The Intra-Cluster Medium

Silvano Molendi

Istituto di Astrofisica Spaziale e Fisica Cosmica, Sezione di Milano, Via Bassini 15, I-20133
Milano, ITALY

Abstract.

The Intra-Cluster Medium (ICM) is a rarefied, hot, highly ionized, metal rich, weakly magnetized plasma. In these proceeding, after having reviewed some basic ICM properties, I discuss recent results obtained with the BeppoSAX, XMM-Newton and Chandra satellites. These results are summarized in the following five points. 1) Currently available hard X-ray data does not allow us to constrain B fields in radio halos, the advent of hard X-ray telescopes in a few years may change the situation substantially. 2) There is mounting evidence that temperature profiles of clusters at large radii decline; however investigation of the outermost regions will have to await a new generation of yet unplanned but technologically feasible experiments. 3) The ICM is polluted with metals, the enrichment has probably occurred early on in the cluster’s life. The abundance excess observed at the center of CC clusters is due to the giant elliptical always found in these systems. 4) Chandra and XMM-Newton observations of relaxed clusters have falsified the previously accepted cooling flow model, heating mechanisms that may offset the cooling are actively being sought. 5) The superb angular resolution of Chandra is allowing us to trace a previously unknown phenomenon intimately related to the formation of galaxy clusters and of their cores.

SETTING THE CONTEXT

In this section I shall review some of the basic properties of the ICM, a more detailed discussion may be found in the excellent book “X-ray emission from clusters of galaxies” [1]. The ICM is a tenuous plasma, typical densities range between $10^{-4}\text{cm}^{-3}$ in the outer regions of clusters and a few $10^{-2}\text{cm}^{-3}$ in the core of more relaxed systems (e.g. [2]). These are very low densities; the tail lobes of the earth magnetosphere, which are considered the "best-vacuum" in the earth’s vicinity, have densities of the order of $10^{-2}\text{cm}^{-3}$. The ICM is hot, temperatures are in the range of $10^7$ to $10^8$ K (1-10 keV), it is also highly ionized; light elements such as H and He are completely ionized, heavier elements are partially ionized. The ICM is chemically enriched, with heavy elements such as O, Mg, Si, Ar, Ca, Fe and Ni, in almost solar proportions. One issue, which is often overlooked, is that the ICM is a magnetized plasma, with B fields in the range between 0.1 $\mu G$ and a few $\mu G$ (e.g. [3] and references therein). These values are the smallest found in any astrophysical context.

The ICM emits radiation at X-ray wavelengths, this emission is resolved by imaging X-ray experiments, current instrumentation traces emission out to 1-2 Mpc from the core. The ICM cools by emitting radiation, the cooling timescale, $t_{cool}$, may be estimated from the ratio $u/\varepsilon$ where $u$ is the energy density and $\varepsilon$ the emissivity,

$$t_{cool} \sim 8.5 \times 10^{10}\text{yr} \left(\frac{n_p}{10^{-3}\text{cm}^{-3}}\right)^{-1} \left(\frac{T}{10^8\text{K}}\right)^{1/2},$$
where \( n_p \) is the proton density and \( T \) is the plasma temperature. Except for the innermost regions where \( n_p \) is high, gas cools on timescales larger than the Hubble time (i.e. the age of the Universe, \( \sim 14 \text{Gyr} \)) which is taken as an estimate of the age of galaxy clusters. Thus, at least to first approximation, we may consider the ICM as a stationary ball of hot plasma. Because of the very slow rate at which the plasma is losing energy by emitting X-rays no major on-going heating of the gas is necessary. The ultimate origin of the bulk of the thermal energy of the ICM is the gravitational energy lost by the plasma as it falls into the cluster’s potential well. Evidence of non gravitational forms of heating have been found over the last decade (e.g. [4]), however the contribution of such heating is thought to be more important in the less massive systems, i.e. galaxy groups, than in galaxy clusters. The temperature of the ICM is related to the depth of the potential well and to the total mass of the cluster.

As already pointed out, the ICM is highly ionized, under such conditions Coulomb collisions are the dominant forms of interaction in the plasma. Under the reasonable assumption that electrons and ions are in thermal equilibrium amongst themselves and each other, the mean free path for both species is:

\[
\lambda_e \sim \lambda_i \sim 23 \text{kpc} \left( \frac{n_p}{10^{-3} \text{cm}^{-3}} \right)^{-1} \left( \frac{T}{10^8 \text{K}} \right)^2.
\]

The mean free path is much smaller than the cluster itself and the ICM may be treated as a fluid satisfying hydrodynamical equations.

The timescale over which a sound wave crosses the cluster, \( t_s \) is:

\[
t_s \sim 6.6 \times 10^8 \text{yr} \left( \frac{D_c}{\text{Mpc}} \right) \left( \frac{T}{10^8 \text{K}} \right)^2,
\]

where \( D_c \) is a measure of the cluster size. Since \( t_s \) is typically smaller than the cooling timescale and of the other timescales regulating the behavior of the cluster, the ICM may be assumed to be, at least to first approximation, in hydrostatic equilibrium.

The pressure associated to the ICM magnetic field is typically much smaller than the thermal pressure of ions and electrons, thus the magnetic field is not expected to drive the dynamics of ICM. This however does not mean that the magnetic field has no effect on the ICM, indeed the electron gyration radius, \( r_e \) which is:

\[
r_e \sim 7.0 \times 10^{-14} \text{kpc} \left( \frac{B}{\mu \text{G}} \right)^{-1} \left( \frac{T}{10^8 \text{K}} \right)^{1/2},
\]

is many orders of magnitude smaller than the electron mean free path. This implies that electrons, as well ions for which a similar results holds, will be forced to spiral along magnetic field lines. This is expected to affect some of the properties of the ICM such as its ability to conduct heat.

**DERIVING PHYSICAL QUANTITIES**

In this section I shall briefly review the methods employed to measure some of the fundamental quantities characterizing the ICM. The ICM density \( n \), temperature \( T \), and
metallicity $Z$ are usually recovered from X-ray measurements. The continuum emission is dominated by thermal bremsstrahlung, whose emissivity, $\varepsilon_\nu$, may be expressed as $\varepsilon_\nu \propto n_e^2 T^{-1/2} \exp\left(-\frac{\hbar \nu}{kT}\right)$; the temperature is determined from the position of the exponential cut-off in the X-ray spectrum. An alternative method, which is sometimes employed, is to measure the ratio of emission lines produced by the same atomic species (e.g. [5]). Since the plasma is in ionization equilibrium the line ratio can be used to estimate the ionization state of the specific atomic species and consequently the temperature of the plasma. The gas density is estimated from the X-ray luminosity:

$$L(\nu_1, \nu_2) = \int_{\nu_1}^{\nu_2} d\nu \int_V dV \varepsilon_\nu \propto \langle n_e^2 \rangle T^{1/2},$$

where $[\nu_1, \nu_2]$ and $V$ are respectively the frequency range and the volume over which $\varepsilon_\nu$ is integrated. The estimate requires some assumptions on the distribution of the gas within the cluster. Alternatively, if spatially resolved measurements are available, deprojection techniques (see [6] and references therein) may be used to derive density profiles. The metal abundances for a given species is recovered from measurements of the equivalent width of emission lines radiated by that specie. Indeed the equivalent width of a line scales linearly with the metal abundance of the element producing it.

Independent constraints on the physical quantities describing the ICM may be obtained from measurements performed at the other end of the electromagnetic spectrum through the Sunyaev & Zeldovich (hereafter SZ) effect. The SZ effect may be described as the distortion of the cosmic microwave background spectrum by the electrons in the ICM through Inverse Compton scattering. A key parameter describing the strength of the distortions is the Compton $y$ parameter defined as: $y \equiv \int \left(\frac{kT}{m_e c^2}\right) \sigma_T n_e dl$, where $\sigma_T$ is the Thompson cross section and the integration is on the line of sight. At the present time SZ measurements are much less sensitive than measurements performed at X-ray wavelengths, however the situation may change radically with the coming on line of new instrumentation over the next decade [7]. It is worth noting that while the bremsstrahlung emissivity scales like $n_e^2$, the $y$ parameter scales like $n_e$, thus the SZ effect may, in the not too distant future, allow us to map the low density ICM in the outer regions of galaxy clusters unaccessible to current X-ray instrumentation. Perhaps of even greater importance is the fact that the $y$ parameter may be viewed as a sort of line of sight integrated pressure ($y$ scales as the product of temperature and density). This of course means that spatially resolved SZ measurements will be sensitive to pressure gradients and discontinuities in much the same way that spatially resolved X-ray measurements are sensitive to $n_e^2$ gradients and discontinuities. Thus spatially resolved SZ measurements may turn out to be the most effective way to detect and characterize shocks (pressure discontinuities) which we know must be present in the ICM (e.g. [8]) but that have so far been very hard to find at X-ray wavelengths, probably because they mostly occur in the low density outer regions of clusters. The characterization of the thermodynamical properties of the ICM in the outer regions of clusters is, in my view, a key issue and I will come back to it in the next section.

The intensity of the magnetic field is generally estimated from radio observations; the Faraday rotation measure, $RM$, of cluster or background radio sources is combined with measurements of the electron density to estimate the magnetic field of the plasma.
from the relation: \( RM \propto \int n_e \vec{B} d\ell \), where the integration is extended over the line of sight.

There are however large uncertainties associated to these measurements. Firstly only a few, not necessarily representative lines of sight are sampled \([9]\); secondly the estimate of the magnetic field intensity is critically dependent upon the scales over which the field is ordered \([10]\).

**Hard tails**

There is an alternative way of estimating magnetic fields, at least in some clusters. This method takes advantage of the fact that some clusters feature diffuse synchrotron emission (radio halos). In these cases, cosmic microwave background photons will interact with the radio emitting electrons and be inverse Compton scattered to high energies, where they can be detected. Since the synchrotron luminosity, \( L_{\text{sync}} \), and the Compton luminosity, \( L_{\text{IC}} \), scale respectively as \( n_e U_B \) and \( n_e U_{CMB} \), where \( n_e \) is the relativistic electron density and \( U_B \) and \( U_{CMB} \) are respectively the magnetic field energy density and Cosmic Microwave background energy density, it is easy to see that: \( L_{\text{IC}} \propto L_{\text{sync}} U_{CMB}/U_B \). Thus joint radio and X-ray measurements can lead to an independent and firmer measurement of the magnetic field in clusters with radio halos. First detection of a possible IC component has been achieved with the PDS instrument on-board BeppoSAX in Coma \([11]\), A2256 \([12]\) and A754 \([13]\). In these objects the Authors report detection of excess emission above the thermal component at high energies (hard tails). The strongest detection was on Coma. In this cluster \([11]\), using the method described above, estimated a magnetic field of \( \sim 0.14 \mu G \).

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**FIGURE 1.** Coma spectrum measured with the PDS on board BeppoSAX, data is from the second Coma observation (December 2000). The crosses are the data, the continuous line is the best fit with a thermal model.
Recently [14] have analyzed a new, longer and lower background PDS observation of the Coma cluster finding no evidence for a hard tail (see Fig. 1). Moreover, work in collaboration with the PDS Hardware Team has lead to the identification of an error in the reduction leading to the spectrum published in [11], once this is corrected for, the significance of the tail drops below 3σ. [14] conclude that there is no compelling evidence for a hard tail in the PDS Coma spectrum (see however [15] for a different point of view). In summary the measurement of the IC component offers an elegant and potentially powerful method to determine magnetic fields in clusters with radio halos. However, to employ this method fruitfully, we need substantially more sensitive hard X-ray instrumentation. A breakthrough may come in the not too distant future when the first hard X-ray telescopes will be flown.

TEMPERATURE PROFILES

Spatially resolved measurements of the ICM temperature are important for two main reasons: firstly they can be used to determine the total mass of clusters through the hydrostatic equilibrium equation (only about 20-30% of the total mass in clusters is in the form of visible matter, while the bulk of the mass is in the form of non-baryonic dark matter); secondly they provide important clues on the thermodynamic state of the ICM.

In Fig. 2 I report the mean temperature profile for a sample of 23 galaxy clusters
observed with BeppoSAX [16]. The sample is divided in cool core (CC) and non cool core (NCC) clusters. As can be seen from Fig. 2, beyond the core where CC clusters show a decrement (this is indeed the reason why they are called Cool Core clusters), the mean CC and NCC profiles are similar. Up to about 0.2 $r_{180}$ the profiles are flat, beyond this radius the profiles decline. It should not go unmentioned that the existence and extension of the outermost region has been the subject of a lively debate [18], [19], [20], [21]. By fitting the temperature profiles from $r > 0.2r_{200}$ with a power law of the form $T(r) \propto r^{-\mu}$ and assuming that the density profile is described by a power law of the form $n(r) \propto r^{-2}$, we find that the polytropic index, $\gamma$, for CC and NCC clusters is respectively $1.22 \pm 0.04$ and $1.16 \pm 0.03$. These values are about half way between the isothermal, $\gamma = 1$ and adiabatic $\gamma = 5/3$ case. In Fig. 2 we also compare the mean BeppoSAX profile with a mean XMM-Newton profile [17]. The latter has been obtained by averaging the recently published temperature profiles of 14 galaxy clusters in the redshift range $0.1 < z < 0.3$. As can be seen the XMM-Newton profile, albeit qualitatively similar, appears to be somewhat flatter than the Beppo-SAX one. However the most interesting point is that, contrary to pre-flight expectations the XMM-Newton profiles do not extend significantly further out than the BeppoSAX profiles. This is particularly unfortunate as the regions around the virial radius ($r_{\text{vir}} \sim r_{180}$) are expected to carry much information on the formation process of galaxy clusters (e.g. [22]). Indeed I am inclined to believe that a solid observational characterization of these regions would allow us to improve considerably our understanding of the physics of galaxy clusters as a whole perhaps providing important clues to the solution of outstanding open problems. It is a matter of considerable concern that currently planned missions will not be able to address this important issue although, from a technological point of view, the problem of constructing an experiment sensitive to low surface brightness regions is not a particularly challenging one.

**ABUNDANCE PROFILES**

Clusters are the largest structures in the Universe to have clearly decoupled from the Hubble flow, in principle the ICM could be made of H and He only. The presence of heavy elements such as Fe in proportions which are almost solar demonstrates that a sizeable fraction of the ICM must have been processed in stars. This establishes an important connection between the Galaxies and the ICM in clusters. Global measurements indicate that the ICM in clusters has a mean metallicity of $Z \sim 0.3Z_\odot$ with a rather small dispersion around this mean. [23] have shown that for a sample of rich clusters, there is a strong correlation between the total Fe mass in the ICM and the bolometric luminosity of early-type galaxies (E/S0). No correlation is present with spiral galaxies indicating that a non-negligible fraction of the ICM likely originates in E/S0 galaxies. Another important piece of information is that there is no evidence of variations of $Z$ with redshift out to $z \sim 1.2$ ([24] and references therein), implying that the bulk of the enrichment occurs at redshifts larger than $\sim 1.2$.

From the analysis of a sample of 23 galaxy clusters observed with BeppoSAX [25] (see Fig. 3) we have found that while NCC clusters show essentially flat abundance
profiles, CC clusters show evidence of an abundance excess in their core. Detailed investigations [26], [25], [27] have shown that the excess observed in the core of CC clusters (see Fig. 3) is due to enrichment from the giant galaxy found at the center of these systems. The amount of iron associated to the excess ranges from a few $10^9$ to a few $10^{10} M_\odot$ and is a relatively low fraction of the total Fe mass contained in the cluster, less than $\sim 10\%$, [27].

THE NEW STUFF

In the last 3 years observations carried out with the latest generation of X-ray satellites, i.e. Chandra and XMM-Newton, have brought about some rather important changes in our understanding of galaxy clusters. In the this section I will cover two topics which have greatly benefited from the new X-ray observations.

Cool Cores

Since this topic is covered in detail elsewhere in this volume [28], I will limit myself to some elementary considerations and then focus on a specific object that I find of particular interest.
Chandra and XMM-Newton observations of relaxed clusters have shown that the cool gas in their core is characterized by a minimum temperature of 1-3 keV (e.g. [29], [30]). Moreover detailed analysis of some close by clusters (e.g. Virgo; [31] and next subsection) have shown that the gas is well described by one or two temperature models. Both these observational findings are in clear violation of the previously adopted cooling flow model. The fall of the standard cooling flow models leaves a fundamental question open: what happens to the gas that should be cooling on very short timescales? Two classes of solutions have been proposed: in the first class [32] the cooling gas is there but is somehow hidden from our view; in the second class the gas is prevented from cooling below a minimum temperature by some form of heating: various mechanisms have been proposed, some have to do with heating from the ICM outside the cool core (e.g. [33], [34], [35]), some invoke heating from the Active Galactic Nucleus commonly found in the core of these systems (e.g. [36], [37]). Although much work has been done, most heating mechanisms that have been identified so far seem to have rather obvious flaws. Further exploitation and digestion of Chandra and XMM-Newton data as well new observations with the soon to be launched ASTRO-E2 satellite may hold the key to the cool core puzzle.

**Virgo/M87**

The core of the Virgo cluster, hosting the giant elliptical galaxy M87, is very close to us. At the distance of M87 1 arcminute corresponds to about 5 kpc and very small structures are resolved. Detailed analysis of the Chandra and XMM-Newton data show that most regions in the core of Virgo are adequately described by one temperature models [31], in a few regions, co-spatial with intense radio emission [38], two temperature models provide a much better description of the data. In these regions we find that most of the gas has a temperature very similar to that of nearby one temperature regions (hot component) and a small fraction has a smaller temperature (cool component). The ratio of the plasma density of the cool, \( n_{cool} \), and hot, \( n_{hot} \), component may be expressed as: \( n_{cool} / n_{hot} \sim (EI_{cool} V_{hot})^{1/2} / (EI_{hot} V_{cool})^{1/2} \), where \( EI_{cool} \) and \( V_{cool} \) (\( EI_{hot} \) and \( V_{hot} \)) are respectively the emission integral and the volume associated to the cool (hot) component. Assuming pressure equilibrium between hot and cool components, \( n_{hot} kT_{hot} = n_{cool} kT_{cool} \), it is easy to show that \( V_{cool} / V_{hot} \sim EI_{cool} / EI_{hot} (KT_{cool} / KT_{hot})^2 \). Typical values of \( V_{cool} / V_{hot} \) range between 10\(^{-3}\) and 10\(^{-2}\), more precise calculations based on actual deprojection of the data are in agreement within a factor of 2. This implies that the size of individual cool structures is much smaller than the size of the regions from which spectra have been extracted. From images accumulated in two different energy bands, the first sensitive to the cool component and the second to the hot component, it is possible to derive \( EI_{cool} / EI_{hot} \) images. This has been done both with XMM-Newton EPIC and Chandra ACIS-S data. The images show that \( EI_{cool} / EI_{hot} \) is almost everywhere smaller than 0.4 implying that \( V_{cool} / V_{hot} \) is smaller than \( \sim 0.2 \). The cool blobs are not resolved by XMM-Newton or Chandra, implying that their typical size must be smaller than \( \sim 300 \) pc. Since the timescale for conduction to operate on such small scales, \( 10^5 \) yr, is much smaller than other timescales presiding over the be-
behavior of the plasma we conclude that conduction must be heavily suppressed. For many years it has been recognized that conduction might be suppressed in the ICM and magnetic fields have been invoked as a possible means to achieve suppression, it is therefore of considerable interest that in the case of M87 the cool blobs, where conduction is suppressed, are co-spatial with radio lobes, where magnetic fields are present.

Cold Fronts

One of the first Chandra observations was performed on the galaxy clusters A2142 \cite{39}. The image revealed two sharp bow-shaped, shock like, surface brightness edges. However these are not shocks: shocks produce compression and heating, if these structures were shocks, one would expect that the denser gas would also be hotter, on the contrary the data reveals that the denser gas is cooler. The discontinuities observed by Chandra are a new phenomenon that has been termed “cold front”. Cold fronts have now been observed in the core of many CC clusters, e.g. A1795 \cite{40}, Centaurus \cite{41}, 2A 0335+096 \cite{42}, and in merging clusters, e.g. A2142 \cite{39} and A3667 \cite{43}. In the latter case the edges mark dense subcluster cores that have survived a merger, while in the former they provide evidence of gas motions possibly associated to past mergers \cite{40} or to the relative motion of the cD galaxy with respect to the ICM \cite{44}. The edges of cold fronts are very sharp, in some cases (e.g. A2142 \cite{46}, A3667 \cite{45}), it has been shown that the surface brightness drops over scales smaller than the Coulomb mean free path, indicating that heat conduction must be suppressed across the discontinuity.

Recently \cite{47} has reported that in a sample of 33 CC clusters density edges are seen in 19 (60%). Since typical velocities of the gas in the CC systems are in the order of 1/2 of the sound speed the associated energy will be about 1/4 of the thermal energy of the plasma. Of some interest is also the fact that gravitational mass estimates of cool cluster cores based on the hydrostatic equilibrium equation must frequently be affected by systematic errors of the order of various tens of percent.

In the case of merging clusters the presence of subcluster cores that have survived a merger indicates that the virialization process in these clusters is far from being complete. Indeed it is quite likely that these substructures, or parts of them, will never be completely dissolved within the ICM and that, after having lost most of their kinetic energy, they will fall to the bottom of the cluster potential well where they will eventually contribute to the formation of a cool core.

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