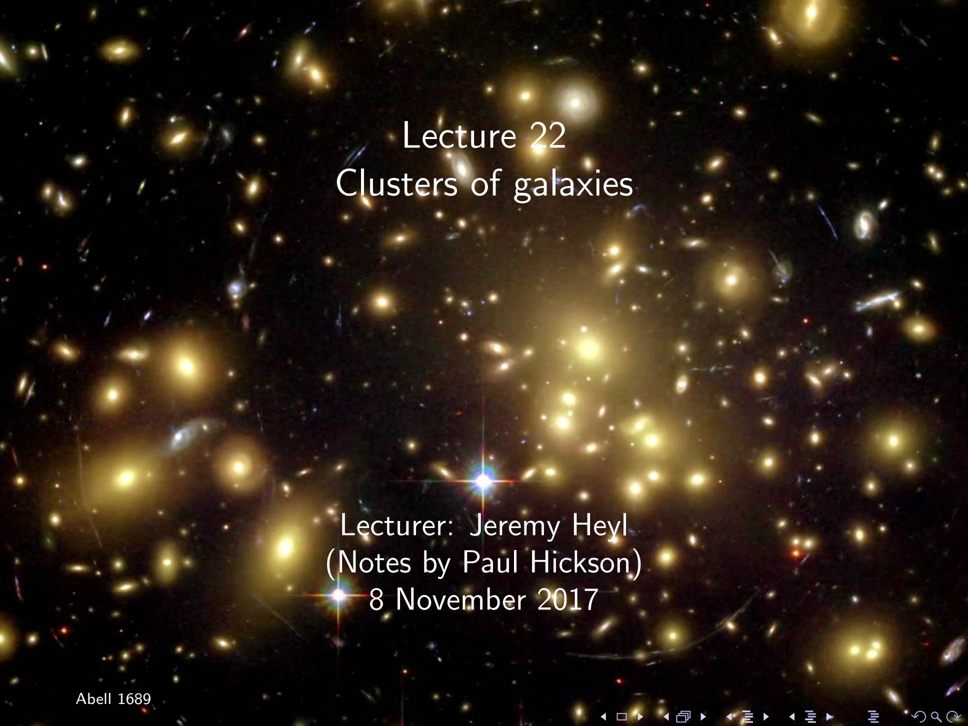
Lecture 22
Clusters of galaxies

Lecturer: Jeremy Heyl
(Notes by Paul Hickson)
8 November 2017



Abell 1689

Clusters

About 5 – 10 % of luminous galaxies are found in large clusters.

These are bound systems of galaxies, typically a few Mpc across, containing on the order of $10^2 - 10^3$ galaxies.

The closest example is the Virgo cluster at a distance of 16.5 Mpc, which contains 150 galaxies of luminosity $10^9 L_\odot$ of greater. It has a core radius (at which the average surface density is half the central value) of 0.5 Mpc and a total luminosity of about $1.3 \times 10^{12} L_\odot$.

Other well-known nearby examples are the Coma, Hercules, Fornax, Perseus clusters.

Some clusters have a cD galaxy at their centre. A nearby example is NGC 1399 in the Fornax cluster.

Fig 7.9 (C. Conselice/WIYN, A. Fabian/HST)
'Galaxies in the Universe'
Sparke/Gallagher CUP 2007

The core of the Perseus cluster. Left, an R-band negative image showing the cD galaxy NGC 1275 on the lower left, with numerous dwarf galaxies, other bright ellipticals, and S0s. Right, an image in a narrow band including the Hα line; bright filaments of glowing gas surround NGC 1275.

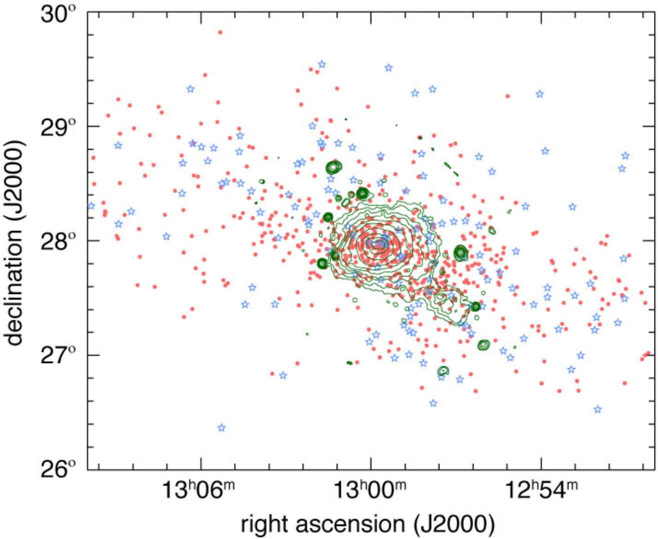


Fig 7.10 (M. van Haarlem) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The Coma cluster: solid dots show elliptical galaxies; open stars are spirals. Contours show the intensity of X-rays: they bulge to the south-west where a clump of gas and galaxies surrounds the D galaxy NGC 4839. The diffuse emission is from hot cluster gas, the point sources are distant active galaxies.

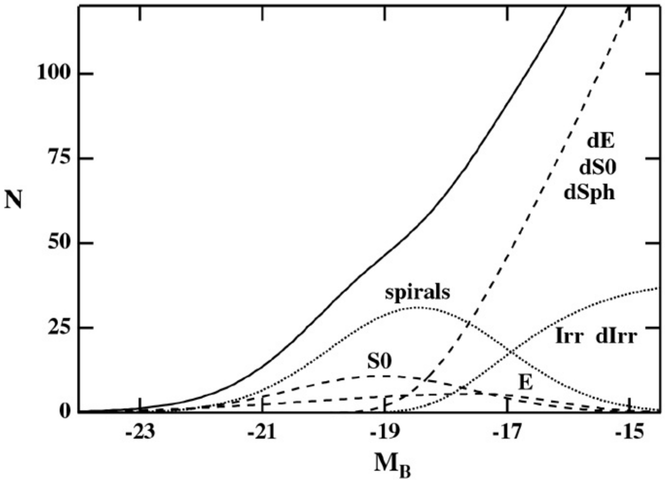


Fig 7.8 (H. Jerjen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Galaxy luminosity function in the Virgo cluster. The luminosity function depends on galaxy type; the Schechter function is only an average. Here, most bright galaxies with $M_B \lesssim 20$ are spirals; there are many faint ellipticals and even fainter dwarf galaxies. The heavy solid curve shows the total.

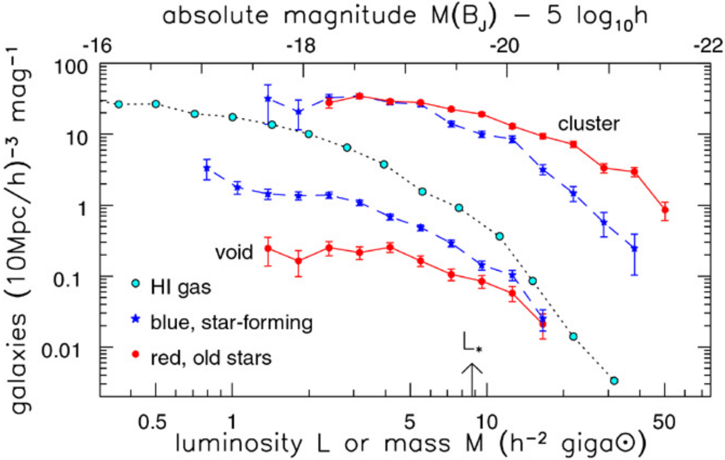


Fig 7.11 (D. Croton, 2dF) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Luminosity functions of blue star-forming galaxies (stars) and red galaxies (filled dots). Bright red galaxies predominate in clusters, but dim blue galaxies are more frequent in the low-density field or void regions. Clouds of neutral hydrogen, found in low-density regions, resemble blue galaxies in that small systems are far more common than big ones.

Hot gas in clusters

Most clusters contain large quantities of hot gas. The mass of gas is comparable to that of stars in poor clusters, and can be as much as ten times the mass of stars in rich clusters such as Coma.

The gas temperature, deduces from the X-ray emission, ranges from 10^6 K to 10^8 K, and is consistent with the kinetic temperature that corresponds to the galaxy velocity dispersion.

For thermal bremsstrahlung, one expects that the power emitted per unit volume

$$\mathcal{L}_{\mathsf{X}} \simeq 1.5 \times 10^{-40} n_e n_p T_{\mathsf{X}}^{1/2} \text{ W m}^{-3},$$

where n_e and n_p are the electron and proton densities in m^{-3} and T_{X} is in degrees K.

Thus, the emission is proportional to the *square* of the gas density.

Hot gas in clusters

The X-ray temperature is found to correlate with the X-ray luminosity of the cluster. Roughly, $L_{\mathsf{X}} \propto T_{\mathsf{X}}^3$.

The gas mass and velocity dispersion both increase with the mass of the cluster, which results in increasing X-ray luminosity and temperature.

The **cooling time** is a measure of the time needed for the hot gas to radiate its thermal energy,

$$t_{\mathsf{cool}} = \left| \frac{E}{dE/dt} \right| \simeq \frac{3 n_e k T}{1.5 \times 10^{-40} n_e^2 \sqrt{T}} \simeq 14 \left(\frac{10^3 \mathsf{m}^{-3}}{n_e} \right) \left(\frac{10^7 \mathsf{K}}{T} \right)^{1/2} \mathsf{Gyr}.$$

One finds that in the cores of clusters, this is smaller than the Hubble time, so a mechanism is needed to heat the gas. This could be supernovae or active galactic nuclei.

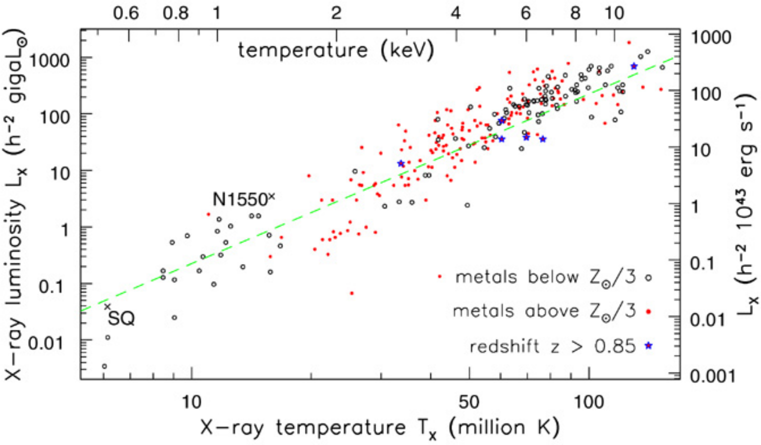


Fig 7.12 (D. Horner) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The X-ray luminosity L_X of a galaxy cluster or group increases with the gas temperature T_X: the dashed line shows $L_X \propto T_X^3$. Stephans Quintet and the NGC1550 group follow the same trend.This relation has changed little since redshift $z \simeq 1$. In most clusters with $T_X > 3 \times 10^7$ K, the gas has roughly one-third of the solar abundance of iron.

Hot gas in clusters

Typically, the metallicity of the gas is about $1/3$ of solar. Gas near the centre of the cluster is more metal-rich than the outer regions.

In X-ray luminous clusters, the gas mass exceeds that of the galaxies. However, it is not enough to explain the high velocity dispersions. The total mass is about ten times greater still, and is dominated by dark matter.

CMB observations indicate that the baryon fraction of the Universe is about $0.03 \lesssim \Omega_B \lesssim 0.07$ (i.e. baryons make up 3 to 7 percent of the critical density). But, the hot and cool gas, and stars, in clusters of galaxies add up to only about 1% of the critical density.

It is likely that many of the baryons and the form of ionized diffuse gas in the intergalactic medium.

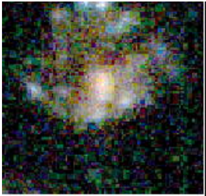
Morphology-density relation

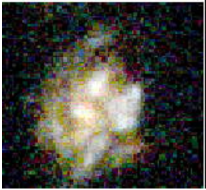
It was first noted by Oemler, that elliptical and S0 galaxies are almost always found in clusters. And, they are more prevalent near the centres of clusters.

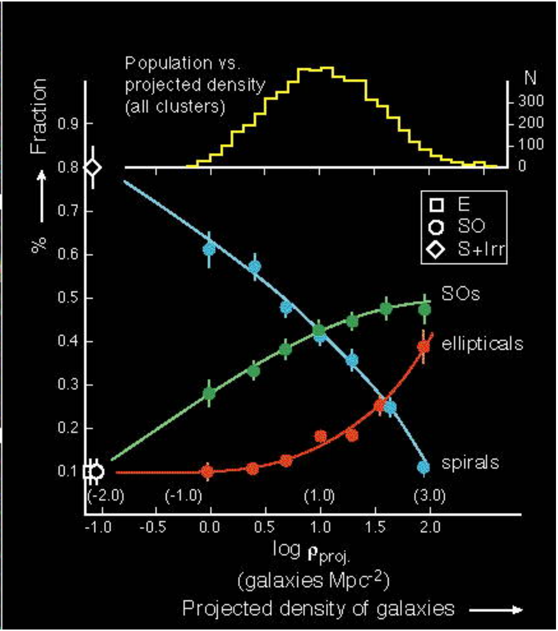
Spiral galaxies, on the other hand, are predominantly found in the outer regions.

In a detailed study of a large sample of clusters, Dressler (ApJ 236, 351,1980) found that the frequencies of these galaxy types depend on the local density of galaxies. This is the **morphology-density relation**.

The preference of ellipticals for high density regions is consistent with the idea that they formed from mergers.







astro.rug.nl/∼weygaert/InleidingStk2/Curriculum/Colleges/College5

The origin of S0 galaxies

van den Bergh was the first to notice that some spirals in clusters appeared to have less than the normal amount of gas. He called these **anaemic spirals**.

It was soon realized that as spiral galaxies fall into a cluster, they feel a ‘wind’ as they move through the hot intergalactic gas. The resulting pressure can push the cool gas right out of the galaxy. This is called **ram-pressure stripping**.

This can not only account for the anaemic spirals, but also for S0 galaxies, which result if all the gas is removed from the spiral.

Recent observations have in fact revealed galaxies, such as NGC 4402, in which the cool gas is displaced, and in the process of being pushed out of the galaxy.

NGC 4402, H. Crowl, WIYN/NOAO/AURA/NSF

The origin of elliptical galaxies

It is tempting to speculate that elliptical galaxies form by mergers of smaller galaxies. This could explain their lack of cool gas, and smooth elliptical shapes.

However, it is not clear if this mechanism can explain the correlations of the fundamental plane.

Also, one finds luminous red galaxies even at quite high redshift, $z \sim 2$, when the Universe was less than 5 Gyr old. These contain as much as twice the mass of the Milky Way and consist of old stars that must have formed at least 1 Gyr earlier.

In fact some red galaxies are seen up to $z \gtrsim 6$, when the age of the Universe was less than 1 Gyr. These have masses of about $1/3$ that of the Milky Way.

How can such systems form so early?