Groups and Clusters

1. Basics

The largest gravitationally bound structures in the universe are massive dark matter halos hosting numerous galaxies. Large mass halos ($M > 10^{14} M_\odot$) are referred to as *clusters*, whereas smaller halos are referred to as *groups*. The virial radii of clusters are around 1–2 Mpc, and the virial velocities are > 700 km s^{-1} and can be up to several thousand km s^{-1}. The gas in these systems reaches temperatures of 10^8 K; it is typically very diffuse, with $n \sim 10^{-3}$ cm^{-3}. The main contents of groups and clusters are galaxies (about 0.03 of the group mass), hot X-ray emitting gas (about 0.15 of the group mass), and dark matter (the remainder).

1.1. Searches for clusters

The first large catalog of clusters was created in the early 1950s by Abell by examining galaxy counts on Palomar plates. More recent methods of finding clusters are:

- Photometric surveys, using photometric redshifts and/or color criteria to mitigate projection effects and find clusters with higher efficiency. Cluster galaxies tend to be red sequence galaxies, a fact that cluster-finders often rely upon.
- Redshift surveys, using more precise three-dimensional redshift information to select clusters.
- X-ray surveys, relying on thermal bremstrahlung emission from hot intergalactic gas in the clusters.
- Sunyaev-Zeldovich effect searches, relying on distortions of background cosmic microwave background light by the hot gas in foreground clusters. Because it is absorption, the SZ effect is dependent on the integrated gas density and is nearly independent of redshift (the redshift dependence comes in only through the angular resolution of the CMB observations).

In principle, one can search for clusters in weak lensing maps as well, though to date this method is not practical.

1.2. Sizes of clusters

1.3. Galaxies in clusters and groups

Clusters contain numerous galaxies. They often have a dominant central, most luminous galaxy, which is termed a *brightest cluster galaxy (BCG)*. Often but not always, BCGs can be classified as *cD* galaxies; this terminology refers to the existence of an extended stellar halo, usually with an r^{-2} radial profile. cD does not stand for "central dominant."

The galaxy population varies with environment, and the larger groups and clusters preferentially contain more massive galaxies and (even at fixed galaxy mass) the red sequence population of galaxies. It is convenient to understand this trend in terms of *central* galaxies and *satellite* galaxies inside of the cluster host halos. Central galaxy masses are roughly monotonically related to the halo masses, though their color distribution does not appear strongly related to halo mass. Satellite galaxy masses also increase with host halo mass (since they are generally smaller than the central galaxy), and in addition the larger the host halo the more prominent the red galaxy population.

In general, the scaling relations for galaxies in clusters are very similar to those of isolated galaxies, with some differences. Elliptical galaxies lie on a slightly different fundamental plane and have slightly different stellar populations at a fixed mass. Both effects are consistent with a slightly older population in clusters. Whether this is because star formation is truncated earlier in these populations or because it started earlier is not clear.

Spiral galaxies have HI disks which are somewhat truncated relative to spiral galaxies in the field, an effect known as *HI deficiency.* This truncation is likely due to ram pressure stripping in the clusters.

For many clusters, the cD galaxy halo contains an enormous number of intergalactic stars. These halos are very low surface brightness but can contain around 50% of the total stellar mass of the cluster. They have been studied in some detail for Coma and Virgo, and in both cases exhibit streams and other tidal structures. They appear to be similar in age and metallicity to the galactic stellar populations. These facts appear consistent with the intergalactic population having been tidally stripped from satellite galaxies, many of which may have been completely disrupted.

These trends exist at least down to scales of groups that contain 2–3 L_* galaxies. Below that scale environmental effects continue to matter for low luminosity satellites of individual L_* galaxies. A notable feature of such low luminosity galaxies is that in the stellar mass range 10^7–10^9 only satellite galaxies ever become red galaxies (dE galaxies).

1.4. Gas in clusters

The dominant baryonic component of clusters is not stars in galaxies, but is hot, diffuse gas, visible in brehmstrahhlung. The total emission is of order $L_X \sim 10^{43}$–10^{45} erg s^{-1} and the gas is 10^7–10^8 K.

The emission per unit volume has a form similar to:

$$\epsilon \propto n^2 \, (T)^{-1/2} \exp\left(-h\nu/kT\right) \tag{1}$$

The wavelength dependence allows determination of the temperature from an X-ray spectrum.

However, in practice the above approximation is not sufficient and a temperature determination requires a detailed model of plasma emission, such as CHIANTI or MEKAL.

With a projected temperature and emission profile, the gas mass and dynamical mass can be derived. The simplest version of this approach is the β *model*, which is spherically symmetric and isothermal. Although it is not precise enough for modern work, it illustrates the general principles. As for static isothermal collisionless systems, isothermal hydrodynamic systems can be approximated by the King model:

$$\rho \propto \left[1 + \left(\frac{r}{r_c}\right)\right]^{-3\beta/2}, \tag{2}$$

where in detail:

$$\beta = \frac{\mu m_p \sigma_v^2}{kT} \tag{3}$$

The resulting emission as projected on the sky becomes:

$$I(R) \propto \left[1 + \left(\frac{R}{r_c}\right)\right]^{-3\beta+1/2} \tag{4}$$

With T determined from the spectra, fitting β the overall amplitude constraints $\rho_g(r)$ and therefore the total gas mass.

In reality, galaxy cluster gas temperatures vary throughout the cluster. Many clusters are *cool core* clusters, whose inner parts are roughly a factor two cooler than the outer parts. These cool clusters are typically more regular and tend to have a clear brightest cluster galaxy. Other clusters appear to be more disturbed, due to mergers and infalls, and have a less regular temperature pattern. They correspondingly tend to lack regularity or a clear brightest cluster galaxy.

One expects cooling near cluster centers theoretically due to the higher density at the center. The cooling time for the gas and the mass rate of cooling at the centers of many clusters is extremely high. These clusters are referred to as *cooling flow* clusters, though there is not direct evidence for any inward flow of gas. Nevertheless, high resolution X-ray spectra of atomic lines in these clusters, which reveal the ionization states and therefore gas temperature distribution, are not consistent with much gas cooling below 3 keV. The mass cooling rate does correlate with BCG star formation signatures, but those star formation rates are only a few percent of the cooling rates except in rare cases.

Highly ionized species of iron and other elements (C, N, O, Ne, Mg, Si, S, Ar, Ca, Cr, Mn, and Ni) create detectable atomic lines in the intracluster gas. Combined with plasma emission models, these lines constrain the abundance distributions of elements. For clusters of galaxies, abundances range from 0.1 to 1 solar. Metallicities generally decrease with distance from the cluster center. The gas was enriched from a combination of in situ enrichment from the galaxies and intergalactic stars and from stripping of previously enriched gas.

The overall cluster X-ray luminosity is a function of mass and temperature, with $L_X \propto T^3$ and $L_X \propto M^2$. The nature of these scaling relations suggests that at lower mass the cluster gas has an entropy floor. The entropy is usually quantified by the *entropy index*:

$$K \equiv \frac{P}{\rho^\gamma} = \frac{kT}{\mu m_p \rho^{2/3}} \tag{5}$$

where the second equality is for a monoatomic, nonrelativistic, ideal gas. The entropy per unity mass s can be written in that case as:

$$s = \frac{k}{\mu m_p} \ln K^{3/2} + \text{ constant} \tag{6}$$

The entropy floor is usually interpreted as the result of a heating source prior to falling into the cluster.

Cluster gas can also be detected through the *thermal Sunyaev-Zeldovich effect*, which is the inverse Compton scattering of cosmic microwave background photons on the electrons in the cluster gas. This process results in a slight increase in energies of the photon distribution, and this spectral distortion is observable. Above $\nu \sim 218$ GHz (near the CMB spectrum peak), this yields an increase in flux, and below that frequency it yields a decrease in flux. Motion of the cluster with respect to the CMB will also yield an additional spectral distortion, called the *kinetic Sunyaev-Zeldovich effect* which tends to be at least an order of magnitude smaller and must be observed at $\nu \sim 218$ GHz.

Gas at lower temperatures exists in groups and individual galaxies as well, but is too cold to be detected in the X-ray regime. The extreme-UV emission from this gas is difficult to observe.

1.5. Dark matter in clusters

The dark matter in clusters can be measured through the dynamics of the galaxies, the luminosity and temperature of the X-ray gas, and through weak and strong lensing.

In the case of galaxies, the virial theorem can be used; the gravitational radius must be estimated from the galaxies assuming they are faithful tracers of the full mass distribution.

In the case of the X-ray gas, the modeling approach emission can be used. With a temperature and density model, spherically symmetric hydrostatics implies that:

$$M(< r) = -\frac{kTr^2}{G\mu m_p} \left[\frac{\mathrm{d} \ln \rho_g}{\mathrm{d}r} + \frac{\mathrm{d}T}{\mathrm{d}r}\right] \tag{7}$$

2. Commentary

The largest halos form galaxies with a low stellar-to-halo mass ratio, a fact which is one of the major goals of galaxy formation theory to explain. This problem must be closely related to the "cooling flow" problem—the lack of cold gas and star formation in the centers of clusters for which the cooling times are short—and the entropy floor in lower mass clusters.

3. Important numbers

- $k(T/10^6 \text{ K}) \approx 0.86$ keV

4. Key References

- *Formation of Galaxy Clusters, Kravtsov & Borgani (2012)*
- *X-ray Properties of Groups of Galaxies, Mulchaey (2000)*

5. Order-of-magnitude Exercises

1. Estimate the virial velocities to expect for a galaxy cluster with $M \sim 10^{14}$ $M_\odot$ and $R \sim 1$ Mpc.
2. Estimate the gas temperature that should be required for hydrostatic equilibrium in such a cluster.
3. For a cluster with a total mass of 10^{14} $M_\odot$, estimate the star formation that would be associated with a cooling time of 10^{10} Gyr.
4. Calculate the cross-section for interaction of a photon traveling through a massive cluster; i.e. for the inverse Compton scattering that causes the Sunyaev-Zeldovich effect.

6. Analytic Exercises

1. Estimate how viable ram pressure stripping will be for a galaxy disk. Assume a thin disk of gas coplanar with the disk of stars, with surface densities such that $\Sigma_{\rm gas} \ll \Sigma_*$.
   (a) Approximate the disks as infinitely thin, and calculate the acceleration that will result for a mass displaced from the center of the stellar disk. Using that acceleration, what pressure will the gas feel towards the disk plane if it is displaced?
   (b) Through dimensional analysis, estimate the form the ram pressure due to motion through the intracluster medium.
   (c) For a spiral galaxy like the Milky Way, compare quantitatively the restoring pressure due to gravitation to the ram pressure.

2. In the Sunyaev-Zeldovich process, the scattering yields a change in frequency $\Delta\nu/\nu \approx kT/m_e c^2$. Show that at $h\nu \ll kT$, the change in brightness temperature is:

$$\frac{\Delta T_b}{T_b} \equiv -2y = -\frac{2k\sigma_T}{m_e c^2} \int \mathrm{d}x n_e T_e, \tag{8}$$

where x is the coordinate along the line of sight.

3. Prove Equation 6.

7. Numerics and Data Exercises

1. Look at specific groups
2. Find groups in a sample
3. SZ in Planck
4. X-ray fluxes in groups
5. Morphological segregation

REFERENCES

Kravtsov, A. V., & Borgani, S. 2012, ARA&A, 50, 353

Mulchaey, J. S. 2000, ARA&A, 38, 289

This preprint was prepared with the AAS LaTeX macros v5.0.