

# 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  $> 700 \text{ km s}^{-1}$  and can be up to several thousand  $\text{km s}^{-1}$ . The gas in these systems reaches temperatures of  $10^8 \text{ K}$ ; it is typically very diffuse, with  $n \sim 10^{-3} \text{ cm}^{-3}$ . 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 bremsstrahlung 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 brehmstrahlung. 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:

$$\epsilon \propto n^2 (T)^{-1/2} \exp(-h\nu/kT) \quad (1)$$

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  $\beta$  *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:

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

where in detail:

$$\beta = \frac{\mu m_p \sigma_v^2}{kT} \quad (3)$$

The resulting emission as projected on the sky becomes:

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

With  $T$  determined from the spectra, fitting  $\beta$  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. Other clusters appear to be more disturbed, due to mergers and infalls, and have a less regular temperature pattern.

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.

## Cooling

**scaling**

SZ effect

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 because **why**

### 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:

$$M(< r) = -\frac{kTr^2}{G\mu m_p} \left[ \frac{d \ln \rho_g}{dr} + \frac{dT}{dr} \right] \quad (5)$$

## 2. Important numbers

Kev to T

## 3. Key References

- *Binney & Tremaine* Cox (2000), Chapter 5

## 4. Order-of-magnitude Exercises

1. Virial velocities
2. Gas temperature
3. Dynamical friction in group
4. Ram pressure stripping
5. Tidal radii

## **5. Analytic Exercises**

1. SZ effect

## **6. 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**

Cox, A. N. 2000, Allen’s astrophysical quantities