DOI:http://dx.doi.org/10.18524/1810-4215.2019.32.182519

LINEAR SUBSTRUCTURES IN GALAXY CLUSTERS

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ABSTRACT. We propose detailed scheme that is describing the morphology of linear substructures in galaxy clusters. Our base morphological scheme divides galaxy clusters using numerical criteria according the parameters: concentration to the cluster center, the presence of linear substructure, orientation of images of galaxies, the role of brightest cluster members, the shape of galaxies.

Our analysis of 2*D* distribution of galaxies based on study more than 500 galaxy clusters. We show the linear substructures are regular peculiarity in galaxy clusters. Our approach allows to divide filamentary and edge-on wall substructures and to select galaxy clusters with possible peculiarities in hot gas and/or DM distribution.

Keywords: Galaxies: clusters: morphology.

АНОТАЦІЯ. Морфологія скупчень галактик є одним з найважливіших ключів до розуміння еволюційних процесів формування великомасштабної структурі Всесвіту та вивчення її інших фізичних компонентів. Результати численних комп'ютерних симуляцій дозволяють стверджувати, що філаментарні субструктури у скупченні не є випадковими, вони відображають розподіл наймасивнішого з його компонентів - темної матерії. При цьому, розташування галактик у скупченні є найдоступнішим індикатором розподілу не тільки темної матерії, а й гарячого газу, а також воно може вказувати на взаємодію з іншим скупченням. Орієнтації галактик у субструктурах також не є випадковими: в одномірних особливостях галактики вирівнюються вдовж смуги найбільшої густини, в двомірних -дискові галактики вирівнюються до перпендикуляру неї.

Розподіл галактик у скупченні зручно описувати як його морфологічний тип. Морфологічна схема, яку у 2013 році запропоновано Панько, спирається на декілька класичних схем морфологічної класифікації різних авторів та основана на чисельних критеріях. Схему реалізовано у пакеті програм «The Cluster Cartography». Це дозволяє проводити аналіз швидко та об'єктивно. Всі скупчення, які вивчалися, є в каталозі Панько та Фліна «The Catalogue of Galaxy Clusters and Groups» (2006); інформацію про галактики кожного скупчення взято з каталогу галактик Мюнстерского Червоного Огляду Неба (Унгруче та ін., 2003).

Ми представляємо результат аналізу особливостей лінійних субструктур в 254 багатих скупченнях без ознак концентрації до центру скупчення, 178 скупченнях з помірною концентрацією до центру, 28 скупченнях з високою концентрацією до центру та 112 скупченнях, які розташовані в областях найбільшої густини галактик. У всіх випадках доля скупчень, в яких присутні лінійні субструктури, складає приблизно 50%, що співпадає з результатами комп'ютерних симуляцій та дає можливість вважати такі субструктури регулярними.

В роботи запропоновано детальну класифікацію скупчень галактик з лінійними субструктурами. Новий підхід дає можливість виділити серед таких скупчень такі, що мають дійсно лінійні особливості або відповідають випадку розташування двомірної субструктури вдовж проміню зору.

Ключові слова: галактики, скупчення галактик, морфологія.

1. Introduction

The morphology of galaxy clusters is the accessible key to understanding the evolution of the Universe as well as to distribution of DM. Distribution of galaxies both in the space and on the celestial sphere reflected the primordial adiabatic fluctuations in beginning moments of Universe, as it shown in big number of works from Silk (1968), Peebles & Yu (1970), Sunyaew & Zeldovich (1970). The results of different numerical simulations from well quoted Millennium Simulation (Springel et al., 2005) to Illustris Project (Vogelsberger et al., 2014; Artale et al., 2017) or Cui et al. (2018) show galaxy clusters as evolved elements of large scale structure of the Universe. Galaxy fraction is smallest part in cluster mass, nevertheless galaxies were and remain the confident optical markers of structure of clusters. The connection between distributions of main components of galaxy clusters – DM, hot gas and galaxies – was established by Dietrich et al. (2012) for A222 and A223 clusters. Their galaxies form linear substructure which duplicate the hot gas bridge and DM arch between the interacted clusters. The another case – collided galaxy clusters show different distribution of intercluster galaxies, hot gas and DM (Markevitch et al., 2004, Pearce at al.,2017).

The distribution of galaxies can be described as their morphology. Based on classical approaches, including both famous Bautz – Morgan (1970), Rood – Sastry (1971) systems and less popular López-Cruz & Gaztanaga (2001) and López-Cruz (2003)ones, Panko (2013) proposed improved and integrated scheme of morphological classification for $2D$ distribution of galaxies on the celestial sphere. According to the Panko scheme, galaxy clusters have types corresponding to cluster "concentration" (from C – compact, to I – intermediate, and O – open), "flatness signs" (L – line or F – flat, and no symbol if no indication of flatness is present) and the role of bright galaxies (cD or BG, if the bright cluster members role is significant). Other peculiarities are noted as P. "Flatness signs" can correspond to filamentary substructure or preferential plane in cluster. The designations can be combined, for example CFcD or ILP.

The Cluster Cartography set (hereafter CC) was created for simplification of the galaxy clusters classification (Panko & Emelyanov, 2015). As a result, it was established the linear substructures present as peculiarities in about 50% of rich galaxy clusters. We can assume the linear substructures are regular peculiarities in galaxy clusters.

The paper is organized in the standard manner. Section 2 contains the description of the observational data and the cluster mapping, section 3 presents the characters of linear substructures and its analysis, and section 4 conclusions and analysis is given at the end.

2. Observational base and the method of analysis

The main base of our research is the list of galaxies of Münster Red Sky Survey (Ungrihe el., 2003, hereafter MRSS). It's a result of scanning of 217 plates of Southern Sky Atlas R (ESO) by $PDS2020GM^{plus}$. The classification of objects into stars, galaxies, and perturbed objects was done by an automatic procedure with a posterior visual check of the automatic classification, which considerably diminished the number of objects erroneously classified as galaxies. External calibration of the photographic magnitudes was carried out by means of CCD sequences obtained with three telescopes in Chile and South Africa. The catalogue of galaxies MRSS is complete to a magnitude limit of $r_F = 18^m.3$. Each form more than 5 millions of MRSS galaxies have equatorial coordinates, r_F magnitude, axes and position angle of best-fit ellipse and some another parameters. Unfortunately, MRSS is last photographic catalogue and their galaxies have not redshifts.

About 1.2 millions of galaxies are in the limit of MRSS complexness. This short list was the observational base of "The Catalogue of Galaxy Clusters and Groups" (Panko & Flin, 2006, hereafter PF catalogue) which was created for statistical study of galaxy clusters properties. PF galaxy clusters having 100 and more galaxies in cluster field we consider as rich ones.

For each PF galaxy cluster we have the list of galaxies in cluster field and each galaxy have full information from MRSS. In our research the data for each galaxy in the cluster are transformed to CC format. Real sizes of galaxies are so small for using in CC mapping. So, the symbols corresponded to galaxies are calculated from magnitudes and ellipticity as:

$$m' = 3 \cdot 2^{0.6(18.5-m)} + 6 \tag{1}$$

$$2a = \frac{m'}{\sqrt[4]{1-2E+E^2}}; \quad 2b = \frac{(m')^2}{2a} \tag{2}$$

were $2a$ and $2b$ are sizes of major and minor axes of symbol; ellipticity $E = 1 - \frac{b}{a}$. The equations (2) transform the circle to ellipse with the same area and connect symbol axes with galaxy magnitude.

The coefficients in the equation 1 were determined for MRSS galaxies and can be changed in case of using another input data. For CC standard map size – 4000×4000 *arcsec* – the symbol sizes calculated according to the equation 1 are optimal for visual control.

Last modification of CC set allows to exclude the central part of cluster in estimation of the degree of concentration to the main band. The degree can be noted as 5, 7, 9, 11, where numerals corresponds the band width relative to cluster diameter (1/5, 1/7, 1/9, 1/11). So we can replace marks F and L to $L5...L11$ (Fig. 1).

The distribution of densities in the bands is calculates taking to account both the square of each band and full number of galaxies in the cluster.

3. The results and discussion

In our previous study we analyzed the $2D$ the distribution of galaxies in the galaxy clusters on the celestial sphere using CC set according to the improved scheme of morphological classification (Panko, 2013, Panko, 2015). We studied 254 rich open (Panko &

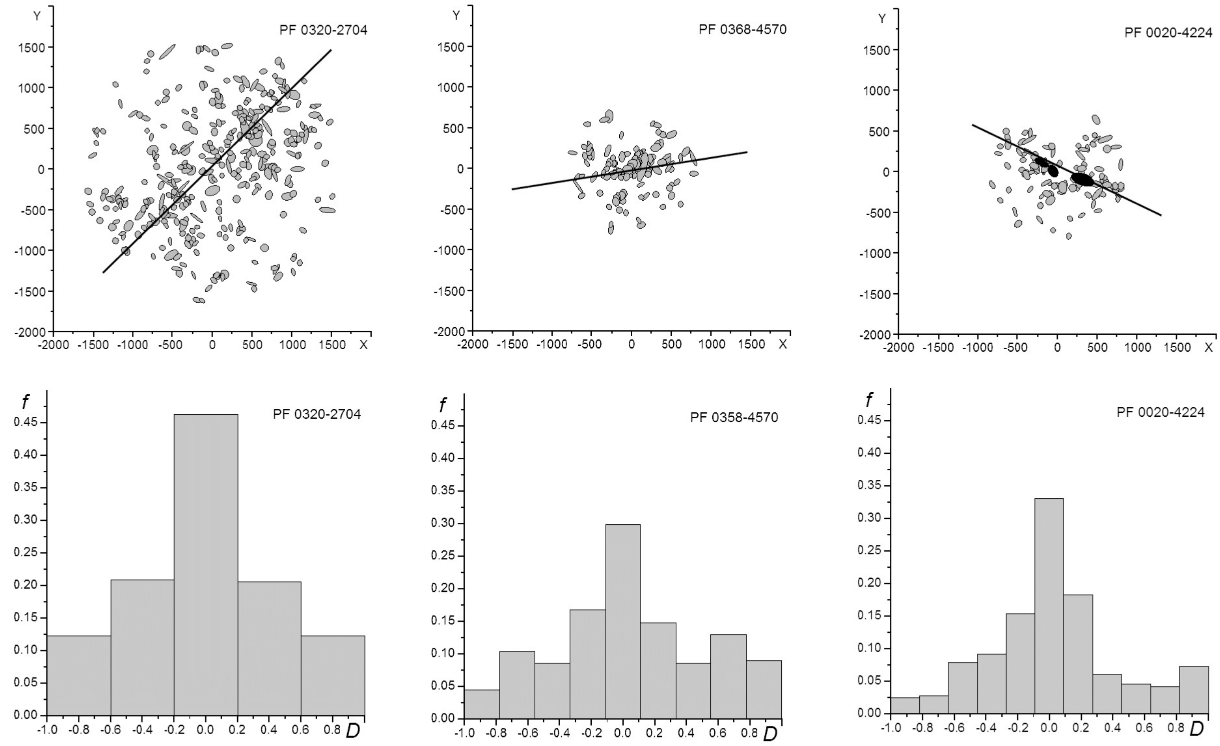

Figure 1: From left to right: maps and distribution of density of galaxies in bands for $L5$, $L9$ and $L11$ subtypes. In case PF 0368-4570, O-type, the central region was excluded.

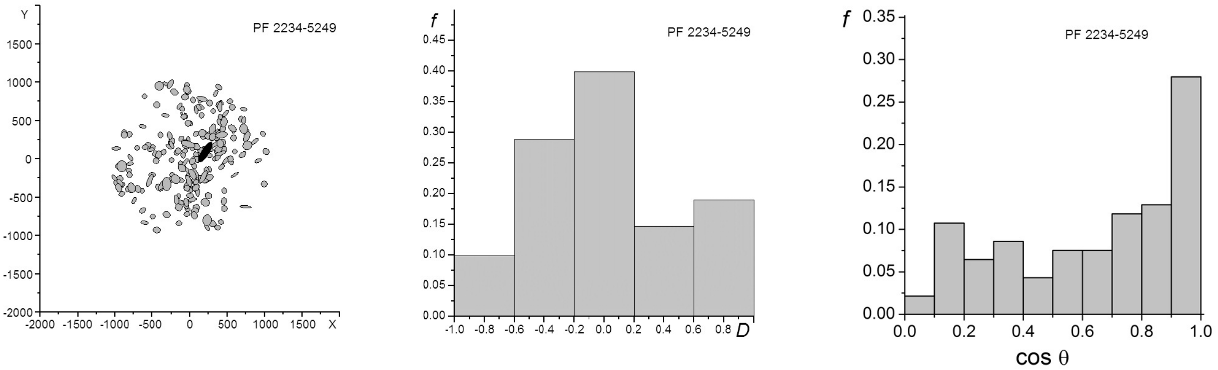

Figure 2: Orientation of galaxies in densest band in PF 2234-5249 cluster. From left to right: map, distribution of density of galaxies in the bands, corresponded to $L5$ subtype and distribution of cosines of acute angles between the direction of $L5$-line and all galaxies inside the central (main) band.

Emelyanov, 2017, Panko et al., 2018), 178 rich intermediate (Panko et al., *in preparation*) and 28 rich concentrated galaxy clusters (Panko et al., 2018), as well as 112 ones placed in richest regions of southern sky (Panko et al., *in preparation*). Our experience allows us to simplify and to specify the detailed classification of linear substructures as $L5...L11$. Connection between hot gas distribution and linear substructure for our input data was found by Tugay et al. (2016) for PF 2187-1958 cluster. In this case the overdense strip has the same direction as major axis of the elongated X-ray halo. The same situation was observed by Mann & Ebeling (2012) in evolved galaxy clusters MACS J0416.1-2403 A2744, A2813, MACS J0358.8-2955; L type according Panko, (2013) morphological scheme or $L9$ - $L11$ according to present paper.

As one can see on Fig. 1, linear substructures are statistically significant, however, the orientation of galaxies in different clusters note the possible presence in cluster filamentary substructures as well as wall-like ones. For filamentary substructures major axes of galaxies in the projection to the celestial sphere are alignment to the direction of the densest band, as it clearly seen in Fig. 2 (PF 2234-5249, $L5$ subtype). In the right panel the distribution of cosines of acute angles between the direction of $L5$-line and all galaxies inside the central band points to statistically significant prevalence for small angles (values of cosine from 0.9 to 1.0). The filamentary substructure in the PF 2234-5249 cluster is curbed, it is seen both in the map and in the histogram on central panel. Trend to alignment of major axes one can note for values of cosine from 0.4. Scatter of cosines in 0.1 to 0.4 bins is connected with small ellipticities of images of galaxies. In this case we have big errors for position angle values. This case corresponds to Joachimi et al.(2015) in full: in $3D$ simulation elliptical galaxies tend to align their major axes with the filament direction, while disc galaxies tend to align their spin perpendicular to the filament direction. For both cases we have the alignment of images of galaxies to to the filament direction.

Another case, described in Joachimi et al.(2015) paper too, is described the galaxy alignments at the surface of a void (wall). Elliptical galaxies tend to align their major axes perpendicular to the radius vector from the center of the void, while disc galaxies tend to align their spin along this direction. We found this case in our data set too. In Fig. 1, left panel, we see different orientations of galaxies in densest band in PF 0320-2704, $L5$ subtype. We can assume in PF 0320-2704 we see edge-on wall.

4. Conclusion

We have constructed the scheme for detailed description of filamentary substructures in galaxy clusters. Our multifactorial analysis the morphology of clusters allows to divide galaxy clusters having the linear substructures for subtypes, described them in details. Linear substructures are regular substructures in galaxy clusters. Our approach allows to select galaxy clusters with possible peculiarities in hot gas and/or DM distribution. We have possibility to divide filamentary and edge-on wall substructures also.

Acknowledgements. This research has made use of NASA's Astrophysics Data System.

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