Emission Lines in X-ray Spectra of Clusters of Galaxies

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Abstract. Emission lines in X–ray spectra of clusters of galaxies reveal the presence of heavy elements in the diffuse hot plasma (the Intra Cluster Medium, or ICM) in virial equilibrium in the dark matter potential well. The relatively simple physical state of the ICM allows us to estimate, with good accuracy, its thermodynamical properties and chemical abundances. These measures put strong constraints on the interaction processes between the galaxies and the surrounding medium, and have significant impact on models of galaxy formation as well. This field is rapidly evolving thanks to the X–ray satellites Chandra and XMM–Newton. Among the most relevant progresses in the last years, we briefly discuss the nature of cool cores and the measure of the Iron abundance in high redshift clusters. Future X–ray missions with bolometers promise to provide a substantial step forward to a more comprehensive understanding of the complex physics of the ICM.

Keywords: X–ray Spectroscopy - Emission Lines – Clusters of Galaxies

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CONTINUUM X–RAY EMISSION FROM CLUSTERS OF GALAXIES

The 0.5-10 keV X-ray band is currently explored by the two X–ray satellites Chandra and XMM–Newton, both launched in 1999. Energies E > 0.5 keV correspond to temperatures T > 5 × 10^6 K. Therefore X–ray astronomy is an ideal observational windows for very hot astrophysical plasmas.

At the beginning of the era of X–ray astronomy, R. Giacconi and collaborators detected X–ray emission from clusters of galaxies with the Uhuru satellite. This emission was identified as bremsstrahlung from hot diffuse plasma (the Intra Cluster Medium, from now on ICM), thanks to its extended distribution and the detection of highly ionized Fe lines in the X–ray spectra. Nowadays the imaging of bright X–ray clusters of galaxies is possible up to redshifts as high as z ∼ 1.3. As an example, in Figure 1 we show the diffuse X–ray emission (in red) from the massive cluster RXJ1252 at z ∼ 1.235. The ICM is generally smoothly distributed according to a beta–profile, consisting in a flat core (sometimes hosting a pronounced spike in emission as in the case of cool–core clusters) followed by an almost isothermal slope ρ_{ICM} ∝ r^{-2} [5]. Typical total luminosities are observed to be roughly in the range L_x ∼ 10^{43} – few × 10^{45} erg/s.

Clusters are bound objects formed via gravitational instability from the fluctuations in the primordial density field [10]. The temperature of the diffuse baryons constituting the ICM is determined by the energy equipartition between the mass components: dark matter, (∼ 80 %), diffuse baryons (∼ 17%) and stars in galaxies (∼ 3 %). The equipartition is reached through violent relaxation during the gravitational collapse
FIGURE 1. Left panel: the X-ray emission (in red) of the cluster RXJ1252 at \( z = 1.235 \) (observed with the Chandra satellite) on top of the optical image (from the VLT). Right panel: Chandra X-ray spectrum of the extended emission in RXJ1252 [14]. The Fe line clearly stands out at the rest-frame energy \( E \sim 6.7 \) keV.

leading to the formation of the cluster. The dark matter, dynamically dominant, and the baryons, rapidly adjust and reach a pressure balance with the gravitational forces. The velocities of particles become randomised, and the structure settles into the virial equilibrium. In its simplest form, the virial theorem writes as \( 2T + U = 0 \), where \( T \) is the average kinetic energy per particle and \( U \) is the average potential energy. This implies that, when virialization can be applied, a measure of the temperature of the ICM gives a good estimate of the total mass of the cluster. Typical cluster masses are in the range \( 10^{14} - 10^{15} M_\odot \), corresponding to \( T_{ICM} \sim 1 - 10 \) keV.

The continuum emission from the plasma is almost entirely given by bremsstrahlung due to the acceleration of electrons in the Coulomb field of positive ions (mainly Hydrogen and Helium nuclei). The relevant case for clusters of galaxies is bremsstrahlung emission averaged over a thermal distribution of electron speeds. This emission can be computed with a classical treatment [15] plus quantum effects (included in the Gaunt factor of order unity) while the relativistic corrections are often ignored (being few percent for \( kT_{ICM} > 10 \) keV). The thermal bremsstrahlung emission simply scales as:

\[
\frac{dE}{dt dV} \propto n_e^2 T_{ICM}^{1/2}.
\]

This implies that the continuum emission of the ICM is strongly dependent on its density distribution (through the electron density \( n_e \)) but only weakly on its temperature.

**X–RAY LINE EMISSION FROM CLUSTERS OF GALAXIES**

While the continuum emission is relatively simple to model, the total emission must also include lines associated to the ions of heavy elements distributed in the diffuse ICM. First, it is important to understand the kind of equilibrium which applies to the
In general, equilibrium is given by a balance between competing processes. In the case of strict thermodynamic equilibrium, every atomic process is as frequent as its inverse process (principle of detailed balance). The classic example is the black body. The detailed balance does not apply to the ICM, nevertheless, it appears to be in the so called collisional (or coronal) equilibrium. To understand what is the collisional equilibrium, we first recall the three main “actors”:

- the kinetic distribution of electrons and ions;
- the atomic level populations;
- the radiation field.

Since the radiation field does not participate to the equilibrium, we consider only the equilibrium between the electron and ion population and the atomic levels. The four key electron–ion collisional processes (and their inverse) are:

- Collisional excitation (Collisional deexcitation);
- Collisional ionization (Three body recombination);
- Radiative recombination (Photoionization);
- Dielectronic Capture (Autoionization).

Only few of these processes are relevant in the collisional ionization equilibrium. In fact, thanks to the very low density of the ICM, atoms are always in their ground state, and collisional deexcitations and three body recombinations are negligible. Since the medium is optically thin, photoionization, photo excitation and scattering are neglected, so that excitation and ionization are dominated by electron ion collisions. Deexcitation is dominated by spontaneous radiative decay, and ions will recombine by radiative or dielectronic recombination. It follows that the equilibrium is given by the balance between impact ionization (and excitation autoionization) and radiative and dielectronic recombination. The interpretation of the resulting spectrum will require a detailed knowledge of the ionization, recombination and excitation rates of several transitions, in particular of K–shell transitions of C, N, O, Ne, Mg, Si and Fe, and L–shell transitions of Si, S, Ar, Ca, Ni and Fe.

To compute the collisional excitation rates we also assume a Maxwellian energy distribution of the electron energies, and a cooling time longer than relaxation time (necessary to achieve equilibrium, condition satisfied thanks to the low density of the ICM except sometimes in the very inner regions). Thus in a steady state the rate of change of the population density $n_j$ of the $j$th ionization state of a given element is given by:

$$0 = \frac{dn_j}{dt} = S_{j-1}n_{j-1} - S_jn_j - \alpha_j n_j + \alpha_{j+1} n_{j+1},$$  \hspace{1cm} (2)

where $S_j$ is the ionization rate for ion $j$ with ejection of one electrons (direct ionization and autoionization), while $\alpha_j$ is the recombination rate of ion $j$ (radiative and dielectronic). The ionization structure is derived by solving for each element with atomic
number \( Z \) a set of \( Z+1 \) coupled rate equations. In the steady state the equation reduces to:

\[
\frac{n_{j+1}}{n_j} = \frac{S_j(T_{ICM})}{\alpha_{j+1}(T_{ICM})}.
\] (3)

Thus the ratio of two adjacent ionization states of a given element depends only on \( T_{ICM} \) and not on the electron density \( n_e \) as long as stepwise ionization (more than one collision) in \( S_j \) and three body recombination in \( \alpha_{j+1} \) can be neglected. The fraction of ions at the stage \( z \) of a given element, \( \eta_z \), can be expressed directly as a function of the ratio of adjacent states.

The emissivity of a given emission line (which is proportional to the Equivalent Width, \( EW \), of a line) is given by \( \varepsilon_{21} = n_e n_i \gamma_{21}(T_{ICM})E_{12} \) where \( \gamma \) is the collisional excitation rate for transition \( E_{12} \) and \( n_i = A_Z \eta_z(T_{ICM})n_H \) is the density of the ion in the ground state. Once the coefficient \( \alpha \) and \( S \) are known from fundamental atomic physics, the concentration of each ion of a given element can be straightforwardly computed from the measure of the equivalent width. An example of the ion concentration of some elements as a function of \( T_{ICM} \) is shown in Figure 2. The equivalent width can be measured directly through X–ray spectroscopy and it is defined as:

\[
EW \equiv \int \left( \frac{I_\nu - I_0}{I_0} \right) d\nu,
\] (4)

where \( I_\nu \) is the spectrum, \( I_0 \) is the continuum component, and the integral is over an energy range close to the line. Since \( EW \) is directly proportional to the ion concentration \( n_i/n_H \), it depends only on temperature and abundance.

There are of course sources of uncertainties. The first one is due to the accuracy of atomic physics. Both ionization and recombination rates can be uncertain by a factor 2–4. Fortunately, ionization and recombination rates for H–like and He–like ions, which emit lines that are among the strongest in astrophysical plasmas, are known more accurately.
The second critical aspect is given by the spectral resolution. X–ray spectra may be obtained directly with CCD imagers or with reflection gratings spectrometers. In the first case, the spectral resolution is limited and several lines often blend with each other. Only few bright sources can be analyzed with grating spectroscopy, due to the high S/N required. Therefore, in some cases, the abundance of several elements cannot be recovered accurately.

Finally, a source of uncertainty comes from an aspect intrinsic to the physics of clusters: in general the ICM may have different temperatures at different radii, with significant gradients in the central regions. This aspect can be modelled, or can be mitigated in bright clusters thanks to spatially resolved spectroscopy and deprojection techniques. In any case, the presence of different temperatures along the line of sight significantly affects abundance measures.

**IRON ABUNDANCE AT HIGH REDSHIFT**

Temperatures and abundances are measured at the same time (from line ratios and shape of the continuum) with the use of fitting packages which implement atomic physics and the collisional equilibrium equations. Heavy elements (generally called metals), among which Iron is the most prominent, are always found in the ICM. Over a wide range of $T_{ICM}$, the EW of the Fe K–shell line (mostly from Fe + 24 and Fe +25) is several orders of magnitudes larger than any other spectral feature. At lower energies O, Si, S, and L–shell transition in lower Fe ions show significant EW. Their abundance is consistent with being produced by the elliptical cluster galaxies [9]. In general, Fe abundance is observed to be about $Z \sim 0.4Z_\odot$ (where the Iron solar abundance is $[1]$) at least for $T_{ICM} > 5$ keV. Abundances of other elements can be measured either in very high S/N spectra, or in low temperature clusters, since for $T_{ICM} \leq 1$ keV the number of ions species of elements lighter than Iron become significant (see Figure 2). The ratio of the abundance of the $\alpha$ elements over Fe is very relevant to understand the relative contribution of TypeII and TypeIa SNe. However, here we will discuss only some results on the Fe abundance at high redshift.

We recall that the Fe line can be measured in the highest redshift clusters selected in X–rays, as shown in the right panel of Figure 1. In a recent work, Balestra et al. (2007) used the Chandra archive for clusters at redshift $z \geq 0.4$ to compute the average Fe abundance in several redshift bins. The result, shown in the left panel of Figure 3, indicate that the Fe abundance in the inner parts of X–ray hot clusters (within ~ $0.2R_{vir}$) is changing by a factor of about 2 between now and $z \sim 1.3$ (which corresponds to a look back time of ~ 9 Gyr).

This simple result requires a complex interpretation. On one hand, we notice that the Fe abundance is already significant at $z > 1$, in line with the expectation that the bulk of star formation in massive spheroids, responsible for the large majority of the metals, occurs at $z \geq 2$. On the other hand, we do not expect much star formation responsible for Iron production after $z \sim 0.5$. Therefore, the most likely interpretation of the increase of the average Iron abundance in the inner 0.2$R_{vir}$ of clusters, may be due to deposition of previously enriched gas towards the center. Currently, several approaches can be used. A phenomenological model based on detailed chemical galactic evolution, shows that the
Fe increase is consistent with the transformation of gas–rich spirals into S0 galaxies, with the consequent deposition of highly enriched gas in the central regions where the ram pressure stripping is more efficient [4]. N–body Hydrodynamic simulations, on the other hand, show that high abundance, low entropy gas, previously associated to galaxies or group–size halos, may sink to the center during the mass growth of the cluster (see Cora et al. in preparation). These models favour a dynamical origin of the observed evolution, but they must also explain the abundance profiles and the temperature gradients in cluster cores observed in spatially resolved spectral analysis (see [12] and [2]).

### THE NATURE OF COOL CORES

The total emission due to bremsstrahlung and lines can be expressed as $L \propto n_e^2 \Lambda(T_{ICM})$ where $\Lambda$ is the cooling function including all the transitions for a given $T_{ICM}$. The cooling time $t_{cool}$ is defined as the ratio of the total internal energy of the ICM divided by the bolometric ICM emission. It turns out that $t_{cool} \propto T_{ICM} \Lambda^{-1} n_e^{-1}$ (see [16]).

If $t_{cool} << t_H$ the baryons are expected to cool out of the hot phase and eventually recombine and form stars or clouds of cold gas. In many local clusters it is possible to compute the cooling time down to very small scales (about few kpc). In several cases a clear decrease of the temperature is observed towards the center, and the cooling time within 10 kpc can be significantly less than 1 Gyr (see [12]). It seems unavoidable to predict that baryons are flowing to the cold phase at a rate of the order of 100, sometimes 1000 $M_\odot$ yr$^{-1}$ in more than half of local clusters. The simplest model based on isobaric
cooling, predicts a spectrum rich in emission lines, which are strongly increasing at low $T_{ICM}$ due to the higher number of ion species. However, grating spectroscopy of the brightest central regions of clusters, with the XMM–Newton satellite, provided a surprising result. Many of the lines expected in cooling flows were missing from the observed spectra [11], as shown in the example of Figure 3 (right panels). It can be shown that the lowest temperature in the center is of the order of 1/3 of the virial one.

This discovery has a strong impact: it implies that the ICM is kept above a temperature floor (not too far from the virial one) by some heating mechanism. It follows that there are no more cooling flows, at least not as strong as previously thought, but only cooling cores. On one hand, this explains why we never observed the cooled gas resulting from the cooling process, neither in form of stars nor of cool gas. On the other hand, there is no consensus on the sources which constantly heat the ICM. This is an open problem, relevant not only for ICM, but also for general framework of galaxy formation and evolution.

In fact, this problem reminds us of the cooling catastrophe (also known as cooling crisis). In the standard galactic formation scenario, baryons in CDM halos cool via thermal bremsstrahlung and line emission. Baryons are assumed to turn into stars when $t_{cool} < H^{-1}$ [18]. But the blind application of this criterion would result in the large majority of the baryons locked into stars. This is a consequence of the high power at low mass scales in the CDM power spectrum. The low fraction of baryons turned into stars, observed to be around 10% everywhere in the Universe, requires an ubiquitous mechanism which hampers the baryons from cooling. It would be nice if the same heating process might explain the cooling core problem and solve the cooling catastrophe at the same time. This still unknown process, or better, these class of processes, are known under the name of feedback, a key ingredient in every model of cosmic structure formation.

The main problem with feedback, is that any process we may think of, scales with volume (and then with density), while cooling is a runaway process proportional to $p^2$. Therefore there is not an obvious, mechanism for self–regulation. Understanding feedback is nowaday the most compelling goal for structure formation models. Main candidates are SNe explosions and stellar winds (as confirmed by the presence of heavy elements in the ICM) and the much more energetic output from AGN. A spectacular example that favours AGN as the best candidates as the main heating sources, is the X–ray image of the Persues cluster [6], where hot bubbles created by the jets are pushing the ICM apart, with a total mechanical energy sufficient to heat significantly the diffuse baryons. Still, how and on which time scale the energy is thermalized into the ICM is still a matter of debate.

**PROSPECTS FOR THE FUTURE AND CONCLUSIONS**

The results discussed so far are based on X–ray spectra from CCD, with a modest energy resolution, and from reflection grating spectrometers, with high energy resolution but suitable only for very bright sources. Given the complex spatial structure of the thermodynamical properties of the ICM, an ideal instrument should attain at the same time good spatial and spectral resolution. This can be achieved with X–ray bolometers in
the soft band, where most of the lines are. The bolometer that is expected to be onboard of the proposed EDGE satellite \[13\] will be able to detect absorption and emission lines from the Warm Hot Intergalactic Medium (WHIM) which includes the majority of the baryons in the Universe \[7\]. With a nominal resolution of few eV, it will be able to resolve most of the X–ray lines, and to measure the thermal broadening and possibly the bulk motions of the ICM in the inner regions of clusters, directly addressing aspects like viscosity and turbulence. In addition, it will be possible to detect the low surface brightness ICM in the outskirts of clusters and in filaments.

In the meanwhile, we still have to exploit the full potential of the Chandra and XMM–Newton satellites, which are still operating, and which already provided many archival cluster observations. The results (among many others) presented in these Proceedings, show that line emission diagnostic in X–ray spectra of clusters of galaxies are an un–valuable tool to study the chemical and the thermodynamical state of the ICM. Another aspect I wanted to stress, is that studies of the chemical enrichment of the ICM and of the temperature structure in cool cores are extremely important for the entire field of galaxy and structure formation. For example, the mechanism responsible for the temperature floor in cool cores of clusters may be tightly related to the one responsible for the quenching of the star formation in massive spheroids at $z \geq 2$. Therefore, the technological challenge toward spatially resolved, high resolution X–ray spectroscopy, will be the way to achieve important steps forward in many aspects of extragalactic astrophysics.

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