The Structure of Galaxy Clusters: Principal Components

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This review summarises the properties of galaxy clusters and their components, namely cluster morphology, richness, morphological types of cluster members and their morphology-density relation, velocity dispersion and mass of clusters, intra-cluster gas and stars, and also Dark Matter in the clusters.

1 Introduction

Galaxy clusters are an element of the large-scale structure of the Universe. They are part of a continuous range of large-scale construction of the Universe: galaxies ⇒ "local groups" of galaxies ⇒ groups of galaxies ⇒ clusters of galaxies ⇒ superclusters of galaxies ⇒ large scale structure. "Local groups" are the smallest aggregates of galaxies.They contain 3 − 5 − 10 big, bright, regular galaxies with dwarf satellites, like our Local Group, or the binary IC 342 − Maffei 1 Group (Karachentsev, 2005). The Local Galaxy Group contains the Milky Way, Andromeda (M31, the largest galaxy in the group) and Triangulum galaxies (M33) and more than 50 satellite small galaxies. The radius of the zero-acceleration surface around the Local Group is typical of these objects − about 2 Mpc (Dolgachev et al., 2003). For distant observers "local groups" appear as binary/triple/multiple galaxies; the satellites are too faint to be registered. So, we can assume "local galaxy groups" contain 3 to 10 bright galaxies; galaxy groups contain from 10 to 30 bright galaxies; galaxy clusters contain from 30 to 300 and more bright galaxies. Galaxy clusters are rare extremes in the galaxy distribution, with local overdense $\Delta\rho/\langle\rho\rangle \sim 10^3$. Both groups and clusters of galaxies form filaments, walls and superclusters.

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 of galaxy clusters summarized by Flin et al. (2008).

2 Galaxy clusters − common information

Galaxy clusters, self-gravitating systems of mass $\sim 10^{14} - 10^{15} h^{-1} M_\odot$ and size $\sim 1 - 4h^{-1}$Mpc, are the largest virialized structures in the Universe. The velocity dispersion of cluster members $\sim 500 - 800$ km s^{-1} and galaxies on the outskirts of a cluster have only made several orbits of the cluster. The greatest galaxy clusters contain thousands galaxies, however difference between clusters and superclusters consists not only of richness and size. Galaxy superclusters − structures larger then clusters − are bound by their own zero-accelerated surface, however they have not had time to virialize. The galactic supercluster virialization time is bigger than the Hubble time: about $10^{10.5}$ yr; in contrast, the virialization time for galaxy clusters is about 10^9 yr, less than the Hubble time. On this large time scale, components have not had a chance to separate during collapse and a cluster is probably a representative sample of the Universe. So, the galaxy clusters have a special place among all large-scale structures. They are small in comparison to cosmological scales, but contain important information about the Universe entirely. This is important when, for example, we measure their Dark Matter (DM) content: $(M_D M/M_{\rm baryons})_{\rm cluster} = (M_{DM}/M_{\rm baryons})_{\rm Universe}$. So, a measurement in clusters can be scaled up to get matter components for the Universe. Furthermore, galaxy clusters are not finally evolved, their evolution at the present time is one more key to understanding of evolution of our Universe. On the other hand, in a cluster we see a large number of galaxies at the same distance and in interactions. It is convenient 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.

3 Galaxies in galaxy clusters

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

3.1 The morphology of galaxy clusters

The distribution of galaxies in the clusters' fields on the celestial sphere allows us to describe the clusters' morphology. Early classifications were made by Abell (1958) and Zwicky et al. (1968). Abell classified galaxy clusters taking into consideration both the number of galaxies and the shape of each cluster. So, the Abell classification scheme is based on two parameters: richness and shape. However, the parameters are interdependent: "Regular" clusters tend to be "Rich" etc. In contrast, Zwicky et al. divided clusters into "Compact", "Medium-Compact" and "Open" according the variations of local density inside the cluster.

Later some authors proposed classification schemes based on one of several possible properties: shape, richness, luminosity, Hubble mix, dominant galaxy types, etc. 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), (revised by Struble

& Rood, 1982) classifies clusters based on the geometry of the distribution of the ten brightest members (from c*D*, 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 (Bahcall, 1999).

Oemler (1974) recognized three types of clusters according to the morphology of cluster member galaxies, “spiral rich”, “spiral poor” and “*cD*”. López-Cruz et al. (1997) and López-Cruz (2003) introduced a more general definition of a cD cluster based around the Rood-Sastry and Bautz-Morgan schemes, the complement to this class is called a non-*cD* cluster. It must reflect the special role of supergiant elliptical galaxies having extra-large extended diffuse envelopes.

The properties of galaxy clusters and groups were summarized by Bahcall (1999). A comparison of classification schemes for galaxy clusters was performed by Panko (2015).

Panko (2013), taking into account the paper by Bahcall (1999), summarized the used classification schemes and proposed an 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 (c*D* or *BG* if the bright cluster members’ role is significant). Other peculiarities were noted as P. “Flatness” signs can correspond to filamentary substructure or a preferential plane in the cluster. The designations can be combined, for example *CF*c*D* or *ILP*. The scheme was created mainly for the galaxy clusters catalogue (Panko & Flin (Panko & Flin, 2006)).

Both the Rood et al. (Rood & Sastry, 1971; Struble & Rood, 1982) and Panko (2013) schemes can be use for study of clusters as evolving objects: the youngest clusters are irregular and open, the oldest are fully virialized, concentrated, compact and have a supergiant *cD* galaxy in the center. The differences in galaxy population – variations of Hubble mix – are significant in the youngest and oldest clusters.

3.2 Hubble mix in galaxy clusters

Shapley (1926) was the first who noted the connection of Hubble type of galaxies with the density of galaxies: elliptical and lenticulars (early-type) galaxies tend to reside in high-density regions, whereas spiral (late-type) galaxies are more common in low-density regions. de Vaucouleurs (1963) studied the distribution of galaxies over Hubble types and found the fraction of irregular galaxies grows for the faintest galaxies. One can assume it is a sign of evolution of the Hubble mix with density variations and time. Variations of the ratio of ellipticals to spirals allows us to connect the difference between Oemler’s “spiral rich”, “spiral poor” and “*cD*” clusters with the clusters’ morphology and age. Oemler’s approach was improved in Butcher & Oemler’s papers (Butcher & Oemler, 1978, 1984). 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 the fraction of elliptical galaxies according to density of galaxies in the clusters, named the Morphology–Density (MD) Relation. So, the morphology-density relation varied both with density and distance. Variations of the MD relation for field galaxies was studied by Hammer et al. (2005), Delgado-Serrano et al. (2010), Mortlock et al. (2013) and galaxies in the clusters by

Fasano et al. (2000). Panko & Flin (2014) found the variation of the MD relation connected with both local density and distance in PF clusters; they also noted the non-uniform way of galaxy evolution. Houghton (2015), found dependence of the fraction of ellipticals from average local density: clusters with the highest elliptical fractions have the lowest average local densities. *cD* galaxies are only in the central part of evolved galaxy clusters, probably they formed by merging of typical galaxies in the central densest regions of clusters.

3.3 Luminosity Functions in galaxy clusters

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

The LF contains information about:
– primordial density fluctuations;
– processes that destroy/create galaxies;
– processes that change one type of galaxy into another
(eg. mergers, stripping etc);
– processes that transform mass into light.

According to Biviano (2000), for faint cluster members the integrated LF can be described as a logarithmic function as proposed by Abell or Zwicky, however for the brightest galaxies this approach does not work. The real LF is described by the Schechter (1976) function, based on Press & Schechter's physical model: $N(L) = N^\star \cdot \Gamma(\alpha, L/L^\star)$, where $L^\star$ 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 slope (Press & Schechter, 1974; Schechter, 1976). The Schechter function fits the observed distribution reasonably well from the faint to the bright end, as long as the very brightest 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).

4 Intracluster Gas in galaxy clusters

The presence of the intracluster medium became strongly needed from the moment when Zwicky (1933) first estimated the mass of a galaxy cluster. He noted that the 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's dynamical analysis of clusters (Zwicky, 1933, 1937) 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. An invisible (optically) gas was eventually found, but its discovery was essentially serendipitous: rocket flights in the 1960s detected X-ray emission from the direction of the Virgo cluster. Extended X-ray emission from clusters of galaxies was first observed in the early 1970's Voit (2005).

The first all-sky X-ray survey, with the Uhuru satellite, established X-ray emission from clusters as a class Gursky et al. (1972). High resolution observations with Chandra show that many clusters have substructure in the X-ray surface brightness: hydrodynamical equilibrium is not a great approximation, and the clusters are still forming Sanders et al. (2013).

The origin of the X-ray luminosity was very early on interpreted as thermal Bremsstrahlung emission from a hot intracluster plasma Felten et al. (1966). The X-ray spectra are 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 in the web was relatively cool (10^4 K) and visible through numerous absorption lines, designated as the so-called Lyman-alpha forest. In the present Universe, however, about half of all the baryons are predicted to be in a warm phase ($10^5 - 10^7$ K). In galaxy clusters, the gas has temperatures of $10^7 - 10^8$ K, density $10^{-3}\,\mathrm{cm}^{-3}$, and is in hydrostatic equilibrium. Temperatures inside are not uniform, numerous "hot spots" associated with galaxies or connected galaxies Sanders et al. (2013). In the densest regions, gas may cool and sink toward the cluster center as a "cooling flow". It is unlikely that all of it has escaped from galaxies –, some must be around from cluster formation process. More about hot gas in galaxy clusters can be found in the reviews by Sarazin (1988), Forman & Jones (1990), and Böhringer & Werner (2010).

The X-ray luminosity of hot intracluster gas of about $10^{43} - 10^{46}\,\mathrm{ergs\,s^{-1}}$ allows us to find galaxy clusters at z from 0.05 to 1.05. The number of X-ray detected clusters is around 5 000 now, with ~ 500 with measured temperatures and Fe abundances. Intracluster gas is chemically enriched relative to primordial gas up to ~ 0.5 Solar abundances (Werner et al., 2008).

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

Another way to detect plasma inside the galaxy clusters is the Sunyaev-Zeldovich (SZ) effect: distortion of the microwave background due to photons scattering off of electrons in the cluster; from this we can estimate the concentration of electrons. One of the more massive distant galaxy clusters, SPT-CL J0546-5345, was found using the SZ effect and spectroscopically confirmed by Brodwin et al. (2010). It places in Pictor, at $z = 1.067$, the velocity dispersion for cluster members is $1179^{+232}_{-167}\,\mathrm{km\,s^{-1}}$ and best-estimate 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 $z = 2$ (Gobat et al., 2013).

Comparison optical and X-ray luminosity leads to next estimate, that galaxies in clusters are the smallest fraction – around $80 - 90\%$ of the baryons in a cluster are in the X-ray emitting plasma.

5 Intracluster Stars in galaxy clusters

Intracluster stars are seen as very faint (1% over the sky brightness) diffuse light (distinct from *cD* halo light) comprising $10 - 50\%$ total galaxy light (in rich clusters;

much less in poor clusters). The stars are probably tidally stripped from galaxies. Zwicky in 1951 first noted the presence of an extended mass of luminous intergalactic matter of very low surface brightness in the Coma cluster. Gregg & West (1998) confirmed the existence of the features with extremely low surface brightness: $> 27^{\rm m}$ per arcsec^2 in R band. They also discoveries of intracluster red giant stars and intracluster planetary nebulae in Virgo and Fornax, up to $\sim 10-30\%$ of the total cluster light (see also Vílchez-Gómez, 1999, for a review).

Deep imaging of the Virgo cluster was obtained by Chris Mihos et al (Mihos et al., 2005). They found 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. This was confirmed by Doherty et al. (2009). Intracluster light properties are reviewed by Mihos (2015).

However all fractions of galaxy clusters visible in the electromagnetic spectrum (galaxies, intracluster gas and intracluster stars) do not correspond to their mass estimations.

6 Dark matter in galaxy clusters

Zwicky (1933, 1937) papers are also noted as the first discovery of the dominance of *DM* (originally called "missing matter") in the Universe. In the early 1970s Rood (1974) gave the first detailed estimations of cluster masses, obtained using the velocity dispersion of the galaxies via the virial theorem. These analyses showed that clusters of galaxies are objects dominated by *DM*. Thus the issue of the "missing mass" or "dark matter" became central to cluster research.

We can detect the *DM* only as gravitating mass, both baryonic and nonbaryonic. At the same time te baryonic fraction is also detected as an emitting fraction.

Besides the 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. The 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 evidence; 6 famous examples 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 faint background galaxies suffering slight distortion due to matter along the line of sight; intervening clusters give slight azimuthal image elongation. For big sample of galaxies it is statistically detectable and allows mapping of the intervening mass distribution. The most distant cluster founded by weak gravitational lensing, IDCS J1426.5+3508, has $z = 1.75$ (Mo et al., 2016).

Dietrich et al. (2012) found the *DM* filament connected A222 and A223 clusters. 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, *WDM*, would result in a "top-down" formation scenario. The properties of galaxy clusters support the presence of *CDM*, which dominates in galaxy clusters.

6.1 Mass Functions of galaxy clusters

The cluster mass function (MF) represents the number of galaxy clusters with masses $N(M > M^{\star})$, describes the number density of clusters above a threshold mass $M^{\star}$, 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 can be compared with expectations from different CDM cosmologies using large-scale simulations. Observed MF is indeed a powerful discriminant among models. A low-density CDM model, with Ω $0.2-0.3$ (with or without a cosmological constant), appears to fit well the observed cluster MF (Bahcall & Cen, 1992) and with $\Omega=0.12$ (Reiprich & Böhringer, 2002).

Both LF and MF are extremely relevant to constrain the cosmological model because they are a very sensitive indicators of the cosmological parameters.

7 Conclusion

If a cluster is an old, evolved one, we can observe simple relations between its global properties, namely mass, richness, galaxy distribution (morphological type) and velocity dispersion, Hubble mix, X-ray luminosity, intracluster gas temperature, etc. For younger clusters these relations vary. This allows us to create scenarios for cluster evolution and to check the correctness of large-scale simulations.

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