7.5 Summary

After having studied this lecture, you should be able to

- describe the surface brightness profiles of Es in terms of the de Vaucouleurs profile.
- explain why we think that this profile results from galaxy encounters
- recall that Es have typically hundreds of GCs.
- explain why dust lanes in ellipticals and shells of stars around them are thought to be evidence for galactic cannibalism.
- contrast the stellar population and ISM of ellipticals with those of spirals
- describe how X-rays are detected, and explain the process with which X-rays are produced in the hot gas in ellipticals
- explain how X-ray observations can be used to infer the gravitational potential and derive the equation for hydrostatic equilibrium, relating gas profile to the underlying gravitational potential.

Chapter 8

Groups and clusters of galaxies

CO §27.3
Galaxies are *not* sprinkled randomly throughout the Universe. Instead, galaxies like the Milky Way tend to huddle together in small groups similar to the Local Group, with more massive elliptical galaxies clumping together in bigger groups and clusters containing thousands of galaxies. Regions of the Universe with a low density of galaxies are called *voids* - they typically contain smaller galaxies. The origin of all this structure is the amplification by gravity of the tiny fluctuations seen in the cosmic micro-wave background (CMB). But why do the properties of the galaxies depend on their surroundings?

8.1 Introduction

The Milky Way, Andromeda, and several hundred smaller irregular galaxies within $\sim$ 2 Mpc or so from the MW, are part of a gravitationally bound system, called the Local Group, discussed previously. Most spiral galaxies like the MW are found in such small **galaxy groups**.

Galaxy clusters, on the other hand, are gravitationally bound systems of 10s-100s of mostly elliptical and S0 galaxies, together with 1000s of smaller dwarf galaxies. Clusters were discovered by eye - by staring at photographic plates of the night sky, and recognising that patches of the sky contained vastly more galaxies per unit area than average, for example by Abell whose numbering scheme is still in use. Examples of nearby clusters include Fornax and Virgo, both at a distance of $\sim 20\,\mathrm{Mpc}$ from the MW. Galaxy clusters are the most massive gravitationally bound structures in the Universe. They were the first systems in which there was evidence for the presence of dark matter.

8.1.1 Evidence for dark matter in clusters from galaxy motions (CO p. 960)

The Swiss astronomer Fritz Zwicky measured Doppler velocities of galaxies in clusters of galaxies. He assumed - correctly - that the *velocity dispersion* of these galaxies could be used to characterise the depth of the gravitational potential in which the galaxies move, and from that the mass of the cluster could be inferred. The values of these *dynamical masses* obtained by Zwicky were *much* higher than the corresponding masses in stars: for any reasonable uncertainty in stellar mass, he concluded that most of the mass in the cluster is not visible[1]. His argument goes as follows.

Assume for simplicity that all cluster galaxies have the same mass m, and that the cluster contains N galaxies. The kinetic energy of the system, due to the random motions of the galaxies, can be written as

$$K = \frac{1}{2}\sum m\,v^2 = \frac{1}{2}\,M\,\sigma^2\,, \tag{8.1}$$

where $M = N\,m$ is the total mass of the cluster galaxies, and the velocity dispersion, σ, is defined by

$$\sigma^2 = \frac{\sum m\,v^2}{M}\,. \tag{8.2}$$

Note that these velocities are measured with respect to the *mean* velocity of the cluster. The potential energy in the system is of order[2]

$$U = -\frac{3}{5}\frac{G\,M^2}{R}\,, \tag{8.3}$$

[1]Zwicky was not aware that the gas mass of a cluster is much larger than the mass in stars. Yet even including this extra mass, it remains true that most mass is invisible.

[2]The factor $3/5$ assumes the density of galaxies is constant inside the cluster, which is clearly an approximation.

where R is a measure of the size of the system. When the system is in *virial equilibrium*, $2K = |U|$ hence M can be determined from measuring σ and R from

$$M = \frac{5}{3}\frac{\sigma^2 R}{G}\,. \tag{8.4}$$

We have now two estimates for the mass of the cluster: (1) the mass obtained from Eq. (8.4) (a *dynamical* mass - inferred from the dynamics of galaxy motions), and (2) the *stellar* mass, $M_\star$. The stellar mass is not directly observable: what we can measure is the total luminosity of all galaxies in the cluster, $L_\star$ (provided we can measure the flux of the cluster, as well as the distance to the cluster.). **If** all cluster stars were the same as the Sun, then the cluster mass would be $M_\odot \times (L_\star/L_\odot)$. However, this not likley to be correct. Zwicky estimated that, if the stellar population of cluster galaxies were similar to that of the Milky Way, then a better estimate of the stellar mass of the cluster would be $M_\star \approx 3M_\odot \times (L_\star/L_\odot)$. This is because low mass stars contribute very little to $L_\star$, but they do contribute to $M_\star$. Therefore, if the cluster galaxies contain low mass stars as well, then this would increase the value of $M_\star$. It turns out this correction is not very important, since in any case,

$$M \gg M_\star\,, \tag{8.5}$$

the dynamical mass is **much** larger than the stellar mass - Zwicky estimated that $M \approx 400M_\star$. The alternative is that the observed cluster is simply unbound, with galaxies now escaping the system.

8.2 Evidence for dark matter from X-rays observations

The hot gas[3] in clusters emits X-rays due to *thermal bremsstrahlung*, which can be used to determine their mass assuming the hot gas is in hydrostatic equilibrium. We did the same for elliptical galaxies in Section 7.3. The (total) mass of the cluster in a sphere of radius r, relates to gas density, ρ, and pressure, p, as (see Eq. 7.3)

[3]Note that the emission is extended, and not just due to the elliptical galaxies themselves: most of the hot gas is between the galaxies, not associated with any particular galaxy.

$$\frac{GM(<r)}{r^2} = -\frac{1}{\rho(r)}\frac{dp}{dr}\,. \tag{8.6}$$

As for ellipticals, the X-ray data can be used to measure the right hand side, allowing a determination of the encloded mass, $M(<r)$. Comparing this to the mass in stars $M_\star$, inferred from the luminosity of the galaxies, and the mass in gas, $M_{\rm gas}$, inferred from the X-ray observations, yields $M_\star + M_{\rm gas} \approx M_{\rm gas} < M$: gas dominates over stars (by a large factor), but the gas mass is still significantly below the dynamical mass: X-rays strongly indicate the presence of dark matter in clusters.

What is the origin of the gas and why is it so hot? A high-mass cluster will attract gas (and dark matter) in from its surroundings due to its large gravitational pull. The accreting gas slams into the gas already there, and the rapid compression of the gas converts kinetic energy into thermal energy in an *an accretion shock*. This works as follows: assume that a parcel of gas starts at infinity with velocity $v = 0$. The parcel feels the gravitational pull from the cluster, gets accelerated and eventually hits the cluster itself, at a distance R from the centre - R is the radius of the cluster with mass M.

Since energy is conserved along the orbit of the parcel of gas, we can compare its energy at infinity to its energy at R:

$$0 = E = \frac{1}{2}v^2 - \frac{G\,M}{R}\,, \tag{8.7}$$

since the energy of the parcel at infinity is zero (its speed is zero, and its gravitational energy GM/r is also zero for $r \to \infty$. So that sets the speed with which the gas slams into the cluster, in terms of M and R. The gas will now converts its kinetic energy into thermal energy, which means its gets heated to temperature T, given by

$$\frac{1}{2}mv^2 = \frac{3}{2}m\frac{kT}{\mu m_p}\,, \tag{8.8}$$

where μm_p is the mean molecular weight per particle. Combining the last two equations yields

$$kT = \frac{2}{3}\frac{\mu m_p GM}{R} = 15\times 10^3\frac{(\mu/0.5)(M/10^{15}M_\odot)}{R/1{\rm Mpc}}{\rm eV}\,, \tag{8.9}$$

corresponding to $T \approx 1.7 \times 10^8$K. This temperature is called the *virial temperature*, and its high value explains why we detect X-rays with energies of the order of 10^{3-4} eV.

8.3 Metallicity of the X-ray emitting gas.

The X-ray spectrum of a galaxy cluster consists of a power-law component with a cut-off at high energy resulting from thermal bremsstrahlung with additional emission lines from highly ionised metals such as Si, N and Fe, see Figure 8.1. The location of the cut-off in the continuum shape, as well as the ratio of emission lines for a given element, can be used to infer the temperature of the gas, T. Once T is known, the gas density - and gas mass - follows from measuring the X-ray luminosity, since the emissivity is $\propto \rho^2 T^{1/2}$ for thermal bremsstrahlung (with a known proportionality constant).

The first surprise of such an analysis is that most of the baryonic mass in the cluster is in the X-ray emitting gas: $M_\star \ll M_{\rm gas}$. Although we originally identified galaxy clusters as regions with a high density of galaxies, most of the baryons in the cluster have not actually collapsed to form stars.

The second surprise is the high abundance of metals in this gas. For example for Fe, we find that the ratio $M_{\rm Fe}/M_{\rm gas} \approx 1/3(M_{\rm Fe}/M)_\odot$, that is: the ratio of iron mass to total gas mass in the cluster is of order 1/3 of the iron mass fraction in the Sun. Such a ratio is higher than for most *stars* in globular clusters. Why is this so surprising? Well - how did these metals - synthesized in *stars inside galaxies* - manage to be flung out of the galaxy and into the gas in between the galaxies? Clearly, we must conclude that galaxies are not simply closed boxes: elements synthesized inside a galaxy manage to escape the galaxy. Our present bet is that the combined action of many super nova explosions manages to eject a considerable fraction of the metal enriched gas outside of the galaxy - see the workshop for some exercises on this.

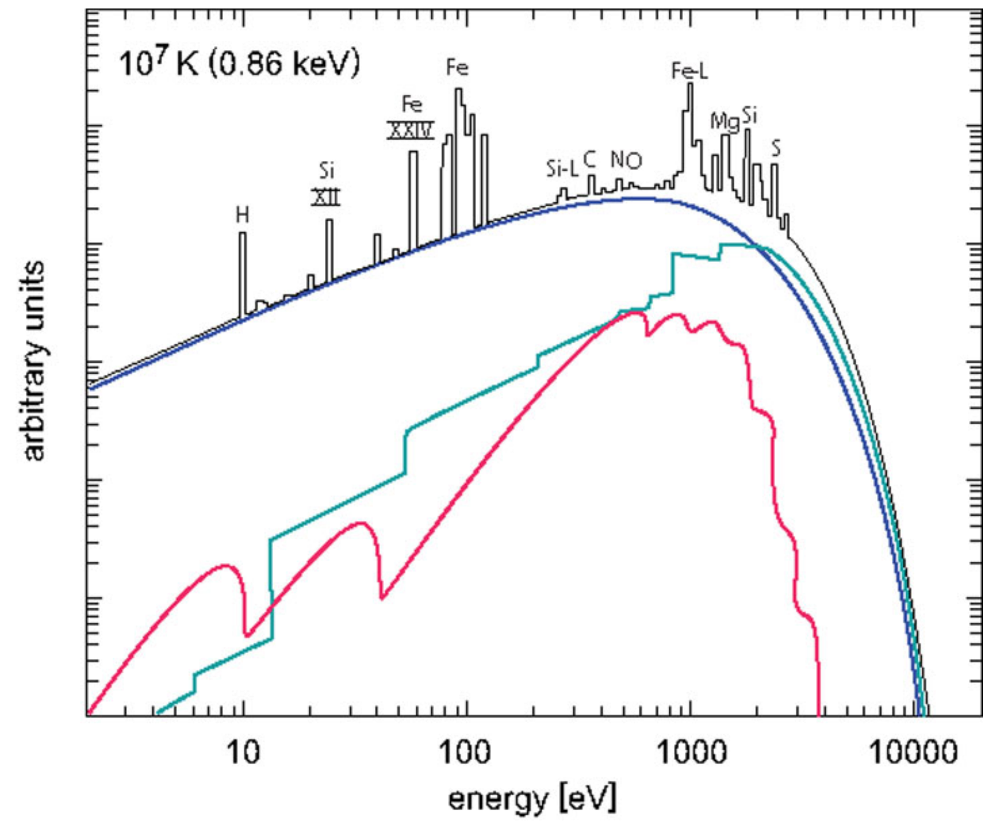

Figure 8.1: Model X-ray spectrum of a plasma with temperature $T = 10^7$ K and a solar abundance pattern. The underlying continuum (the smooth line) is due to thermal bremsstrahlung - notice the sharp cut-off in the emissivity above $\sim 2 \times 10^3$ eV. The emission lines are due to electronic transitions in highly ionised gas.

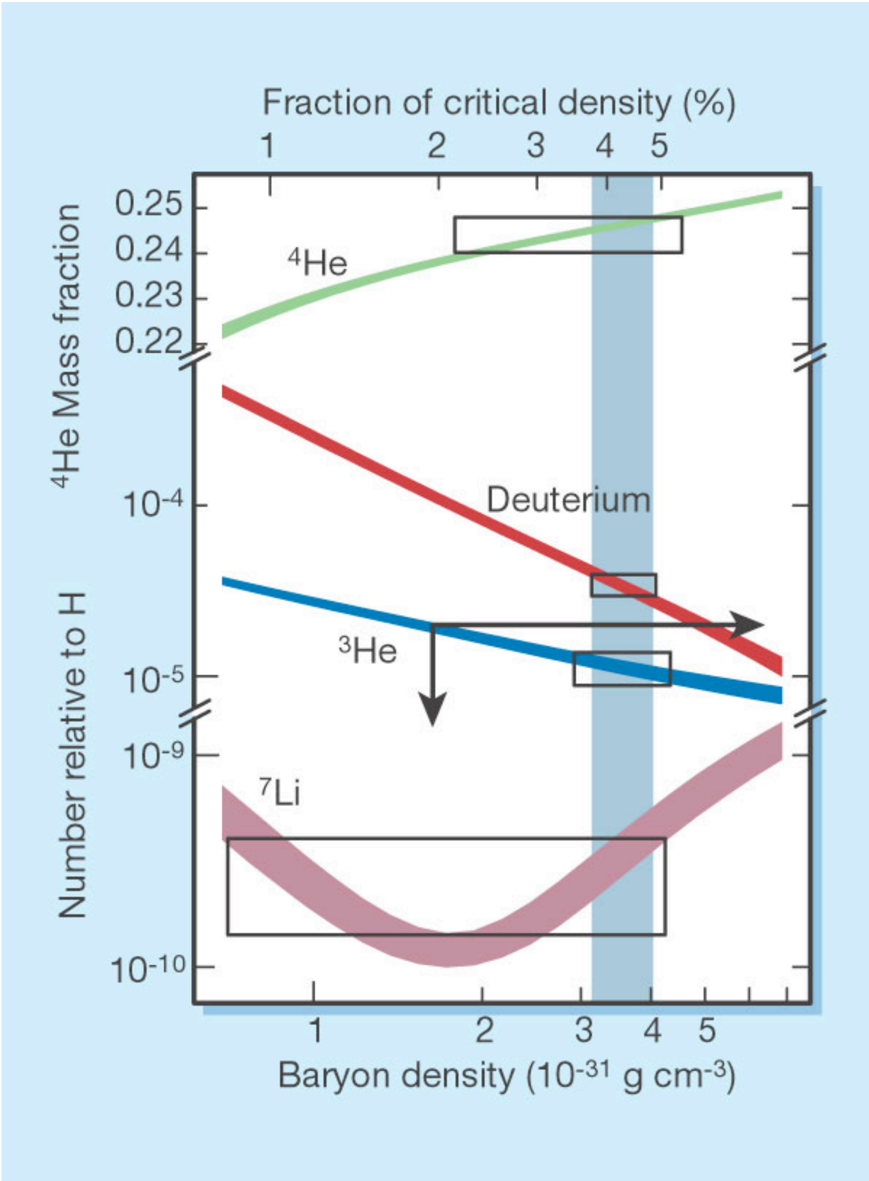

Figure 8.2: The production of various elements during Big Bang nucleosynthesis as a function of the baryon density. (*Nature* **415**, p. 27, 2002)

8.4 The dark matter density of the Universe

Clusters have been used to estimate the mean dark matter density of the Universe as follows. Assume that the Universe starts-out smooth, with a (nearly) constant ratio ω of dark matter to baryons[4]

$$\omega = \frac{\rho_{\rm dm}}{\rho_{\rm b}}\,. \tag{8.10}$$

A cluster forms by accreting both dark matter and baryons. As the gravitational potential well of the forming cluster deepens, it is (probably) a good approximation to assume that eventually, neither dark matter nor baryons can ever escape from the cluster's potential well[5]. As a result, the ratio of dark matter mass to baryon mass of the cluster, is also equal to ω:

$$\omega \approx \frac{M_{\rm dm}}{M_{\rm b}}\,. \tag{8.11}$$

Therefore we can determine ω by measuring the dark matter mass of a cluster, $M_{\rm dm} = M - M_{\rm b}$, and the baryonic mass, $M_{\rm b}$. Recall that we could determine M from either galaxy motions (Eq. 8.4) or X-ray observations, with $M_{\rm b} = M_\star + M_{\rm gas}$ from combining the stellar mass (from the observed stellar luminosity) and the gas mass from the X-ray emissivity. Doing so for a range of clusters yields $\omega \approx 6$.

An estimate for the mean baryon density, $\rho_{\rm b}$, follows from the *abundance of deuterium*[6] *relative to ordinary hydrogen*, $\rho_{\rm D}/\rho_{\rm H}$. The reason is that deuterium is produced during Big Bang nucleosynthesis, with the ratio $\rho_{\rm D}/\rho_{\rm H}$ depending on the total baryon density, as illustrated in Fig.8.2.

We can measure the deuterium fraction in intergalactic gas clouds. This, together with Big Bang nucleosynthesis calculations yields ρ_b, and given ω from cluster observations, finally yields $\rho_{\rm dm}$:

[4]According to Cern, baryons are composed of three quarks. Astronomers use the term *baryon* to mean ordinary matter (such as stars and gas) composed of protons and neutrons - as opposed to dark matter whose composition is presently unknown.

[5]We know for a fact this is not true for the gravitational potential of the Milky Way - recall our discussion on high and hyper velocity stars, for example.

[6] Deuterium is an isotope of hydrogen: a deuterium nucleus consists of a proton and a neutron, a opposed to the nucleus of ordinary hydrogen which is just a single proton. Deuterium is not produced but is destroyed in stars.

$$\rho_{\mathrm{dm}} \approx 4 \times 10^{-31}\mathrm{g\ cm}^{-3}\,. \tag{8.12}$$

This is astonishingly low compared to the density of you, the reader, which is ~ 30 *orders of magnitude higher!* More recent estimates of ρ_{dm}, based on the cosmic microwave background, are consistent with the value found from clusters.

8.5 Summary

After having studied this lecture, you should be able to

- Define what is a cluster and a group of galaxies by listing some of their properties.
- Explain how galaxy motions suggest the presence of dark matter in clusters.
- Explain how X-ray observations suggest the presence of dark matter in clusters.
- Explain the origin of the high temperature of the cluster gas.
- Explain how we know that most of the baryons in a cluster are in hot gas, and not in stars.
- Explain why the high observed metallicity of the cluster gas suggests that a large fraction of the products of stellar evolution are blown out of galaxies
- Explain how clusters have been used to estimate the mean dark matter density of the Universe.