galaxy clusters (Panko et al., 2022). In all cases, we detected the different kinds of regular substructures, such as linear ones from wide bands to thin filaments, crosses and semi-crosses, and short dense curve stripes.

The next key question is the alignment of galaxies in the clusters or substructures. The Binggeli effect (Binggeli, 1982) was confirmed in a lot of works on both galaxies and galaxy clusters (Godlowski et al., 2010; Biernacka et al., 2015; Pajowska et al., 2019).

The goals of the present study are based on the following points:

- the galaxy clusters are evolved objects, and the general direction is:
- from open structure to cluster having a distinct concentration of galaxies in the center of gravity;
- from open structure to structure having some kinds of substructures and the final stage will be the same distinct concentration of galaxies in the center of gravity;
- the substructures can arise due to the gravity of the neighbor;
- the alignment of galaxies is not random;
- the substructures in the galaxy clusters belonging to elongated triplets the nonrandom alignment must be seen.

We select galaxy clusters belonging to elongated and rounded triplets as an object for present study.

2. Observational Data

The main base of our study is the list of galaxies obtained from 216 digitized plates of the Muenster Red Sky Survey (Ungrue et al., 2003), hereafter MRSS and the Catalogue of Galaxy Clusters and Groups (Panko & Flin, 2006), hereafter PF, created on the MRSS. Both catalogs cover about 5000 square degrees of sky with galactic latitudes $b < -45^o$ and completeness limit in red magnitude $r_F = 18.3^m$. For each galaxy in MRSS, the next parameters are shown: equatorial coordinates, r_F magnitude, the size of axes of the galaxy image in best-fitted ellipse approximation (in *arcsec*), ellipticity, and the position angle of the major axis of a galaxy image. Unfortunately, MRSS is the last photographic sky survey with corresponding weaknesses, and their galaxies have no redshifts.

The estimated redshifts for PF galaxy clusters were obtained from the comparison of PF catalog with ACO (Abell, 1989) and APM (Dalton et al., 1997) catalogs according to $logz$ vs. m_{10} relation (Biernacka et al. 2009), following Dalton et al. (1997). 1711 PF galaxy clusters with $z_{est} < 0.15$ and richness over 50 galaxies allowed to create the list of galaxy superclusters (Panko, 2011) using *FoF* method in Zeldovich et al. (1982) form. Simultaneously, for each of these clusters, the distance to the nearest neighbor was determined. It allows to create also the separate lists of isolated galaxy clusters, pairs of clusters, and triplets of clusters (TCl).

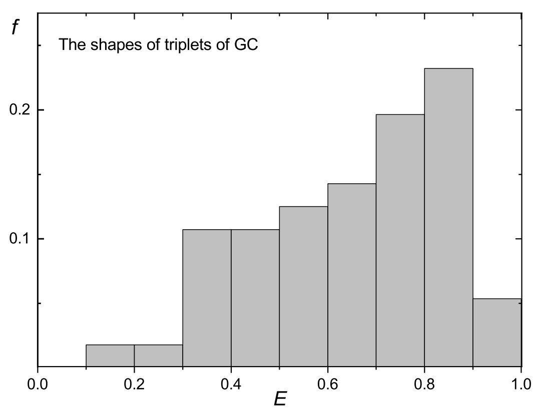

Figure 1: The distribution of the estimated shaped of triplets of galaxy clusters

The full list of triplets contains 56 records with TCl identifier, the equatorial coordinates of their centers, redshif, the full number of galaxies, the maximal size of the triplet, and the estimated shape (ellipticity), calculated using the seconds statistical moments. The distribution of the shapes is shown in Fig. 1. One can see the main part of the triplets are elongated objects like the straight chain, nevertheless, the rounded triplets with small ellipticity are present too.

The data set for the present study contains 58 galaxy clusters belonging to 18 triplets: 11 triplets are elongated structures with ellipticities in the range $0.8 - 1.0$ and 7 ones are rounded with the ellipticities in the range $0.1 - 0.4$. We supposed two subsets must have the difference in the galaxy substructures kinds. The estimated redshifts for our data set are from 0.06 to 0.114.

3. Cluster Mapping and Substructures Detection

We used the advanced version of the “Clusters Cartography”, hereafter CC (Yemelyanov & Panko, 2021), for this study. The new Web version of CC was created in JavaScript to implement dynamic data visualization in a web environment. The Web version of the CC code includes functions for processing data, calculating statistics, and plotting maps, histograms, and graphics, which are built using different parameters, such as the radii and widths of the rings in determining the degree of the concentration to the center, the widths of the bands in determining of the degree of the concentration in the linear substructures etc. we also added to the code the possibility to study the Bunggeli effect both for all galaxies and separated substructure. We conserved in the new version the base functions: the search for the position of the greatest density of galaxies in the cluster field, the detection of the regular linear and cross-type substructures, the analysis of the shape of the members of the cluster (Yemelyanov & Panko, 2021). All CC maps in the new version also have the same size $4000 \times 4000\,arcsec$. The size, shape, and orientation of symbols for galaxies correspond to MRSS data: magnitude m, ellipticity E, and positional angle of the major axis PA of the galaxy image in the best-fitted ellipse. The size of the symbol m' is calculated from the magnitude as

$$m' = 3 \cdot 2^{0.6(18.5-m)} + 6,$$

And the axes A and B of the ellipse having the same square, as:

$$A = \frac{m'}{\sqrt[4]{(1-2E+E^2)}}, \;\; B = \frac{(m')^2}{A}.$$

The results of the analysis are based on the correspondent distribution of the selected parameter, so, they are statistically significant.

We studied the next parameters for 54 galaxy clusters: the cluster type according to the advanced morphological scheme (Panko, 2013), the presence of the regular substructures, the distribution of the ellipticities of the cluster's members, the appearances of the Binggeli effect both all galaxies in the clusters field and galaxies included in substructures.

Table 1: The morphology of galaxies in elongated and rounded triplets

Type	Elongated triplets				Rounded triplets			
	Main	L	Y	BG	Main	L	Y	BG
O	25(8)	3	4	1	16(4)	4		
I	7(1)	3	1	2	4			1
C	1				1			1
	33(9)	6	5	3	21(4)	4		2

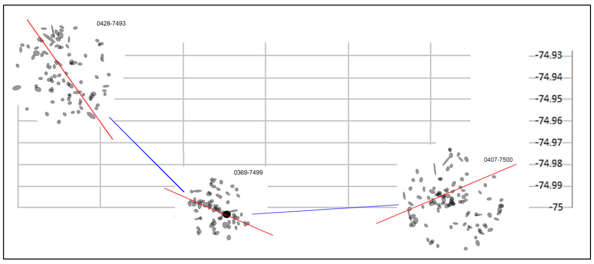

Figure 2: The triplet TCl 040-750 unites galaxy clusters PF 0369-7499, PF 0407-7500, PF 0428-7493. Red lines illustrate the detected substructure direction, and blue ones correspond od the direction of the neighbor. The position of the centers of the clusters are in the scale, at the same time the cluster images are enlarged for clarity.

4. Results and Discussion

The common results for the studied 33 galaxy clusters, belonging to elongated triplets and 21 galaxy clusters belonging to rounded ones are presented in Table 1. The values in brackets in Table 1 indicate the number of clusters with some uncertain classification of the degree of concentration toward the center. That is, for the first subset of 25 clusters of type O from the first subset, 8 ones showed a slightly pronounced concentration that can be described as OI. Similarly, in the second subset the analogical situation: OI type of cluster was detected for 4 clusters from 16. For I type in the first subset we detected only one cluster which can be classified as IC. In our previous studies pronounced OI, IO, or IC types were extremely rare.

We did not detect X-type substructures in 58 selected clusters, Y-type substructures are present only in clusters belonging to elongated triples. The correspondence between the direction of the substructure and the direction of the neighbor is seen (Fig. 2). Corresponded acute angles are small, we can suppose the inner substructures trace the parent filament direction.

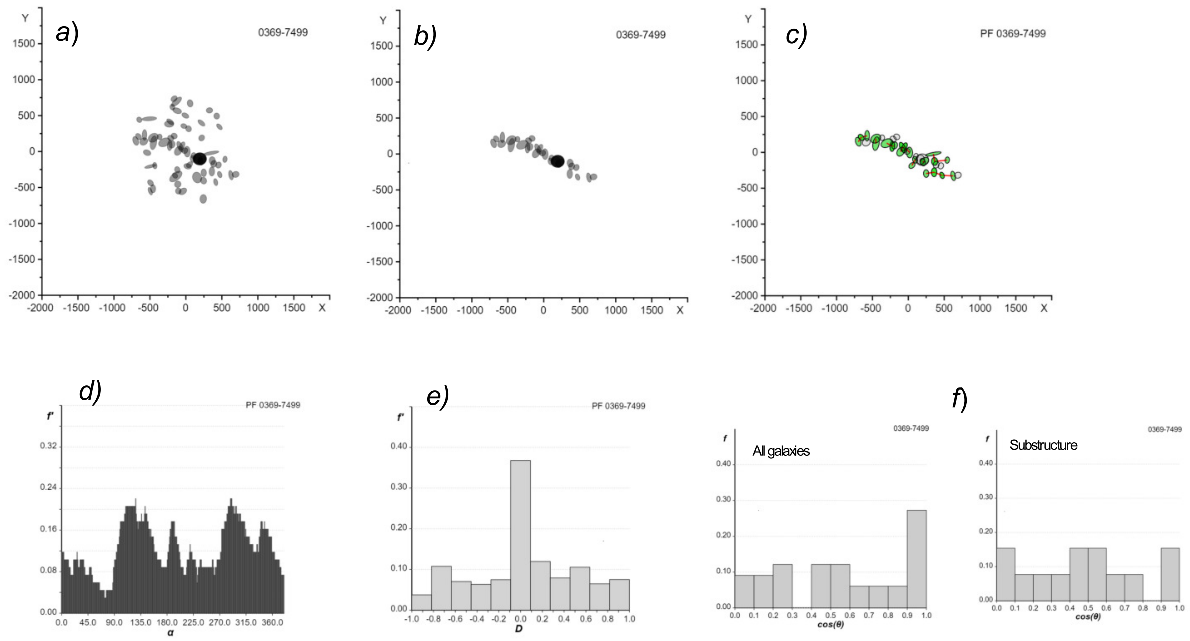

Figure 3: PF 0407-7500 cluster and its L11 substructure. In the upper panel, the maps are shown: *a* – the cluster, *b* – substructure, and c – the alignment of galaxies with E¿0.2 (green) in the substructure. the brightest cluster member is shows as black symbol. In the bottom panel: *d* – LHB diagram with four peaks, *e* – normalized galaxy densities in 11 bands, and *f* – alignment of galaxies as according to Binggeli effect presence

The cluster PF 0407-7500 (OL11 type) has so interesting and perspective substructure (Fig. 3*a*). Light-Houses Beam diagram, LHB regime in CC (fig. 3*d*) notes to powerful linear substructure (two wide peaks) as well as allows us to suppose the presence of the small short chain (two thin peaks). The crossing points of these substructures have the brightest galaxy, which is shown as black in Fig. 3*a*,*b*. The linear substructure is detected not only using LHB. Linear mode in CC (Fig. 3*e*) demonstrates a significant peak in the middle band, corresponding to the L11 type. Only galaxies in the linear substructure are shown in Fig. 3*b* and the example of Binggeli effect analysis for this substructure is shown in Fig. 3*c*. The alignment of galaxies in the L11 substructure on common is in the perpendicular direction to the direction of the neighbor galaxy. In contrast, all galaxies of the PF 0407-7500 show the Biggeli effect in classical form (Fig. 3*f*). The galaxies having an ellipticity less than 0.2 were.

Other triplets show similar peculiarities for linear and Y-type substructures.

5. Conclusion

We analyzed the inner structure of galaxies in both elongated and rounded triplets. About half of the clusters in both subsets are open clusters without features. For round triplets, we did not detect crosses or semi-crosses. There are linear substructures on O type that, are present only in four cases. Clusters of I and O types in this subset have no regular substructures.

For elongated triplets the part of clusters having the regular substructures, linear or semi-cross, are present in about 30% for O-type clusters and in 57% for I-type clusters.

The Binggeli effect was detected in a major part of the clusters. In the linear substructure in PF 0369-7499 galaxies show also perpendicular alignment in contrast to other galaxies of this cluster.

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