Course of Galaxies

course organizer: Goeran Ostlin

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“X-ray physics of Galaxy Clusters”

Student: Angela Adamo
angela@astro.su.se

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The double cluster A1750. The contours of the *XMM-Newton* emission are overlaid on the temperature map. An arc-like hot region can be seen between the two sub-clusters, A1750N in the north and A1750C in the South. The two clusters have started to collide and the gas is being shocked and compressed. The hot regions in A1750 C are regions of shocked gas from an older merger which occurred about 1-2 billion years ago. Figure from [1].
Chapter 1

Clusters in X-rays

1.1 About Galaxy Clusters

In the standard CDM (Cold Dark Matter) cosmological scenario, initial density fluctuations, generated in the early Universe, grow under the influence of gravity. The Universe gets more and more structured with time. At large scale, the matter density distribution exhibits a web-like topology with expanding voids surrounded by contracting sheets and filaments. Massive clusters of galaxies, located at the crossing of filaments, define the nodes of this cosmic web. Clusters of galaxies are the largest collapsed structures, with masses ranging from $10^{13} \, M_\odot$ for small groups to $10^{15} \, M_\odot$ for the richest clusters. Because of their size, their mass content reflects that of the Universe: $\sim 85\%$ of the mass is made of Dark Matter (DM). The main baryonic cluster component is a hot X-ray emitting intracluster gas (ICM), as shown by the first X-ray images obtained with the Einstein satellite. Only a few percent of the mass in clusters lies in the optical galaxies.

In the CDM scenario, the amplitude of the initial density fluctuations decreases with increasing scale. As a result, low-mass objects form first and then merge together to form more massive objects. Clusters of galaxies are the last manifestation of this hierarchical clustering. They started to form in the recent cosmological epoch ($z \sim 2$) and the cluster population is continuously evolving. A cluster continuously accretes matter and smaller groups along the filaments, and, occasionally, merges with another cluster of similar mass.

Clusters of galaxies are key objects for cosmological studies (see the review [12]). By studying the properties of clusters of galaxies we can test the scenario of structure formation and better understand the gravitational collapse of the DM and the baryon specific physics. In this essay, I will focus on the X-ray observations and on properties of these structures.

1.2 Observations in X-ray band

The X-ray selection has the advantage of revealing physically-bound systems, because diffuse emission from a hot ICM is the direct manifestation of the existence of a potential-well within which the gas is in dynamical equilibrium with the cool baryonic matter (galaxies) and the DM. Moreover the X-ray luminosity is well correlated with the cluster mass and the X-ray emissivity is proportional to the square of the gas density, hence cluster emission is more concentrated than the optical bidimensional galaxy distribution. In combination with the relatively low surface density of X-ray sources,
this property makes clusters high contrast objects in the X-ray sky, and alleviates problems due to projection effects that affect optical selection. Finally, an inherent fundamental advantage of X-ray selection is the ability to define flux-limited samples with well-understood selection functions. This leads to a simple evaluation of the survey volume and therefore to a straightforward computation of space densities.

X-rays are absorbed by the Earth’s atmosphere. Therefore X-ray observatories are put on board satellites. Already from the first pioneering attempts to map the X-ray sky, clusters were associated with extended sources, whose dominant emission mechanism was recognized to be thermal bremsstrahlung from optically thin plasma (the ICM) at a temperature of several keV. The all-sky survey conducted by the the HEAO-1 X-ray Observatory was the first to provide a flux-limited sample of X-ray identified clusters.

Now, two X-ray satellites are in operation, XMM-Newton and Chandra. The XMM-Newton and Chandra observatories are complementary. Chandra has an extremely good spatial resolution of $\Delta \theta = 0.5''$ (compared to 8'' for XMM-Newton). The strength of XMM-Newton is its exceptional collecting area and thus sensitivity: three high-throughput telescopes are operating in parallel. The Field of view is 30' in diameter, well adapted to cluster studies. Chandra has only one telescope, a smaller field of view of 17'X17' (for the ACIS-I instrument) and an effective area typically 3(5) times lower than XMM-Newton at 1.5(8) keV.

As compared to the previous generation of satellites, XMM-Newton and Chandra represent a giant step forward in term of sensitivity and spatial resolution. With XMM-Newton and Chandra:

- We can map the gas distribution in nearby clusters from very deep inside the core, at the scale of a few kpc with Chandra, up to very close to the virial radius with XMM-Newton. Temperatures profiles (and thus mass profiles) can be measured over a wide radial range with Chandra and to close the virial radius with XMM-Newton.

- We can measure basic cluster properties up to high $z$ ($z \sim 1.3$). This includes morphology from images, gas density radial profile, global temperature and gas mass. Total mass and entropy can be derived assuming isothermality. For the brighter distant clusters, crude temperature profiles or maps can be obtained.

The X-ray images showed that clusters present a large variety of morphology, from regular clusters to very complex systems with multiple substructures. Since substructures in the ICM are erased on a typical time scale of a few Gyr, their detection is the signature of recent dynamical evolution. This manifold morphology indicates a variety of dynamical states in the local cluster population. These observations were consistent with the idea that clusters are still forming to-day, as expected in the hierarchical formation model. The Chandra observation of the merging cluster 1E0657-56 provides a clear example of a shock. The derived Mach number is about $M = 2$. Evidence of strong shocks is rare, but they might be difficult to detect due to projection effects. More surprisingly, Chandra revealed the presence of “Cold fronts” in merging clusters, first discovered in A2142 [7] and A3667 [11]. Cold fronts are contact discontinuities between the cool core of a subcluster moving at near sonic velocity and the surrounding main cluster gas. Across the discontinuity, there is an abrupt jump of the gas density and temperature. The pressure is approximately continuous, which shows that the discontinuity is not a shock. The observations of cold fronts show that the cool core of infalling subclusters can survive the passage through the main cluster core, whereas the gas in the outer region of the subcluster is stripped by ram pressure [7].
1.3 Why do galaxy clusters emit in X-rays?

The Intra-Cluster medium (ICM) is a hot, tenuous and optically thin plasma. The gas density varies from $\sim 10^{-4}$ cm$^{-3}$ in the outer regions of clusters to a few $\sim 10^{-2}$ cm$^{-3}$ in the center. The ICM has mean temperatures in the range $kT = 0.5 - 15$ keV, reflecting the depth of the potential well ($kT \propto GM/R$). Note that the ICM is not an isothermal plasma, although temperature variations are usually small. The ICM is enriched in heavy elements, with typical abundances of 1/3 the solar value. At the temperature of the ICM, H and He are fully ionized. Most electrons come from these two elements. The electron density is nearly independent of the ionization state and is given by $n_e \sim 1.2 n_H$, where $n_H$ is the hydrogen density. The ionization stage of the other elements depends on the temperature.

The X-ray emission is that of a coronal plasma at ionization equilibrium [6]. For a plasma with electronic density $n_e$, temperature $T$, abundances $[Z/H]$ the emissivity scales as:

$$\epsilon_\nu \propto n_e n_i g(\nu, T) T^{-1/2} \exp\left(-\frac{h\nu}{kT}\right)$$ (1.1)

where $g(\nu, T) \propto \ln\left(k_B T / h\nu\right)$ is the Gaunt factor. Whereas the pure bremsstrahlung emissivity is a good approximation for $T \geq 3$ keV clusters, a further contribution from metal emission lines should be taken into account when considering cooler systems. By integrating the above equation over the energy range of the X-ray emission and over the gas distribution, one obtains X-ray luminosities $L_X \sim 10^{43} - 10^{45}$ erg/s$^{-1}$. These powerful luminosities allow clusters to be identified as extended sources out to large cosmological distances.

Examples of X-ray spectra for typical cluster temperatures are shown in Fig. 1.1. Due to the high temperature, the continuum emission is dominated by thermal Bremsstrahlung, the main species by far contributing to the emission being H and He. The emissivity of this continuum is very sensitive to temperature for energies greater than $kT$ and rather insensitive to it below. This is due to the exponential cut-off of the Bremsstrahlung emission. Indeed, it scales as $g(E, T) T^{-1/2} \exp(-E/kT)$. The only line that clearly stands out at all temperatures is the Iron K line complex around 6.7 keV (see Fig. 1.1). We can also observe the K lines of other elements ($Z > 8$, H and He-like ionization states), as well as the L-shell complex of lower ionization states of Iron. However the intensity of these lines rapidly decreases with increasing temperature. Except for the cool clusters ($kT \leq 4$ keV) or in the cooling core present in some clusters, one cannot expect to measure the abundance of elements other than Iron because they are completely ionized.

From above, it is clear that X-ray observations give access to the two characteristics of the ICM, which are the density and the temperature. The shape of the spectrum determines the temperature whereas the normalization provides the emission measure $EM = \int n_e^2 dV$.

The ICM is not strictly isothermal. This means that a temperature inferred from an isothermal fit to the data is actually a ‘mean’ value along the line of sight and in the considered cluster region. This temperature is not simply, as often thought, the ‘emission weighted’ temperature.

The gas density radial profile $n_g(R)$ is usually derived assuming spherical symmetry. In that case:

$$EM(r) = \int_{r}^{\infty} n_g^2(R) R dR / \sqrt{R^2 - r^2}.$$ (1.2)

One can use deprojection techniques or parametric models fitted to the data. A popular model is the so-called isothermal $\beta$-model: $n(R) = n_0 \left[1 + (R/R_c)^2\right]^{-3/2}$, which gives $S(\theta) = S_0 \left[1 + (\theta/\theta_c)^2\right]^{-3\beta+1/2}$. This model fits reasonably well cluster profiles at large radii, but it
underestimates the density in central cooling core of clusters.

In order to characterize the role of cooling in the ICM, it is useful to define the cooling timescale, which for an emission process characterized by a cooling function $\Lambda_c(T)$, is defined as $t_{\text{cool}} = k_B T / (n \Lambda(T))$, $n$ being the number density of gas particles. For a pure bremsstrahlung emission:

$$t_{\text{cool}} \simeq 8.5 \times 10^{10} \text{yr} \left( \frac{n}{10^{-3} \text{cm}^{-3}} \right)^{-1} \left( \frac{T}{10^8 \text{K}} \right)^{1/2}$$

(1.3)

(see [6]). Therefore, the cooling time in central cluster regions can be shorter than the age of the Universe. A substantial fraction of gas undergoes cooling in these regions, and consequently drops out of the hot diffuse, X-ray emitting phase. Observations indicate that the decrease of the ICM temperature in central regions has been recognized as a widespread feature among fairly relaxed clusters. The canonical picture of cooling flows predicted that, as the high–density gas in the cluster core cools down, the lack of pressure support causes external gas to flow in, thus creating a superpositions of many gas phases, each one characterized by a different temperature. Our understanding of the ICM cooling structure is now undergoing a revolution thanks to the much improved spatial and spectral resolution provided by XMM-Newton. Cooling in itself is a runaway process, leading to a quite large fraction of gas leaving the hot diffuse phase inside clusters. Analytical arguments and numerical simulations have shown that this fraction can be as large as $\sim 50\%$, whereas observational data indicates that only $\leq 10\%$ of the cluster baryons are locked into stars. This calls for the presence of a feedback mechanisms, such as supernova explosions or Active Galactic Nuclei which, given reasonable efficiencies of coupling to the hot ICM, may be able to provide an adequate amount of extra energy to balance overcooling.

### 1.4 Mass estimates using Xray data

The condition of hydrostatic equilibrium determines the balance between the pressure force and the gravitational force: $\nabla P_{\text{gas}} = -\rho_{\text{gas}} \nabla \phi$, where $P_{\text{gas}}$ and $\rho_{\text{gas}}$ are the gas pressure and density, respectively, while $\phi$ is the underlying gravitational potential. Under the assumption of a spherically symmetric gas distribution, the above equations read:
\[ \frac{dP_{\text{gas}}}{dr} = -\rho_{\text{gas}} \frac{d\phi}{dr} = -\rho_{\text{gas}} \frac{GM(< r)}{r^2} , \]  

where \( r \) is the radial coordinate (clustercentric distance) and \( M(< r) \) is the total mass contained within \( r \). Using the equation of state of ideal gas to relate pressure to gas density and temperature, the mass is then given by

\[ M(< r) = -\frac{r}{G \mu m_p} \left( \frac{d\ln \rho_{\text{gas}}}{d\ln r} + \frac{d\ln T}{d\ln r} \right) \]  

(1.5)

where \( \mu \) is the mean molecular weight of the gas (\( \mu \approx 0.59 \) for primordial composition) and \( m_p \) is the proton mass. An often used mass estimator is based on assuming the \( \beta \)-model for the gas density profile,

\[ \rho_{\text{gas}}(r) = \frac{\rho_0}{[1 + (r/r_c)^2]^{\beta/2}}. \]  

(1.6)

In the above equation, \( r_c \) is the core radius, while \( \beta \) is the ratio between the kinetic energy of any tracer of the gravitational potential (e.g., galaxies) and the thermal energy of the gas, \( \beta = \mu m_p \sigma_v^2 / (k_B T) \) (\( \sigma_v \): 1-dimensional velocity dispersion). In its original derivation, the \( \beta \)-model was aimed at representing the distribution of isothermal gas sitting in hydrostatic equilibrium within a King–like potential.

It is clear that the two crucial assumptions underlying any mass measurements based on the ICM temperature concerns the existence of hydrostatic equilibrium and of spherical symmetry. While effects of non-spherical geometry can be averaged out by performing the analysis over a large enough number of clusters, the former can lead to systematic biases in the mass estimates. So far, ICM temperature measurements have been based on fits of the observed X-ray spectra of clusters to plasma models, which are dominated at high temperatures by thermal Bremsstrahlung. However, local deviations from isothermality, e.g., due to the presence of merging cold gas clumps, can bias the spectroscopic temperature with respect to the actual electron temperature. This bias directly translates into a comparable bias in the mass estimate through hydrostatic equilibrium.

1.5 Scaling properties of GC in X-rays

The self-similar model assumes that during the process of hierarchical structure formation, under the action of gravity, the baryonic matter follow the dark matter gravitational potential well of the clusters. There, it is heated by adiabatic compression during the halo mass growth and by shocks induced by supersonic accretion or merger events. Since gravity does not have any preferred scale, clusters and groups are in principle expected to appear as scaled version of each other, provided gravity dominates the process of gas heating (Kaiser 1986). Under the additional assumptions that gas is in hydrostatic equilibrium within the dark matter (DM) potential wells and that Bremsstrahlung dominates the emissivity, this scenario predicts self-similar X-ray scaling relations for cluster and group properties:

(i) \( L_X \propto T^2 \) for the relation between X-ray luminosity and gas temperature;

(ii) \( M_{\text{gas}} \propto M_{\text{vir}} \propto T^{3/2} \) for the relation between gas mass, total virialized mass and temperature.

The overall validity of these scaling relations has been confirmed by hydrodynamical simulations of galaxy clusters that included only gravitational heating (e.g., Navarro, Frenk & White 1995; etc).
However, a variety of observational evidences demonstrates that this simple picture does not apply to real clusters. The luminosity–temperature relation is observed to be steeper than predicted, $L_X \propto T^\alpha$, with $\alpha \simeq 2.5$–3 for clusters with $T > 2$ keV (e.g., Arnaud & Evrard 1999; etc), with indications of an even steeper slope at the scale of groups, $T \leq 1$ keV (e.g., Osmond & Ponman 2003).

Also, the relation between gas mass and temperature is observed to be steeper than the self-similar one, $M_{\text{gas}} \propto T^\alpha$, with $\alpha \simeq 1.7$–2.0 (e.g., Vikhlinin, Forman & Jones 1999; etc.).

These observational results indicate that non-gravitational processes (SN and AGN feedbacks, radiative cooling, winds, etc.) that took place during cluster formation must have substantially affected the physics of the ICM and left an imprint on its X-ray properties. A variety of models have been developed so far to explain the resulting ICM properties and, in particular, the lack of self-similarity between clusters and groups.

It is very important to constraint these two relations because they link an intrinsic property, the total mass of the structure (DM+ICM+galaxies), with the luminosity in X-band of the ICM, now simple to observe.
Bibliography


