Galaxy clusters, their components and evolution

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This review summarizes the properties of galaxy clusters and their main components as well as morphology and peculiarities connected with co-evolution of clusters main components.

1 Introduction

Galaxy clusters are huge structures suitable for study of the common properties of the Universe. The large scale structure (LSS) of the Universe is determined by primordial density fluctuations. The LSS elements corresponding to overdense regions we observe as concentration of galaxies. Voids and supervoids on the contrary are the elements of a large scale structure of Universe with depressed density. The galaxy clusters are the element in the chain: galaxies with satellites ⇒ “local groups” of galaxies ⇒ groups of galaxies ⇒ clusters of galaxies ⇒ superclusters of galaxies ⇒ large scale structures such as filaments and walls. All links in the chain excluding superclusters, filaments and walls have virialization time less than the age of Universe. The greatest galaxy clusters contain thousands of galaxies, however difference between clusters and superclusters consists not only in richness and size. Galaxy superclusters – structures larger than clusters – are bound by own zero-accelerated surface, however they have not had a time to virialize. So, we can observe the evolution of groups and clusters of galaxies and the forming features of the largest structures. It can be a key for the solving the common problem of the LSS formation.

At present the most realistic self-consistent ΛCDM model describes the Universe as spatially, homogeneous and isotropic one in a large scale. In the model the structures were formed from the primordial adiabatic, nearly scale invariant random fluctuations (beginning from Silk, 1968; Peebles & Yu, 1970; Sunyaev & Zeldovich, 1970). Both theoretical predictions and various numerical simulations (see famous Millennium Run Springel et al. 2005; or van de Weygaert & Bond 2008a,b papers and detailed “The EAGLE project” – Schaye et al. 2015), point to possibility to find the evolution signs in observations of the galaxy clusters. Note that some superstructures, in particular, Hercules-Corona Borealis Great Wall (Horvath et al., 2014), Giant GRB Ring (Balázs et al., 2015), Huge Large Quasar Group (Clowes et al., 2013), KBC Void (Keenan et al., 2013), Giant Void or Canes Venatici Supervoid (Kopylov & Kopylova, 2002) Caelum Supercluster (SCl 59) (Einasto et al., 2001) were discovered during last decades. Structures of such sizes (from 300 to 3000 h^{-1}Mpc) initiate the next stage in study of the Universe.

The history of our imaging of galaxy clusters from the first list of 6 nebulae by Edmond Halley and the Messier Catalogue to Abell’s 2712 northern galaxy clusters is described in detail by Biviano (2000). The modern view on galaxy clusters summarized by Flin et al. (2008). Short review of galaxy clusters and their principal components were presented at the Second Cosmology School Introduction to Cosmology (Panko, 2017).

2 Main components of galaxy clusters

Galaxy clusters, self-gravitating massive systems contain thousands galaxies, however the main component of the clusters is not galaxies. Typical size of galaxy cluster is approximately $4h^{-1}$Mpc, and mass around $10^{14}-10^{15}h^{-1}M_{\odot}$. Velocity dispersion of cluster members is $500-800$ km s^{-1} and galaxies on the outskirts of a cluster have only made several orbs of the cluster. Virialization time for galaxy clusters is about 10^9 yrs, it is less than the Hubble time. On this large time scale, as a rule, components have not had a chance to separate during collapse and a cluster is probably a representative sample of the Universe. Most distant galaxy clusters IDCS J1426.5+3508 with $z = 1.75$ (Mo et al., 2016) and CL J1449+0856 with $z = 2.00$ Gobat et al. (2013) can be assumed to be the oldest observed one.

Interactive and colliding clusters allowed to show clusters as evolving objects. For the first time colliding 1E 0657-558 Bullet cluster allows to observe separate moving hot gas and DM (Markevitch et al., 2004). A giant collision of several giant galaxy clusters (the region is collectively known as Abell 2744), generated shock waves seen as bright radio and X-ray emission (Pearce et al., 2017). Giant Kelvin-Helmholtz instability in a hot gas in Perseus Galaxy Cluster as well as Centaurus and Abell 1795 ones (Walker et al., 2017) testify to the evolution too. So we have an evidence that the galaxy clusters are not finally evolved. From another hand, in the cluster we see a large number of galaxies at the same distance and in an interaction. It is a proper place to look for environmental effects on galaxy formation and evolution.

The four principal constituents of the clusters include:

- galaxies;
- intracluster gas;
- intracluster stars;
- dark matter.

The interaction of all cluster components determines the observed properties of clusters and their evolution. Note, that the youngest galaxy clusters may not be fully virialized.

2.1 Galaxies in galaxy clusters

At the optical wavelengths the galaxy clusters were identified as over-densities of galaxies with respect to the field average density from the time of the first study of sky nebulae distribution. Note, W. Herschel describing about 2500 nebulae drew attention to their non-random distribution in the sky. He gave relevant description “the nebulous stratum of Coma Berenices”, well studied Coma Cluster at present, and recognized several other nearby clusters of galaxies, such as Leo, Ursa Major, Hydra, etc. (for details see Biviano, 2000). So galaxy fraction is well studied component of clusters.

2.2 Hubble mix in galaxy clusters

Shapley (1926) was the first who noted connection of Hubble type of galaxies and the spatial density of galaxies: elliptical and lenticulars (early-type) galaxies tend to reside in the high-density regions, whereas spiral (late-type) galaxies are more common in the low-density regions. de Vaucouleurs (1963) studied distribution of galaxies by the Hubble types and found that the fraction of irregular galaxies grows for faintest galaxies. One can assumes that it is a sign of evolution of the Hubble mix with density variations and time. Variations of ratio ellipticals to spirals allows to connect the difference between Oemler's "spiral rich", "spiral poor" and "cD" clusters with clusters morphology and age. Oemler' approach (Oemler, 1974) was improved in Butcher & Oemler (1978, 1984) papers. They directly noted the evolution of galaxies in the clusters: the fraction of blue galaxies is found to be higher in distant clusters ("Butcher-Oemler Effect").

Dressler (1980) studied the morphology of galaxies in 55 nearest clusters and in 15 background fields. He found the variations of fraction of elliptical galaxies according to density of galaxies in the clusters, named "the Morphology vs Density Relation" (MD). So, the MD relation varied both with density and distance. Variations of MD relation for field galaxies was studied by Hammer et al. (2005); Delgado-Serrano et al. (2010); Mortlock et al. (2013) and for galaxies in clusters by Fasano et al. (2000). Panko & Flin (2014) found the variation of MD relation connected with both local density and distance in PF clusters (Panko & Flin, 2006); they also noted about non-uniform way of the galaxy evolution. Houghton (2015) found dependence of fraction of ellipticals from an average local density: clusters with the highest ellipticals fraction have the lowest average local densities. cD galaxies are only in the central part of evolved galaxy clusters, probably they formed by merging of usual galaxies in the central densest regions of clusters.

2.3 Luminosity functions in galaxy clusters

The luminosity function (LF) of galaxies in a cluster gives the number distribution of the luminosities of the galaxies. The integrated luminosity function $N(L)$ is the number of galaxies with luminosities greater than L, while the differential LF $n(L)$ gives is the number of galaxies with luminosities in the range from L to $L + dL$. Obviously, $n(L) = -dN(L)/dL$. LF are often defined in terms of galaxy magnitudes $m\ -2.5\log_{10}(L)$; and $N(\leq m)$ is the number of galaxies in a cluster brighter than magnitude m. Sure, LF depends upon Habble mix in cluster.

LF contains information about:

– primordial density fluctuations;

– processes that destroy/create galaxies;

– processes that change one type of a galaxy into another (e.g. mergers, stripping etc);

– processes that transform mass into light.

According to Biviano (2000), for the faint cluster members integrated LF can be described as logarithmic function proposed by Abell or Zwicky, however for brightest galaxies this approach does not work. The real LF is described by Schechter (1976) function, based on Press & Schechter's physical model: $N(L) = N^{\star} \cdot \Gamma(\alpha, L/L^{\star})$, were $L^{\star}$ is a characteristic luminosity, $N^{\star}$, is the number of galaxies with $L > L\star$,

$\Gamma(\alpha, x)$, is the incomplete gamma function, and $\alpha = 5/4$ for the faint end of the slope (Press & Schechter, 1974; Schechter, 1976). The Schechter function fits the observed distribution reasonably well from the faint to the bright end, as soon as the very bright galaxies, the cD galaxies, are excluded. The classical approach for LF in optical, radio and infrared for galaxies and galaxy clusters was reviewed by Dickey (1988).

2.4 Intracluster gas in galaxy clusters

Intracluster medium presence became strongly needed from the moment when Zwicky (1933) at first estimated the mass of a galaxy cluster. He noted that observed dispersion in the radial velocity of the galaxies in the Coma cluster was very large and the gravity provided by the luminous matter in the cluster was not enough to hold the cluster together. Zwicky (1933, 1937) dynamical analysis of clusters showed that there must exist much more gravitational material than indicated by the stellar content of the galaxies in the cluster. This was the first evidence of the presence of invisible matter in galaxy clusters.

Invisible in optic gas was on 1966 detected as X-ray emission from the region around the galaxy M87 in the center of the Virgo cluster (Byram et al., 1966; Bradt et al., 1967). Five years later, X-ray sources were also detected in the directions of the Coma and Perseus clusters (Fritz et al., 1971; Gursky et al., 1971; Meekins et al., 1971). Since these are three of the nearest rich clusters, it was suggested that clusters of galaxies might generally be X-ray sources (Cavaliere et al., 1971). Extended X-ray emission from clusters of galaxies was first observed in the early 1970's (Voit, 2005).

The launch of the Uhuru X-ray astronomy satellite permitted a survey of the entire sky for X-ray emission (Giacconi et al., 1972) and established that this was indeed the case. Early Uhuru observations indicated that many clusters were bright X-ray sources, with luminosities typically in the range of $10^{43} - 10^{45}$ erg s^{-1}. The first all sky X-ray survey, with the Uhuru satellite discovered X-ray emission from clusters as a class (Gursky et al., 1972), see also review by Sarazin (1988).

High resolution observations with Chandra show that many clusters have substructure in the X-ray surface brightness: hydrodynamical equilibrium is not a good approximation, clusters are still forming (Sanders et al., 2013).

The origin of the X-ray luminosity was very early interpreted as thermal Bremsstrahlung from a hot intracluster plasma (Felten et al., 1966). The X-ray spectra dominated by the thermal emission from the hot gas, but in some cases there appears to be evidence for hard X-ray tails or soft X-ray excesses. Hard X-ray tails are difficult to detect, and one of the topics for the team is a discussion on the significance of this detection (yet contradictory) in existing and future space experiments. Various models have been proposed to produce these hard X-ray tails, and our team reviews these processes in the context of the observational constraints in clusters.

In the early Universe most of the gas was relatively cool (10^4 K) and detectable through the numerous absorption lines, designated as the so-called Lyman-alpha forest. In the present Universe, however, about half of all baryons are predicted to be in a warm phase ($10^5 - 10^7$ K). In galaxy clusters gas has temperatures approximately $10^7 - 10^8$ K, density $10^{-3}\mathrm{cm}^{-3}$, and is in hydrostatic equilibrium. Temperature inside is not uniform, there are the numerous "hot spots" associated with galaxies or connected galaxies Sanders et al. (2013). In densest regions, gas may cool down and sink toward the cluster center as a "cooling flow". More about hot gas in galaxy clusters is in reviews by Sarazin (1988); Forman & Jones (1990); Böhringer & Werner (2010).

X-ray luminosity of hot intracluster gas is about $10^{43} - 10^{46}$ erg s^{-1} allows to detect the galaxy clusters in the range of z from 0.05 to 1.05. The number of the detected X-ray clusters is around 5000 now with 500 ones with measured temperatures and Fe abundances. Intracluster gas is the chemically enriched relatively to the primordial by about ≈ 0.5 of the Solar abundance (Werner et al., 2008b).

X-ray luminosity is one more classification parameter: no X-ray (nXD) with low X-Ray luminosity ($< 10^{44}$ erg s^{-1}) and X-ray (XD) with high X-ray luminosity ($> 10^{44}$ erg s^{-1}) (Jones & Forman, 1984). The examples for XD and nXD clusters are A262 (BM III) and A1367 (BM II-III) respectively.

Another way to detect plasma inside the galaxy clusters is the use of Sunyaev-Zeldovich effect: distortion of the microwave background due to photon scattering on electrons in the cluster: we can estimete the concentration of electrons. One of the more massive distant galaxy cluster SPT-CL J0546-5345 was detected using SZ effect and spectroscopically confirmed Brodwin et al. (2010). It is situated in Pictor constellation, at $z = 1.067$, the velocity dispersion for cluster members is 1179^{+232}_{-167} km s^{-1} and the best-estimated mass is $M = (7.95 \pm 0.92) \times 10^{14} M_{\odot}$. One more distant galaxy cluster CL J1449+0856 was detected by XMM-Newton at $z = 2.00$ (Gobat et al., 2013).

Comparison of optical and X-ray luminosities leads to the next estimate: galaxies in a cluster are the smallest fraction. $80 - 90\%$ baryons in a cluster are in the X-ray emitting plasma. Tugay et al. (2016) compare the orientations of extended elliptic X-ray haloes with orientations of major axes of elongated corresponded PF clusters. It was shown that the galaxies and gaseous halo in clusters are involved in significant gravitational interaction, the processes of cluster evolution continue in the current cosmological era.

2.5 *Intracluster stars in galaxy clusters*

Intracluster stars are seen as very faint, in level 1% above the sky brightness, diffuse light (distinct from cD halo light) and comprises $10 - 50\%$ total galaxy light in rich clusters; intracluster stars diffuse light is much less in poor clusters. The stars are probably tidally stripped from galaxies. Zwicky in 1951 first noted about the presence an extended mass of luminous intergalactic matter of very low surface brightness in Coma cluster. Gregg & West (1998) confirmed the existence of the features with extremely low surface brightness: $> 27^{\mathrm{m}}$ arcsec^{-2} in R band. They also discovered intracluster red giant stars and intracluster planetary nebulae in Virgo and Fornax, up to $\approx 10 - 30\%$ of the total cluster light (see also Vílchez-Gómez, 1999, for review).

Deep image of Virgo cluster was obtained by Mihos et al. (2005). They found that intracluster light is not radially symmetric around M87, the nominal central galaxy of Virgo; much of the diffuse light is centered upon the M84/M86 complex. The diffuse halo of M87 they traced out to nearly 200 kpc. It was confirmed by Doherty et al. (2009). Intracluster light properties are reviewed by Mihos (2015).

Intracluster stars and intracluster medium are least significant component in evolution of clusters. They could be important for determination of full cluster mass, however all visible in electromagnetic spectrum fractions of the galaxy clusters (galaxies, intracluster gas and intracluster stars) do not correspond to their mass estimates.

2.6 Dark matter in galaxy clusters

In Zwicky's classical papers (Zwicky, 1933, 1937), it is indicated about existence of the DM dominance (originally called "missing matter") in the Universe. In the early 1970's (Rood, 1974) the first detailed estimations of cluster masses were obtained using the velocity dispersion of the galaxies via the virial theorem. This analysis showed that clusters of galaxies are objects with dominated DM. Thus the issue of the "missing mass" or "dark matter" became the central in the cluster research.

We can detect the DM only as gravitating mass, both barionic and nonbarionic. At the same time barionic fraction is detected as the light-emitting fraction too. Dark matter can be divided into cold, warm and hot categories. Cold dark matter, CDM, leads to a "bottom-up" formation of structure while hot dark matter, HDM, would result in a "top-down" formation scenario. The properties of galaxy clusters support the CDM presence, which is dominated in galaxy clusters.

Besides velocity distribution, we can detect the DM evidence, abundance and distribution from strong gravitational lensing – the distortion of background galaxy images as light passes through the cluster. First evidence of DM was obtained for MACS J0025.4-1222 the Bullet Cluster (Markevitch et al., 2004). Later 72 galaxy clusters gave us the same evidences, 6 famous are MACS J0416.1-2403, MACS J0152.5-2852, MACS J0717.5+3745, Abell 370, Abell 2744 and ZwCl 1358+62 (Harvey et al., 2015).

Weak gravitational lensing leads to distant background galaxies suffer slight distortion by matter along the line of sight intervening clusters give slight azimuthal image elongation. For a big sample of galaxies it is statistically detectable and allows mapping of intervening mass distribution.The most distant cluster detected by a weak gravitational lensing, IDCS J1426.5+3508, have $z = 1.75$ (Mo et al., 2016).

Dietrich et al. (2005) report about the detection of the DM filament connected A222 and A223 clusters and corresponding bridge of hot, low-density gas (Werner et al., 2008a; Dietrich et al., 2012). More results are in Dark Energy Survey (Chang et al., 2018).

3 Mass Functions of galaxy clusters

The cluster mass function (MF) represents the number of galaxy clusters with masses $N(M > M^{\star})$, and describes the number density of clusters above a threshold mass $M^{\star}$. It can be used as a critical test of theories of structure formation in the Universe. The richest, most massive clusters are thought to form from rare high peaks in the initial mass-density fluctuations; poorer clusters and groups form from smaller, more common fluctuations. If the power spectrum of the primordial perturbations of the mass density field in the early Universe is a power law with index n, the number per unit volume $[dn(M)/dM]dM$ of galaxy systems with total mass in the range $(M, M + dM)$ is described according to Press & Schechter (1974).

The observed cluster mass function (in comparison with expectations from different CDM cosmologies using large-scale simulations) is indeed a powerful discriminant among models. A low-density CDM model, with $\Omega \approx 0.2 - 0.3$ (with or without a cosmological constant), appears to fit well the observed cluster MF (Bahcall & Cen, 1992) and modern approach with $\Omega = 0.12$ (Reiprich & Böhringer, 2002).

4 The morphology of galaxy clusters and signs of evolution

Morphological classification of galaxy clusters is based mainly on $2D$ distribution of galaxies, primarily on Palomar Sky Survey. Classification schemes of galaxy clusters take into consideration several their properties: visual shape, richness, lumpiness, Hubble mix, dominant galaxy types, etc. Beginning approach was: "rich" clusters vs. "poor" clusters, "regular" vs. "irregular" clusters (Abell, 1958) and separation to "compact", "medium-compact" and "open ones" (Zwicky et al., 1961, 1963, 1966, 1968).

The prevalent Bautz-Morgan (BM) classification scheme (Bautz & Morgan, 1970) is based on the relative contrast (dominance in extent and brightness) of the brightest galaxy to other galaxies in the cluster, ranging from type I to III in decreasing order of dominance. The Rood & Sastry (RS) system (Rood & Sastry, 1971) classifies clusters based on the geometry of the distribution of the ten brightest members (from cD, to binary B, core C, line L, flat F, and irregular I). The Rood-Sastry and Bautz-Morgan schemes are in agreement and complement each other. Oemler (1974) recognized three types of cluster : "spiral rich", "spiral poor" and "cD". Than, López-Cruz et al. (1997) and López-Cruz (2003) introduced the definition of a cD cluster, the complement to this class is called a non-cD cluster. The main properties of clusters and groups of galaxies are summarized by Bahcall (1999); see also Panko (2013, 2015).

The last 2D high-quality catalogue of galaxies (MRSS) based on Münster Red Sky Survey covers an area of about 5000 square degrees with galactic latitudes $b < -45°$; it is complete to a magnitude limit of $r_{\mathrm{F}} = 18^{\mathrm{m}}.3$ (Ungrue et al., 2003). It allowed to create "The Catalogue of Galaxy Clusters and Groups" (Panko & Flin, 2006, PF catalogue) for statistical study of galaxy clusters properties. The lists of galaxies in cluster field created for each cluster allow to study the cluster morphology. Panko (2013), by taking into consideration the input data, summarized the classical schemes and proposed adapted morphological classification for galaxy clusters. The new types can be assigned corresponding to "concentration" (C - compact, I - intermediate, and O - open), "flatness" (L - line, 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 were 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.

Taking into account both Rood & Sastry (1971) "tuning-fork" and revised later classification scheme by Struble & Rood (1982) we can consider clusters with different morphology as clusters on difference stages of evolution. Panko (2013) scheme allows to describe cluster evolution in details – from young clusters without concentration to the center to old ones with compact and overdense core. It can be in short way:

$O \Rightarrow I \Rightarrow C$, or, through filamentary substructures inside the cluster:

$O \Rightarrow OF \Rightarrow IF \Rightarrow CF \Rightarrow C$,

$O \Rightarrow OF \Rightarrow OL \Rightarrow IL \Rightarrow C$. Peculiarities in clusters indicate to an interaction

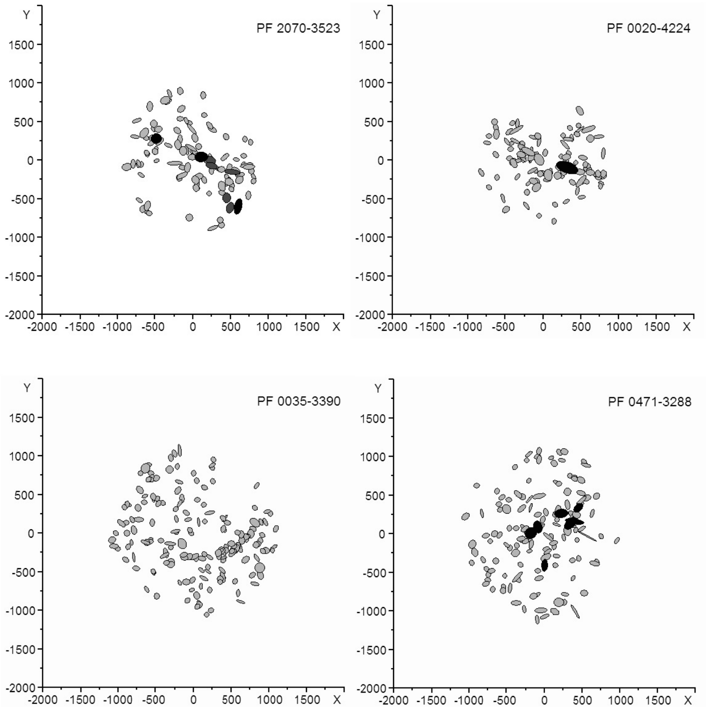

Fig. 1: *PF* galaxy clusters as examples of peculiar clusters: ones with cross belts (upper panel), curved strip and Y-type substructure (bottom panel). Cluster maps are constructed in arcseconds, the size of symbol corresponds to the magnitude of galaxy. The shape and orientation of each symbol correspond to those noted in MRSS.

with neighbours of peculiarities in DM distribution. The more interesting peculiarities are crossing the two overdense belts (Panko & Emelyanov, 2017); Y-type or curved overdense region; the alignment of brightest galaxies along to the main belt or both belts; the positions of tree and more bright cluster members are connected with overdense regions (Fig. 1). The maps of *PF* galaxy clusters (Panko & Flin, 2006) were constructed in arcseconds using magnitudes, shapes and orientations of galaxies acoording to MRSS data. One can name they as regular peculiarities, indicating the special, non-uniform distribution of DM.

5 Conclusion

If a clusters are evolved huge structures, we can observe simple relations between old clusters global properties, namely mass, richness, galaxy distribution (morphological type) and velocity dispersion, Hubble mix, X-ray luminosity, intracluster gas temperature, etc. Younger clusters have involved morphology, non-uniform distribution of radiative matter and (possibly) DM; relations between old clusters global properties vary. This allows us to create scenarios for cluster evolution and check the correctness of the large-scale simulations.

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