

Summary: Clusters of Galaxies and the High Redshift Universe Observed in X -Rays

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This Meeting featured the recent advancements in our understanding of galaxy clusters and the distant Universe, achieved by the past and new generation of X -ray satellites. I summarize here the main themes that have been discussed: (*a*) Clusters of galaxies as probes of cosmological models; (*b*) The physics of cosmic baryons trapped within the potential wells of galaxy clusters; (*c*) The origin of the cosmic X -ray background and the nature of the contributing sources.

1 Introduction

X -ray extragalactic astronomy is experiencing a sort of revolution. The unprecedented observational capabilities, which are offered by the Chandra and the XMM–Newton satellites, are triggering a significant change of perspective in our understanding of the processes of formation and evolution of cosmic structures. At the same time, X -ray observations are complemented and integrated by data at other wavelengths, from radio, to optical, to EUV and γ . Undoubtedly, this Conference has been organized in the right moment (and in the right place!) to gather people working on frontier observations and modelling of galaxy clusters and on high-redshift X -ray sources.

As for galaxy clusters, we are approaching the full exploitation of the data flow provided during the last decade by the ROSAT, ASCA and Beppo–SAX satellites. At the same time, the X -ray observations realized during the last year or so with the Chandra and XMM–Newton satellites are drastically improving our knowledge of the physics of the intra–cluster medium (ICM). The unprecedented spatial resolution of the Chandra satellite reveals a variety of small scale details in the distribution of the baryonic component of clusters, which are witnessing the complex dynamical and physical processes taking place in cluster central regions. At the same time, the good spectral resolution of XMM–Newton, joined with a good spatial resolution, allows an order-of-magnitude refinement in the mapping of the temperature and cooling structure of the ICM, and of the pattern of its metal enrichment. There is no doubt that such a detailed description of the ICM physics is challenging the theorist's view of clusters as arising from semi-analytical and numerical modelling. Furthermore, the possibility of using clusters as high-precision probes of cosmological models relies on an accurate understanding of the connection between their internal properties, which are affected by gas physics, and the cosmic evolution of the global structure of the Universe, which is mainly driven by gravity.

Besides the detailed investigation of nearby objects, deep X -ray pointings are now peering deep into the distant Universe and are unveiling the evolution of different population of cosmic

structures. A handful clusters at $z > 1$ have been secured, mostly by **ROSAT** data, and there is little doubt that their number will significantly increase in the next future. Observations of such extreme clusters with satellites of the last generation are tracing the epoch at which they shape out from the cosmic web and make baryons switching on in the X -ray light.

Finally, deep pointed observations are nowadays providing the solution to the long-standing debate about the nature of the X -ray background (XRB). The spatial resolution of Chandra is now resolving a large fraction of the XRB into discrete sources, up to energies of about 7 keV. At the same time, XMM deep fields are extending this study to higher energies, $\simeq 12$ keV, therefore recovering the very hard sources which are missed by the softer energy coverage of Chandra.

2 Cosmology with X -ray galaxy clusters

Using X -ray galaxy clusters for cosmological purposes has two main advantages with respect to clusters selected in the optical band. First of all, X -ray emissivity is proportional to the square of the local gas density, while optical light has, to a good approximation, only a linear dependence on the galaxy density. This makes clusters looking sharper in the X -ray than in the optical sky, with the obvious consequence of reducing projection contamination and allowing for a better definition of the sample selection function¹. Furthermore, the X -ray luminosity, L_X , is better correlated to the total collapsed cluster mass, both from a theoretical and a phenomenological point of view, than the optical (i.e., Abell-like) richness. Press-Schechter-inspired approaches and N-body simulations allow cosmological models to predict statistical properties (e.g., number density and correlation function) for the cluster population of a given mass. Therefore, X -ray clusters have the obvious advantage of being selected according to an observable quantity, L_X , which is well correlated with the theoretically predicted mass.

2.1 Large-scale structure

The **ROSAT** All Sky Survey (RASS) has been a sort of gold mine over the last decade for the extraction of large samples of galaxy clusters. The most recent of these samples, the REFLEX and the NORAS surveys, contain ~ 1000 clusters, down to a flux of a few $\times 10^{-12}$ erg s $^{-1}$ cm $^{-2}$ ([0.1-2.4] keV energy band), and allow to trace the large-scale structure (LSS) of the Universe out to $\sim 10^3$ Mpc, through the estimate of the two-point correlation function and the power spectrum^{2,3}. Although a firm detection of a large-scale turn-over of the power spectrum has still to be confirmed, nonetheless there is a clear sign that it stops continuously increasing toward small wavenumbers, thus witnessing the “end of greatness” in the cosmic LSS. Taking advantage of the X -ray selection, it is then possible to compute the biasing factor for these clusters once a cosmological framework is assumed⁴. As a result, it is shown that the clustering of X -ray clusters is consistent (surprise, surprise!) with a low-density CDM model, with $\Omega_m \simeq 0.3$, flatness restored by cosmological constant, and $h \simeq 0.7$ ^a.

An intrinsic limitation of available wide-area samples of X -ray clusters lies in their limited depth (median redshift $z \simeq 0.1$), which is definitely too shallow to probe cosmology through the redshift evolution of the LSS. Further squeezing the RASS to reach fainter fluxes shouldn’t help much in this respect. A real step forward should require, instead, a survey-dedicated X -ray satellite, which would be able to search for clusters over a large ($\sim 10^4$ sq. deg.) contiguous area, while reaching fluxes two orders of magnitude fainter than the RASS. A satellite with these characteristics is surely within the reach of available technology and there are good chances for it to become reality in the next future.

^aAs usual, I define here the Hubble parameter as $h = H_0/100$ km s $^{-1}$ Mpc $^{-1}$

2.2 Evolution of the cluster population

A complementary approach to constrain cosmological models with galaxy clusters is represented by the evolution of their number density or, formally speaking, the evolution of the cluster mass function. After the pioneering work of the Einstein Medium Sensitivity Survey (EMSS), several independent X -ray samples have been constructed over the last 5 years, all based on deep **ROSAT** exposures (e.g., RDCS, 160 sq.deg. CfA, SHARC, WARPS, NEP, BMW), each containing $\sim 50\text{--}100$ clusters^{2,5,6}. Thanks to their fairly large redshift baseline ($z \lesssim 1.3$), they provide nowadays the most effective probe for the evolution of the cluster population. Since cluster evolution depends on the growth of the cosmic density perturbations over $\sim 10 h^{-1}\text{Mpc}$, it constrains the r.m.s. density perturbation over this scale, σ_8 ^b, and the cosmic density parameter, Ω_m , while being much less sensitive to the value of the cosmological constant^{7,8,9,10}.

Analyses of the redshift dependence of the X -ray cluster luminosity function for these samples, based on the Press–Schechter (PS) approach or on refinements of it, are providing constraints on σ_8 and Ω_m . Although some debate is still present, I think it is fair to conclude that values of the density parameter $\Omega_m \gtrsim 0.5\text{--}0.6$ are disfavored by these analyses at the 3σ level. Still, such results are not providing a precision determination (i.e., with $\lesssim 10\%$ accuracy) of cosmological parameters, the main source of error being represented by the limited size of the samples and the uncertainties which are anyway present in the relation between L_X and cluster mass. In order to overcome these sources of uncertainties, one should look for a better calibration of this relation, for instance through weak lensing determinations of cluster masses¹¹.

As a further possibility, one can resort to the X -ray temperature of the ICM, T_X , which is better connected than L_X to cluster mass, once hydrostatic equilibrium is assumed. Follow up observations to determine T_X for samples of nearby clusters have been already realized, while extensions to include a fair number of distant ($z \gtrsim 0.5$) clusters are still underway. However, precise estimates of T_X at high redshift are observationally quite demanding. Furthermore, the relation between T_X and collapsed mass is also prone to some degree of uncertainty, connected to complex cluster dynamics, temperature gradients, cooling–flow structures, etc. Finally, analytical methods also introduce some degree of approximation in the theoretical description of the distribution of cluster virial masses, which propagates into errors in the determination of cosmological parameters.

What should we do, then, to improve the analysis of the cluster evolution and make it competitive with other high-precision cosmological tests, such as the spectrum of CMB fluctuations?

2.3 High-precision cosmology with galaxy clusters?

There is no doubt that statistics of distant clusters will be no longer an issue in years to come: XMM–Newton and Chandra data will allow to enlarge **ROSAT**–based samples of high- z clusters by at least one order of magnitude^{12,13}. Furthermore, other methods to identify distant clusters, based e.g. on the Sunyaev–Zeldovich effect (see below), will push to higher z the mapping of the cluster population. At the same time, simulation campaigns aimed at describing the LSS evolution over volumes comparable with the whole size of the observable Universe, are providing accurate calibrations of PS–like methods and, therefore, allows to keep under control the theoretical uncertainties in the description of the DM halo mass function¹⁴.

Therefore, the possibility for the high- z evolution of the cluster population to be promoted as a precision test for cosmology will ultimately rely on our ability to connect to each other theoretical and observational clusters and, ultimately, to answer to the following question.

^bI use here the standard definition of σ_8 as the r.m.s. density fluctuation within a top-hat sphere of $8 h^{-1}\text{Mpc}$ radius

3 What is a cluster of galaxies?

3.1 Clusters with SZ

One session of this Meeting has been devoted to cluster studies through the Sunyaev–Zeldovich (SZ) effect¹⁵. Although this subject is far (in terms of wavelength) from X –ray studies, nevertheless the two approaches nicely complement each other in several respects. The SZ signal has been now detected at a high significance for several tens of already known clusters out to $z \sim 0.8$, while hints of serendipitous cluster detections have been also reported. The SZ effect, which is caused by the inverse Compton scattering of ICM electrons onto CMB photons, manifests itself as a distortion of the Planckian CMB spectrum in the direction of galaxy clusters, with a decrease of the effective CMB temperature in the Rayleigh–Jeans region. Due to its nature, the SZ effect is proportional to the ICM pressure, integrated along the line-of-sight. For this very reason, it has two fundamental characteristics, which make it a powerful tool for clusters studies: **(1)** The SZ signal scales linearly with the electron number density, n_e , and **(2)** it is essentially independent of redshift.

The most important applications of the SZ effect, which have been discussed at this Meeting, are the following.

- Determination of H_0 via the apparent–size distance, taking advantage of the different dependencies of the X –ray and SZ fluxes on n_e ¹⁶. Although the accuracy of this method to determine the cosmological distance scale relies on assumptions on the cluster geometry, this uncertainty can be reduced by averaging over a sufficiently large ensemble of galaxy clusters. First determinations of H_0 from SZ provided values which were quite lower than those from other distance indicators. Thanks to the much improved accuracy of the analysis and quality of the data, current estimates range now in the interval $H_0 \simeq 55\text{--}75 \text{ km s}^{-1}\text{Mpc}^{-1}$, thus quite consistent with estimates from other distance indicators.
- Determination of the gas fraction, f_{gas} . Since the SZ signal is less prone than X –ray emissivity to gas clumping, it should provide a more robust determination of the mass fraction contributed by hot diffuse baryons¹⁵. Reported results indicate values in the range $f_{\text{gas}} = 0.05\text{--}0.10 h^{-1}$, thus consistent with X –ray determinations, for reasonable values of H_0 . Also, the weaker dependence on n_e makes the SZ signal suitable to trace the ICM properties out to larger radii than accessible by X –ray observations. Taking advantage of this property, SZ observations could allow to study the ICM over the whole cluster virial region, thus tracing the accretion pattern of the gas and the gravitational shocks occurring at the cluster outskirts.
- Detecting and mapping distant clusters, thanks to the redshift–independence of the SZ signal^{17,18}. In principle, this feature could allow the selection of clusters according to a genuine mass–limit criterion¹⁹. Several ground–based SZ surveys over reasonably large area are currently planned, which could lead to the serendipitous detection of very distant, $z > 1$, clusters. Furthermore, the Planck satellite could provide in about five years an all-sky SZ survey. Although this survey will be performed with worse sensitivity and spatial resolution than reachable by ground–based observations, it will allow accurate statistical studies from a sample containing several thousands SZ sources.
- Cluster peculiar velocities through the kinematic SZ effect¹⁵. The bulk motion of ICM electrons, caused by the peculiar velocity of clusters in the CMB reference frame, generates a distinct distortion of the Planckian spectrum, which adds to the thermal SZ one. The amplitude of this kinematic SZ effect depends on the cluster peculiar velocity and, therefore, could be used to map cosmic flows through sub-mm observations. However,

the size of the kinematic SZ distortion is so small to place only weak constraints on the peculiar velocity of individual clusters, while it would be more effective for statistical characterization of cosmic velocity fields. For instance, the all-sky SZ survey expected from the Planck satellite, should provide typical errors in individual cluster velocities of several hundreds km s^{-1} , while it should be able to put significant constraints on bulk motions over large scales, $\sim 100 h^{-1}\text{Mpc}$, and even to trace its cosmic evolution out to $z \simeq 0.5$.

3.2 *The Chandra view*

The arcsec resolution achievable with the Chandra satellite is revealing a variety of small-scale structures in the ICM, which are witnessing the presence of complex physical processes²⁰. Features in the gas distribution have been detected for several clusters, although spatially resolved measurements of gas temperature, density and pressure shows that they don't have a common origin. In some cases (e.g., A665) complex patterns in temperature and gas distributions clearly suggest the presence of gas shocked by an ongoing merging. In other cases (e.g., A3667), sharp features in the X -ray emissivity correspond to jumps in temperature and gas density, which balance each other to give a continuous pressure variation²¹. Rather than to shocked gas, these features correspond to fronts of cold gas moving within the cluster. These fronts are associated to the presence of magnetic fields, whose field lines run parallel to them and inhibit gas mixing during subsonic merging.

Detailed investigations of the X -ray emission from the two dominant elliptical galaxies in the Coma cluster show that it is originated from high-density gas at a temperature $T_X \sim 1\text{--}1.5 \text{ keV}$, with an estimated cooling time $t_{cool} \sim 10^8 \text{ yr}$ ²². This time scale turns out to be somewhat smaller than that over which supernova (SN) explosions from the stellar population provide energy feedback to the diffuse gas, $t_{SN} \sim 10^9 \text{ yr}$. If these order-of-magnitude estimates will be confirmed by accurate computations, then the question would arise as to what mechanism (e.g., suppression of heat conduction) would prevent the diffuse gas, surrounding these galaxies, to cool down and disappear from the hot phase. As I will discuss in the following, when reviewing results from XMM, the physics of gas cooling is actually one of the most intriguing open problems, and is severely challenging our understanding of the ICM.

At a first glance, the complexities revealed by Chandra observations would lead to conclude that real galaxy clusters are indeed much different from the spherical and dynamically relaxed Press–Schechter clusters, that theorists have in mind. If true, one could then wonder whether clusters can indeed be used as cosmological probes: do they represent fair reservoirs of the cosmic baryons? is their dynamics known to sufficient precision to allow reliable determinations of the collapsed mass and of the density profiles? Although real clusters deviate from the ideal picture on small scales, there are good reasons to consider them as fairly well behaved structures when looking at their global properties. Indeed, Chandra data for several nearby clusters show that: (a) baryon fraction profiles flatten already at $\sim 0.1R_{vir}$ (cf. also ref.²³); (b) DM profiles, reconstructed from hydrostatic equilibrium equation, are consistent with NFW profiles and, when available, also with profiles from weak-lensing mass reconstruction²⁴. This confirms the standard picture that clusters are fair reservoirs of cosmic baryons, with its gas content being in equilibrium within gravitational potential wells created by hierarchical gravitational collapse.

Besides high-resolution details of nearby clusters, the Chandra satellite is also proving to be a powerful instrument to detect ICM emission from high- z clusters. This is demonstrated by the observations of distant clusters reported at this Conference^{25,26,27}, from $z \sim 0.5$ out to the very distant clusters at $z \sim 1.3$ detected in the Lynx field²⁸, and the $z \sim 1.8$ extended X -ray emission identified in correspondence of a radio galaxy²⁹. Such studies allow to map the structure of the ICM soon after it was assembled from DM gravitational collapse, thus further pushing back in cosmic time our knowledge of the evolution of the intra-cluster gas.

3.3 The XMM–Newton view

Due to its technical characteristics, XMM–Newton is providing information which are complementary to those derived from Chandra data: the larger collecting area of XMM mirrors, especially at high energy ($\gtrsim 5$ keV), and the better energy resolution is coupled with an adequate spatial resolution (PSF of about 5 arcsec on axis), so as to allow spatially and spectroscopically resolved observations of the ICM³⁰. Although its instrumental background turns out to be quite larger than expected from pre-launch calibrations, there is no doubt that this satellite is providing unprecedented insights into the ICM physics^{31,32,33,35,34}. The observation of the Coma cluster shown at this Meeting is a spectacular example of such capabilities³⁶: the combination of temperature and emission maps shows two subgroups undergoing merging along a filamentary structure, with evidences of tidal gas stripping and bulk shocks, much like seen in hydrodynamical simulations of hierarchical cosmic structure formation. Available data on the gas temperature profiles for a few nearby clusters show that they are generally flat out to $\sim 0.5R_{vir}$, with a drop, detected in some cases in the central regions and associated to gas cooling^{30,37}. Quite remarkably, the reconstruction of the mass density profile shows agreement with the NFW profile, at least in the outer cluster regions. This reinforces the picture of clusters as structures which are well behaved and dynamically relaxed on large scales, while showing significant complexities on small scales.

Besides the determination of the gas temperature, the XMM–Newton satellite also represents a very well suited instrument to measure the amount and distribution of metals in the ICM and, therefore, to reconstruct the history of its enrichment from the past star formation within cluster galaxies³⁸. The XMM energy coverage ([0.2-12] keV) is large enough to encompass atomic transitions for several elements (e.g., *C*, *Ne*, *Si*, *S*, *Fe*). As data will be accumulating, the possibility to determine relative and absolute abundances, along with their spatial distribution, will allow to constrain the contribution of supernovae to ICM metal enrichment³⁹ and, therefore, to infer the total energy injected into the diffuse gas from SN explosions. At present, XMM is confirming the picture of a polluted ICM with $Z \simeq (0.3 \pm 0.1)Z_\odot$ and no redshift evolution out to $z \sim 0.5$. As for abundance gradients, they are found to be significant only in a few cases, seemingly at variance with respect to results from ASCA and Beppo–SAX, which instead show evidence of gradients in most cases. As the potentiality of XMM will be fully exploited in the next future, it will provide *Fe* abundance out to $z \sim 1$ and trace other elements to lower redshifts³⁸. Such potentialities are clearly demonstrated by the XMM observation of M87 in the Virgo cluster⁴⁰, which allowed to determine abundance gradients for six different elements.

The physics of gas cooling merit a special mention among the fields where XMM is bringing a major contribution⁴¹. Gas in the central part of clusters has high enough density to cool down and drop out of the hot diffuse phase over a time scale, t_{cool} , shorter than the dynamical time scale. According to the standard cooling flow model, one should observe at each radius a superposition of gas at different, even very low, temperatures (multiphase model), flowing inside from outer cluster regions. If gas is left free to cool, then t_{cool} is short enough to allow a large fraction ($\gtrsim 50\%$) of the whole ICM to pass to the cold phase. This is at variance with respect to observational evidences, which indicates that only $\sim 10\%$ of cluster baryons are locked into a cold phase, mostly contributed by stars. The question then arises as to how one can prevent gas from over-cooling. In principle both SN explosions and AGN activity could provide energy feedback to heat back the gas to the diffuse phase. However, although some evidence is emerging for association of cooling gas with star-forming regions⁴², no evidence has been found to date for the presence of central heating in correspondence of cooling regions. Results from XMM observations are now adding a further complication to this puzzle: spatially resolved spectroscopy of central regions of cooling-flow clusters are showing no evidence for line emission associated to gas at $T_X < 2$ keV. Where does the cold gas end up? Is it heated back?

If this is the case, then a large power would be needed, while we don't see any signature of it. Although such findings could represent a serious challenge for the multiphase model, still a good fit to measured spectra can be provided by a model with two gas phases, one at the virial temperature, T_{vir} , and the other at $\sim 1/3 T_{vir}$ ⁴¹. A proposed solution for the lack of low- T metal lines is based on assuming a bimodal distribution of ICM metals, with small lumps of high- Z gas surrounded by $\sim 90\%$ of very low- Z gas. This model could have the virtue of behaving like $\sim 0.3 Z_\odot$ gas for $T_X > 3$ keV and as metal poor gas at lower temperatures, thus justifying the lack of emission lines from low- T_X gas. Of course one has then to motivate the presence of such metal nuggets. There is no doubt that the accumulation of more XMM data will soon clarify once for all whether ICM cooling has to be associated with a multiphase flow or a different picture needs to be elaborated.

3.4 The non-thermal ICM

Sharp features in the gas distribution as observed in the X -ray band are not the only expected consequence of merging events. Actually, mergers represent among the most energetic cosmic phenomena⁴³: merging structures collide with a velocity of $\sim 1000 \text{ km s}^{-1}$ with an involved gravitational energy as large as $\sim 10^{64}$ ergs. Although the major part of this energy goes into thermal heating of the ICM, thus boosting its X -ray luminosity, a small fraction of it can be converted into the acceleration of relativistic electrons. Depending on their energy, a significant fraction of such electrons is retained within the cluster regions over a time scale comparable to the Hubble time. The resulting emissivity from these electrons, by inverse-Compton (IC) scattering with CMB photons, dominates over the thermal bremsstrahlung emission in the EUV region of the spectrum, where most of the energy is stored, and in the hard X -ray band ($\gtrsim 20$ keV).

Claims for detection of excess EUV emission by the EUVE satellite have been reported for six galaxy clusters⁴⁴. The currently favored explanation for this emission is the IC scattering of electrons with a Lorentz factor $\gamma \sim 300$ (corresponding to energies of about 150 MeV). Similarly to the SZ effect, this emission is spatially more extended than the bremsstrahlung emission, thanks to its linear dependence on the local electron number density. More energetic electrons, with $\gamma \sim 10^4$, are expected to produce by the same mechanisms a hard X -ray (HXR) tail in excess with respect to thermal bremsstrahlung, as well as synchrotron emission, in case a strong enough intra-cluster magnetic field is present. Evidences for HXR excess have been presented for the Coma cluster and A2256⁴⁵. An alternative explanation for this HXR excess is based on bremsstrahlung emission from high-energy non-thermal electrons, whose origin would however be quite unclear. The spatial localization of this emission is still poorly determined, due to the coarse angular resolutions of the detectors used to date. With the improvement of the angular resolution (e.g., with the INTEGRAL satellite), it could be possible to see whether the HXR emission is localized in the radio emitting regions, which are associated with the shock fronts where electrons are accelerated.

Radio emission represents a further manifestation of non-thermal ICM behavior⁴³. Diffuse radio halos have been detected in several tens of clusters and have no obvious associations with member galaxies. These sources are commonly classified as radio halos and relics, depending on whether they are observed in projection near the cluster center or in its periphery. In all the known cases, such structures are found in clusters with evidences of recent mergers. Therefore, the widely accepted explanation for the radio emission is based on synchrotron emission from relativistic electrons, that are accelerated within the merger shocks and spiralize along the lines of the intra-cluster magnetic field. This picture is also supported by magneto-hydrodynamical simulations of a blob of radio plasma passing through a cluster merger shock wave, and producing radio emitting regions with morphologies resembling the observed ones⁴⁶.

In some cases, radio activity is also connected with features in the pattern of X -emission^{43,47,48}. A clear example has been recently provided by the Chandra observation of Abell 2052, where the radio emission surrounding the central cD corresponds to holes in the X -ray brightness, with shells of X -ray bright features surrounding the radio-emitting region. Since the gas pressure is observed to be continuous across such X -ray discontinuities, they do not correspond to ongoing shocks. Instead, they are likely to arise from ICM regions where gas is compressed by the non-thermal pressure associated to radio lobes. If this additional pressure term is a non-negligible fraction of the thermal one, then one may wonder whether the assumption of hydrostatic equilibrium provides a correct description of the cluster internal dynamics. Since these features are localized around radio galaxies, instead of being ubiquitous, one expects non-thermal support not to be dominant.

3.5 The theorist's view

The amount of information on the cluster physical properties, that I have discussed so far, still deserves an adequate interpretative framework. In this context, numerical simulations are undoubtedly valuable instruments to describe the gravitational dynamics of DM and basic properties of the gas physics^{50,49}. N-body experiments including hydrodynamics are shedding light on the detailed structure of DM halos, on the effect of merging on global cluster dynamics, on the connection between their morphology and the surrounding environment⁵¹, and on cooling structure of the gas⁴⁹. In most cases, the treatment of the simulated gas is such that it reacts only to the effect of gravitational processes, like adiabatic compression and accretion shocks. However, a variety of observational evidences demonstrates that other physical processes should play an important role. Thanks to the availability of specialized codes running on massive parallel supercomputers, mass and dynamical resolution achievable nowadays in cluster simulations seem accurate enough to warrant numerically convergent results⁵². The real challenge, instead, is represented by the inclusion of a believable treatment of more complex physical processes, like the gas cooling and its interplay with processes of star formation and galaxy evolution within cluster galaxies⁵³, or the effect of magnetic fields^{46,54}.

Gravity in itself does not introduce characteristic scales. Therefore, if gravity only acts on the gas, then the ICM should behave in a self-similar fashion. In fact, this prediction is at variance with respect to observations. Scaling relations among global observable quantities of the ICM, like X -ray luminosity, temperature, gas mass and entropy, violate self-similarity: the gas distribution within galaxy groups and poor clusters ($T \lesssim 2$ keV) is relatively shallower, with suppressed density and entropy excess in central regions, with respect to hotter ($T \gtrsim 3$ keV) systems. The common interpretation is that the gas should have been heated by some non-gravitational process before the cluster collapse. The amount of this extra energy introduces a characteristic scale into the problem and, therefore, breaks self-similarity. Numerical simulations including pre-heating, in the form of pre-collapse gas entropy floor, show that an extra-energy of about 1 keV per particle is required to reproduce observational results on the entropy excess and the shape and evolution of the L_X-T relation^{53,50}. Furthermore, if this pre-heating affected the high-redshift ($z \sim 3$) intergalactic medium, it should have left its imprint also on the X -ray emission from large-scale filamentary structures⁵⁵: the decreased gas density in filaments would correspond to a suppressed emissivity and, therefore, to a reduced contribution to the soft X -ray background (XRB; see the discussion on the XRB here below).

First attempts to include the effect of SN feedback in cluster simulations⁵³ indicate that they can hardly provide the correct amount of heating energy, thus requiring a further contribution from other mechanisms, such as AGNs. However, my impression is that our current understanding of the relative role played by type Ia and II SN and their efficiency in dumping energy into the hot diffuse medium is not yet accurate enough to draw firm conclusions. The

improved accuracy in the determination of ICM chemical abundances will soon provide useful insights into our understanding of the effect of star formation on the ICM physics. Finally, whatever the source of ICM pre-heating is, it should act on spatial and temporal scales tuned so as to stop the cooling runaway and to allow only a small fraction ($\sim 10\%$) of the diffuse gas to cool down into a collisionless phase. In this sense, gas cooling and non-gravitational heating are inextricably linked aspects which should be accounted for in a self-consistent way.

4 Resolving the X -ray background

Besides galaxy clusters, a session of this Conference has been devoted to discussing the X -ray background (XRB) in the light of recent Chandra⁵⁶ and XMM–Newton⁵⁷ observations. Taking advantage of the exquisite angular resolution of the Chandra satellite, independent groups are actively working on the analysis of long-exposure pointings to resolve the contribution of discrete sources to the soft and the hard XRB. In fact, the results reported from the one-million seconds ACIS-S observation of the Chandra Deep Field South (CDFS) clearly demonstrate that the most part of the XRB is contributed by discrete sources⁵⁶. At the flux-limit, $4 \times 10^{-16} \text{ erg s}^{-1} \text{cm}^{-2}$, reached in the hard ([2–7] keV) band, 65–95% of the background is resolved, the exact fraction depending on the assumed level for the observed background. Furthermore, number counts show evidence of flattening at faint fluxes, $\lesssim 10^{-14} \text{ erg s}^{-1} \text{cm}^{-2}$, thus demonstrating that we are actually identifying most of the discrete sources making up the hard XRB. Although the comparison among different fields observed with Chandra deep pointings shows a fairly good agreement, differences have been detected in some cases which can hardly be explained by Poissonian fluctuations. The likely explanation should lie in the intrinsic clustering of Chandra sources, which enhances the field-to-field scatter of the flux number counts.

Another long-standing problem from pre-Chandra XRB observations concerned the so-called “spectral paradox”, that is the difference between the hard profile of the XRB spectrum and the relatively softer spectrum of the detected sources. Spectral analysis of the sources, identified now by Chandra observations, shows that they become progressively harder at fainter fluxes. Therefore, the spectral paradox is solved by a faint population of hard sources, contributed by $z \lesssim 1$ absorbed AGNs. Such results on the hard XRB are reinforced and extended to higher energies by the results of deep XMM–Newton observations, like that of the Lockman hole⁵⁷. Despite the lower angular resolution, the better sensitivity of this satellites to harder photons provides the deepest determination of number counts in the [5–10] keV band and resolves about 60% of the XRB at these energies. The identification of the XMM sources, both in the Lockman hole⁵⁷ and in the Groth–Westphal strip⁶⁰, confirms the picture that the hard XRB at these energies is mainly contributed by intrinsically absorbed AGNs.

As for the soft ([0.5–2] keV) XRB, it is virtually completely resolved ($\simeq 80$ –95%) by Chandra deep exposures. As already mentioned in Section 3.5, this result provides a non-trivial constraint on the diffuse emission from the warm diffuse gas permeating the large-scale cosmic web⁵⁵. Much like for the ICM, the suppressed X -ray emission is consistent with the picture of non-gravitational heating placing the gas on a higher adiabat, and preventing it from reaching high densities within large-scale filamentary structures. Finally, the knowledge of the flux and redshift distribution of X -ray (and UV) sources are a necessary ingredient for phenomenological recipes aimed at describing the spectrum of cosmological background at different wavelengths⁵⁸, as well as the physics and ionization properties of the IGM⁵⁹. Programs of multi-wavelength imaging and spectroscopic follow-up of the distant X -ray sources identified by Chandra and XMM–Newton are currently underway^{56,57,61,62,60}. Once completed, they will provide invaluable information about the process of galaxy formation and its interplay with the history of cosmic baryons.

Acknowledgments

It is a pleasure to thank the Conference Organizers, particularly Doris Neumann, for setting up such a successful meeting in the wonderful environment of Les Arcs.

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