X-ray Clusters of Galaxies as Cosmological Tools

Isabella Maria Gioia

This paper was written as part of a book entitled: “Questions of Modern Cosmology - Galileo’s Legacy” which is a celebrative book dedicated to Galileo Galilei. The book is published in 2009, the International Year of Astronomy, since it is intended to be a modern tribute to the astronomer who, 400 years ago, first pointed a telescope towards the night sky. The book is written in the form of interviews between the editors and many physicists, astrophysicists and cosmologists from all over the world. The editors engaged in several discussions on the formation and evolution of the Universe with the aim of summarizing the most important and significative advances made by cosmology over the past century and at the beginning of the new millennium. This paper deals with X-ray clusters of galaxies and how they can be used to constrain fundamental cosmological parameters.

**Question:** Clusters of galaxies are powerful X-ray emitters that can be easily detected out to high redshifts, and therefore are very important tools for cosmologists. In particular, the relation between the X-ray luminosity and the temperature, and temperature and mass of the Intra Cluster Medium (ICM) offers a way to convert a luminosity function into a mass function with obvious consequences for present day cosmology. Can you comment on the state-of-the-art of these studies? How can they constrain cosmological parameters?

The properties of clusters are investigated through a multi-frequency approach: from radio emission and Sunyaev-Zel’dovich effect, to IR-Opt-UV mapping, to X-ray emission. For example, a cluster typically appears more extended when mapped through the Sunyaev-Zel’dovich effect than through its X-ray emission. Can you discuss the wealth of astrophysical information achievable through the comparison among data at various bands? What advantages for cosmology come from such a multi-wavelength approach?

Isabella Maria Gioia
INAF-Istituto di Radioastronomia, Via Gobetti 101, 40129, Bologna, Italy,
e-mail: gioia@ira.inaf.it
Answer: To answer my cosmology question I need to give a little introduction on why clusters of galaxies have always been a preferred tool of cosmologists. I will start with a short description of what clusters are, give a quick background on the different wavelengths, and describe why X-ray clusters play such an important role in astronomy. Finally, I will give some description of the data that can be collected at the different wavelengths and discuss the advantages of the multi-wavelength approach for cosmology, and what needs to be done to improve our understanding of galaxy clusters.

1 Clusters of Galaxies: an Introduction

About thirty years ago all clusters of galaxies were selected at optical wavelengths since the easiest way to identify a cluster is to search for an overdensity in the projected distribution of galaxies in optical images. The pioneering work of Abell \([1]\) and later the catalogs by Zwicky and collaborators \([100]\) made astronomers aware of how many concentrations of galaxies were present in the nearby Universe (that I define here as objects with a redshift \(z \leq 0.15\)). However, the most visible part of galaxy clusters, all of the stars in all of the galaxies that make up the cluster, con-

Fig. 1 This composite image contains two views of the cluster Abell 2255. Superimposed onto the ROSAT-PSPC X-ray emission \([32]\) (in shades of grey) are the VLA 1.4 GHz radio emission \([51]\) represented as iso-contours. Courtesy of F. Govoni and M. Murgia.
Fig. 2 This composite image contains two views of the cluster Abell 1914. Superimposed onto the Chandra X-ray emission [50] (in shades of grey) are the VLA 1.4 GHz radio emission [6] represented as iso-contours. Courtesy of F. Govoni and M. Murgia.

tributes only a small fraction of the mass of the cluster. Clusters host manifold components, such as individual galaxies and hot gas (the baryonic component), invisible dark matter, and what are commonly referred to as “non thermal components”. It is well known that a fraction of clusters (about 40% among rich, hot clusters [42]) shows large scale synchrotron radio emission with no obvious connection to the cluster galaxies, and therefore associated with the ICM (see [34] for a review on the subject). Such extended radio sources are a direct and clear probe of the existence of cluster scale magnetic fields and relativistic particles spread over the same large volume. The composite images in Fig. 1 and Fig. 2 are an illustration of the different features seen in radio with the Very Large Array and in X-rays with the ROSAT-PSPC and with Chandra, for two clusters, Abell 2255 and Abell 1914.

The total mass of a cluster is dominated by the non-baryonic component (the invisible dark matter) that we know exists because of its gravitational pull on the luminous matter. While the baryonic component of a cluster can be directly observed at optical and X-ray wavelengths, the invisible dark matter can only be measured through the effect of gravitational lensing on the background galaxies or observing other dynamical manifestations of the clusters. Roughly, it is estimated that the composition of a cluster is 3% galaxies, 17% Intra Cluster Medium (ICM), and 80% dark matter. Thus the total mass of a cluster, which is the property we need to know to
use clusters as cosmological tools, is dominated by the invisible, collisionless dark matter.

2 Clusters of Galaxies in X-rays

Observations of galaxy clusters in the X-ray band trace the intracluster gas, and hence provide an efficient and physically meaningful method for the identification and selection of galaxy clusters. Over the past decade, studies based on the current generation of X-ray satellites (Chandra and XMM-Newton) have completely changed our X-ray view of galaxy clusters. The large collecting area of XMM-Newton, combined with the very fine angular resolution of Chandra, have contributed to unveiling the complex structure and physics of the hot ICM.

The physics of X-ray emission from clusters of galaxies is pretty straightforward. Simple gravitational processes dominate cluster formation and evolution and imply that clusters are still forming today. The evolution of clusters is simple, being driven by the gravity of the underlying mass density field of the Universe and of a collisionless collapse of the cluster dark matter. These same formation processes also heat gas trapped by the cluster potential, which then produces optically thin thermal radiation. The evolution of cluster X-ray emission can be more reliably calculated compared to that of other objects visible at cosmological distances, such as galaxies and quasars, and the cluster evolution calculations may be verified by direct observations of nearby objects. Thus observations of the X-ray evolution of clusters provide a robust measure of the evolution of cosmic structure and therefore constrain the cosmology of the Universe.

The advent of X-ray imaging in the 80’s revealed that clusters are extended and powerful sources, with luminosities up to $10^{45}$ erg s$^{-1}$ for the richest clusters, that emit by optically thin thermal bremsstrahlung from hot ($\sim 10^8$K), low-density ($\sim 10^{-3}$ atoms cm$^{-3}$) gas. Their total masses are in the range from a few times $10^{13}$ M$\odot$ for the poorest groups to more than $10^{15}$ M$\odot$ for the most massive clusters. In the X-ray sky clusters appear as high contrast objects, given the dependence of the X-ray emission on the square of the gas density, and can be seen up to high redshift. In addition the X-ray luminosity, $L_X$, correlates well with the cluster mass, the cluster property most directly related to cosmological parameters (even though, as I will discuss later, $L_X$ is not the most accurate of all proposed X-ray indicators for the total mass of a cluster).

Since the early 90’s searches for clusters in X-ray surveys discovered many bound systems out to cosmologically interesting distances (see the pioneering work by Gioia and collaborators with the Einstein Observatory [39, 40, 54], and the many X-ray surveys that came out later with the ROSAT-PSPC detector (cf. among others [86, 94, 41, 19]). X-ray selection has the unique advantage of revealing physical objects, deep potential wells in the case of clusters, thus avoiding the problem of contamination by foreground galaxies and stars as can happen with optical selec-
tion. This is a fundamental point, especially when one deals with very distant clusters which are the main players in cosmological studies. An additional fundamental advantage of X-ray selection is the ability to define flux-limited samples with well understood selection functions that allow one to evaluate the volume surveyed and thus lead to a straightforward computation of comoving number densities. Fig. 3 illustrates the sky coverage of several X-ray surveys carried out over the last two decades. Completeness is an important quantity in observational cosmology. A well defined and complete sample is designed to detect all objects with luminosity (or any other cluster quantity) above a given value and within a given redshift, and thus it can be reliably used for cosmological studies.

However, the most important cluster parameter, its mass, is not directly observable. So observers generally proceed by using some other observable like X-ray luminosity or temperature as a surrogate for cluster mass and linking that observable with mass through a simple scaling relation. Numerical simulations of cluster formation indicate that these relations can be quite accurate (e.g., [30] and [18] show in simulations without radiative cooling or star formation, that cluster temperature tracks cluster mass to within about 15%; see among others also [72, 28, 62] for simulations with cooling and star formation). Several proxies of the total cluster mass
have been proposed based on cluster observables such as galaxy velocity dispersion \[43\], optical light \[82, 46\], mass of the ICM (many papers by many authors), Sunyaev-Zel’dovich decrement \[22\], gravitational lensing \[56, 93, 61\] (see \[98\] for description of all these methods). Two easy to obtain X-ray observables are X-ray luminosity and X-ray gas temperature, which are both found to correlate more tightly with the cluster virial mass than other cluster properties like for instance optical richness.

The cluster X-ray luminosity \(L_X\) is the most straightforward mass indicator to measure observationally since a minimum number of X-ray photons is required. However, since most of the luminosity comes from the dense central region of the clusters (the radius of the core is much smaller than the virial radius), \(L_X\) is the least accurate of all proposed X-ray indicators for the total mass given the large scatter and deviations of the slope of the luminosity-mass, \(L_X-M\), relation \[84\] from self-similar model prediction.\[1\] One way to calibrate the \(L_X-M\) relation is to combine the \(M-T_X\) relation (whose scatter has been found to be considerably smaller e.g., \[55, 4, 96\]) with the observed \(L_X-T_X\) relation. Observational studies have found that the slope of the \(L_X-T_X\) relation is steeper than self-similar predictions (e.g., \[69, 3\]), and the entropy in cluster cores is higher than predicted (e.g., \[81\]) indicating important non-gravitational effects (such as cooling, mergers, etc) on the energy budget of clusters. One has to pay attention also to the evolution of the mass-observable relations. For instance, Branchesi and collaborators \[16, 17\] find a significant evolution in the \(L_X-T\) of a sample of 40 archival Chandra and XMM clusters, similar or stronger than the self-similar model, from \(z = 0\) to \(z \leq 0.3\), followed by a much weaker, if any, evolution at higher redshifts (see also \[71\]). The higher-\(z\) weaker evolution seems compatible with an increasing importance at high redshift of non-gravitational effects in the structure formation process (e.g. \[98, 99\]).

The X-ray temperature of the ICM \[53, 76, 56\] is another common indicator for mass. The X-ray temperature is closely related to the depth of a cluster potential well and can be observed with current X-ray detectors up to \(z \sim 1\) and beyond. Under the assumptions of hydrostatic equilibrium and isothermality (simplifying assumptions which are not necessarily true in reality), one can derive the total mass in X-rays by knowing the baryon density from the X-ray surface brightness and the temperature of the hot gas. These two quantities are readily available today with the detectors onboard Chandra and XMM-Newton satellites which can measure both simultaneously. The masses obtained in this way are very close to those obtained through the virial theorem namely \(T \propto M^{2/3}\). It is worth mentioning here that the very accurate temperature profiles out to large radii now provided by the current X-ray telescopes have actually allowed Vikhlinin and collaborators \[96\] to relax the assumption of isothermality. They have used the best available Chandra observations for thirteen

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\[1\] Those ICM models whose physics is based on the assumption that only gravity determines the thermodynamical properties of the hot diffuse gas are called self-similar models \[60\]. In such models clusters of different sizes are expected to be scaled version of each other since gravity does not have a preferred scale.
low-redshift clusters and made direct hydrostatic mass estimates from the gas temperature profiles.

In the recent past several authors have used the cluster baryon mass as a proxy for the total mass thus avoiding all the uncertainties of the $M-T_X$ and $M_{\text{tot}}-L_X$ relations [95, 97, 27, 2]. The advantage is that it can be measured from X-ray imaging alone and is a robust and complementary indicator to the others for constraining cosmological parameters. An additional recently proposed [64] mass indicator is defined as the product of the X-ray derived gas mass and the average temperature, $Y_X = M_g T_X$, that strongly correlates with cluster mass with only 5 – 8% intrinsic scatter. However, non-gravitational processes can potentially alter the mass-temperature relation, the baryon-to-dark-matter ratio of clusters, and the redshift evolution of both these quantities. Maughan 2007 [70] followed up on this and found from the $L_X - Y_X$ relation for 115 Chandra clusters that the X-ray luminosity is a robust, low-scatter mass proxy.

Fig. 4 Galaxy cluster XMMU J2235.32557, at z=1.393. Left: VLT FORS2 R-band image overlaid with X-ray contours from a 45 ks XMM-Newton observation. Right: VLT ISAAC Ks image overlaid with the same X-ray contours. Spectroscopically confirmed members ($1.38 < z < 1.4$) are indicated as circles or triangles. From Mullis et al. 2005.

To wrap up this part I would say that X-ray is a fundamental band to identify and characterize galaxy clusters. Current X-ray telescopes show us the very detailed fine structure of cluster emission up to distant redshifts (see for instance Fig 4 for an XMM image of one of the most distant serendipitously selected X-ray clusters at $z=1.4$, [75]) something unthinkable until a decade ago. The many X-ray surveys from previous missions, either serendipitous or all-sky surveys, have been demonstrated to be promising tools for the characterization of the properties of galaxy clusters. I believe that we can get even more stringent constraints on cosmological parameters as more sensitive and statistically significant surveys made with the current telescopes become available.
3 Clusters of Galaxies as Cosmological Tools

Clusters of galaxies are the highest peaks in a cosmic terrain driven by gravitational clustering and represent the largest scale of fully collapsed structures in the Universe [78, 77]. Thus they offer a unique insight into the formation of structures and into the parameters governing their evolution. The internal mix of components within clusters, as well as the space density and temperature distribution function of the most distant and massive clusters, can be used to determine fundamental cosmological parameters. Other clusters measurements useful for cosmological studies include the power spectrum of the three-dimensional distribution of clusters, and the baryon fraction and its evolution. These studies have been carried out by a number of authors over the years. Among them see for instance: [55, 26, 14, 15, 87, 27, 79, 56, 95, 97, 2] which is not a complete list. These works have used the mass function as given by Press-Schechter [83] or by Sheth & Tormen [90] or by Jenkins [59]. The values of the mean mass density, $\Omega_m$, and dark energy density, $\Omega_\Lambda$, of the universe are fundamental data for cosmological theories. These quantities are conveniently parameterized in terms of the critical density, $\rho_0 = 3H_0^2/(8\pi G)$ (here $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$ is the Hubble constant, G is the gravitational constant and h is the value of the Hubble parameter in units of 100 km s$^{-1}$ Mpc$^{-1}$). The growth rate of the density perturbations depends primarily on $\Omega_m$ and, to a lesser extent, on $\Omega_\Lambda$ at least out to $z \approx 1$ where we can study clusters observationally. The abundance of rich clusters of galaxies is extremely sensitive to.

![Fig. 5 Evolution of n(M, z) for M > 5 \times 10^{14} h^{-1} M_\odot for three cosmologies (solid line, $\Omega_m = 1$; long-dashed line, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$; short-dashed line, $\Omega_m = 0.3$, $\Omega_\Lambda = 0$) with $\sigma_8 = 0.5$ for the $\Omega_m = 1$ case and $\sigma_8 = 0.8$ for the low-density models. From Rosati, Borgani & Norman, 2002.](image-url)
the amplitude of the mass density fluctuations on a scale of 8 \( h^{-1} \) Mpc, or \( \sigma_8 \).\(^2\) while the evolution of the abundance is extremely sensitive to \( \Omega_m \) and to a lesser extent to \( \Omega_A \). An additional parameter is the dark energy parameter \( w \)\(^3\), the ratio between the pressure and energy density in the equation of state of the dark energy component.\(^4\) The value of \( w \) is less constrained by clusters.

Fig 5 shows the sensitivity of the cluster mass function to cosmological models. Both the X-ray luminosity function (XLF, the number density of galaxy clusters having a given X-ray luminosity) and the X-ray temperature function (XTF, the number density of galaxy clusters having a given temperature) for both nearby and distant clusters have been used as a proxy for the mass function by a number of authors. When only local cluster data are used, there is a degeneracy between \( \sigma_8 \) and \( \Omega_m \). See discussion in [14, 15] on how the resulting constraints on the \( \sigma_8-\Omega_m \) plane vary by changing the parameters which define the M-L\(_X\) relation. To break this degeneracy one can either use the evolution of the XLF with redshift, or consider measurements at other spatial scales, such as the fluctuations in the cosmic microwave background (CMB) with appropriate assumptions. Many X-ray surveys have shown that the comoving number density of clusters at a given luminosity from \( z \approx 0.8 \) to the present changes very little for \( L_X \leq 10^{44} \). Evolution is seen only for clusters with \( L_X \geq 10^{45} \) (see among others, e.g. [40, 87, 74] and Fig. 5 for a compilation of high-redshift XLFs which highlights evolution). The situation becomes worse when one wants to investigate the dark energy parameter \( w \). In that case investigators combine constraints from both Supernovae and clusters, or weak lensing, the cosmic microwave background and clusters to improve the constraints.

The degeneracy between \( \sigma_8 \) and \( \Omega_m \) may also be broken by measuring the evolution of the cluster temperature function. The first cosmological measurement using the evolution of the XTF at redshift greater than zero was done by Henry in 1997 [55] who derived \( \Omega_m \approx 0.5 \pm 0.15 \). Many updates on both theoretical and observational side followed, among others see [26, 24, 12, 15]. Henry 2004 [56] measured the X-ray temperature with ASCA of all but one cluster in the Einstein Extended Medium-Sensitivity Survey [39] high-redshift (\( z \geq 0.3 \)) sample and compared the data to a complete sample of low-redshift clusters that also had temperature measurements [53]. Using constraints provided by the SNIa Hubble diagram and the cosmic microwave background fluctuations he found that all three bands (clusters, SN, CMB) intersect at \( \Omega_m \approx 0.3 \) and \( \Omega_{\Lambda} \approx 0.7 \) with the quintessence equation of state \( w = -(0.42 \pm 0.21) \) and \( \sigma_8 = 0.66 \pm 0.16 \). The last determination by the same author (Henry, in preparation) can be considered the state-of-the-art in the field. Fig. 7 shows the intersect in the \( \Omega_m-\sigma_8 \) plane of three bands representing three different clusters analyses. The cluster constraints (dotted line) define a narrow band in the \( \Omega_m-\sigma_8 \) plane which intersects with constraints from the Wilkinson Microwave

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2 \( \sigma_8 \) describes the amount of structure in the Universe and is represented as the rms matter fluctuations in spheres of \( 8 \ h^{-1} \) Mpc.

3 If \( w=-1 \) then the dark energy is the cosmological constant, if \(-1<w<0 \) then it is called “quintessence” or Q component [21].
Anisotropy Probe Five-Year data [25] (solid line) (WMAP5), and weak lensing data [5] (dashed line). Allen et al. [2] use Chandra measurements of the X-ray mass gas fraction for 42 clusters in the range $0.05<z<1.1$ to constrain the mean matter density, the dark energy, and dark energy parameter $w$. Combining the X-ray gas fraction $f_{\text{gas}}$ with constraints from supernova and WMAP3 studies and for a flat cosmology they obtain a tight $\Omega_m=0.253\pm0.021$ and $w=-0.98\pm0.07$. Mantz and collaborators [68] derive a precise determination of the dark energy equation of state combining the X-ray luminosity function data of the most luminous clusters out to $z=0.7$ with supernova, WMAP3 and cluster gas fraction data. They find $\Omega_m=0.269\pm0.016$, $\sigma_8=0.82\pm0.03$ and $w=-1.02\pm0.06$, in agreement with earlier galaxy cluster studies. This demonstrates that we have already enough information from cluster samples to also constrain the Dark Energy content of the Universe, one of the most ambitious targets of modern cosmology. Thus we understand why cosmologists love to work with galaxy clusters. The reason is simple: they are tools for precision cosmology through the evolution of their mass function.

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4 WMAP mission was designed to determine the geometry, content, and evolution of the Universe through a full-sky map of the temperature anisotropy of the cosmic microwave background radiation [7].
4 Multi-Wavelength Approach

A multi-wavelength approach in any branch of astronomy is of importance since different bands highlight different properties of the emission mechanisms or detect different components of the astronomical objects which contribute to our understanding of their physics, formation and evolution. The composite image of Abell 520 in Fig. 8 highlights the usefulness of the multi-wavelength approach to detect different emission sources from clusters of galaxies [67]. The different waveband measurements are complementary in setting more stringent cosmological constraints. X-ray clusters can be used alone to constrain cosmological parameters or can be combined with independent methods (weak-lensing, CMB anisotropies, Sunyaev-Zel’dovich, supernovae, to name a few) and different wavelength data (optical, radio, infrared etc.). As we have seen the cluster mass is a parameter of great value in observational cosmology. A combination of several, independent cluster mass estimates is likely to provide the most accurate results.

In the optical the mass-to-light ratio or the mass-richness relation, as well as mass estimates based on the dynamics of member galaxies, have been used by a number of authors with some success, [43, 44, 11, 47]. I would like to mention here some of the optical cluster surveys which have overcome the problem of projection effects. I am referencing to the work of Gladders & Yee [46] (the Red-Sequence Cluster Survey) who demonstrated that two filter imaging is sufficient to perform a clean cluster search using the cluster red sequence of early-type galaxies, even when probing deeply into the mass function. Zaritsky and collaborators (see Las Campanas Distant Cluster Survey [48]) adopted a different method where clusters are detected as positive surface brightness fluctuations in the background sky.
Fig. 8 This composite image (which appears in the Chandra online Photo Album at http://chandra.harvard.edu/photo/2007/a520/index.html) contains three views of the cluster Abell 520. The hot gas as detected by Chandra is colored red. Optical data from the Canada-France-Hawaii and Subaru telescopes show the starlight from the individual galaxies (yellow and orange). The location of most of the matter in the cluster (blue) was also found using these telescopes, by means of weak gravitational lensing of the distant galaxies by the intervening matter. Credits: NASA/CXC/CFHT/University of Victoria/A. Mahdavi et al. (2007). Courtesy of A. Mahadavi and CXC.

An unquestionable unique tool to study the matter distribution of the Universe is the use of the weak gravitational lensing of distant galaxies by intervening matter. We have seen in the previous section how the use of weak-lensing coupled with CMB and X-ray data has led to much more stringent constraints on $\Omega_m$ and $\sigma_8$. Weak lensing has benefitted from the excellent optical surveys currently available with multi-color data and superb image quality over wide areas \cite{23, 5, 37}. The larger areas enable the measurement of the lensing signal out to much larger radii, thus
improving the reliability of the results [58]. See Hoekstra and collaborators [57] for a review on weak gravitational lensing.

In the radio band the pioneering work of Feretti and collaborators, i.e. [31, 33, 34, 49, 50, 45], have unveiled large diffuse cluster components in the ICM due to synchrotron radio emission not directly related to the cluster galaxies. The study of these sources (called radio halos, relics and mini-halos according to their size, shape and location with respect to the cluster center) is very important since they are large scale features which are related to other cluster properties in the optical and X-ray domain, and are thus directly connected to the cluster history and evolution. The radio halos are indicators of cluster mergers, probes of the ICM magnetic fields. They will eventually allow us to constrain models of decaying/annihilating dark matter species. The radio relics are likely tracers of shock waves during the structure formation. The radio mini-halos are found in the center of clusters with cooling cores and will allow us to investigate the interaction between the relativistic plasma and the thermal plasma at the cluster centers. The future Square Kilometer Array (SKA) will dramatically improve the knowledge of these sources, thanks to the detection of new objects, and to detailed studies of their spectra and polarized emission. See also [20] for the contribution of SKA to future CMB spectrum space experiments.

I would like to mention that the non-thermal component in clusters with radio halos has been detected in the hard (above 25 keV) X-ray band (HRX) due to inverse Compton scattering by relativistic electrons of the cosmic microwave background photons. Fusco-Femiano and collaborators [38] found it in Coma, A2256 and A754, among other clusters. This is another manifestation of the same relativistic electrons which emit by synchroton in the radio band. The detection of the non-thermal HRX has enjoyed healthy debate up until now among the different observers.

Another powerful observational tool for cosmology is the Sunyaev Zel’dovich effect or SZE (see review by [10, 22]), which is a distortion in the CMB spectrum caused by the CMB photons passing through the hot ICM and inverse Compton scattering off the energetic electrons. The effect is insensitive to the redshift of the clusters, thus making the method well suited for studies of clusters at high redshift where the abundance of galaxy clusters critically depends on the underlying cosmology. While the thermal SZE is a function of the electron number density, \( n_e \), the X-ray emission scales as \( n_e^2 \). Thus clusters are more extended when mapped in SZE than in X-rays (see Fig 9 for X-ray and SZE maps of three distant clusters). The different dependence on the gas density enables a determination of the direct distance to the galaxy cluster which is independent of the extragalactic distance ladder, up to high-z clusters. The great merit of SZE is that combined with other observational diagnostics of clusters (X-ray emission, weak and strong lensing, galaxy velocity dispersion measurements) can provide a measure of the basic cosmological parameters like for instance the Hubble constant. Recently Bonamente et al. [13] used 38 clusters with Chandra and SZE data to find a value for \( H_0 = 76.9^{+3.9}_{-3.4} \) km s\(^{-1}\) Mpc\(^{-1}\).

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5 The radio telescope will have an effective collecting area more than 30 times greater than the largest current telescope “Galaxy evolution, cosmology and dark energy” is one of five projects identified by the radio astronomy community as being the key science drivers for the SKA.
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Fig. 9 SZE effect measurements (contours) overlaid on XMM-Newton X-ray images of Cl J1415.1+3612 (z=1.03), Cl J1429.0+4241 (z=0.92), and Cl J1226.9+3332 (z=0.89) (from left to right). The SZE observations were obtained at 30 GHz during the commissioning period of the new, eight-element interferometer SZA (Sunyaev-Zeldovich Array). In each panel, the FWHM of the synthesized beam of the SZE observations is shown by the filled ellipse in the bottom left corner. Taken from Muchovej et al. (2007).

(68% confidence level) with $\Omega_m=0.3$ and $\Omega_\Lambda=0.7$ cosmology in agreement with result obtained by the Hubble Space Telescope for clusters at low redshift, and with the $\Lambda$CDM concordance model.\footnote{According to the $\Lambda$CDM model the Universe is spatially flat, homogeneous and isotropic on large scales, composed of radiation, ordinary matter (electrons, protons, neutrons, and neutrinos), nonbaryonic cold dark matter, and dark energy and with adiabatic initial conditions of the density fluctuations. The direct confirmation of this theory was the detection of the acoustic Doppler peak structure in the CMB angular power spectrum. A wide range of astronomical datasets are consistent with the predictions of the $\Lambda$CDM model with its parameters fitted to the WMAP data. These data range from large scale structure galaxy surveys, supernovae luminosity distance, Lyman-$\alpha$ forest, weak and strong lensing etc. \cite{8,9,10}.}

The Cosmic Soft Excess (CSE) is a phenomenon exhibited by a fraction of clusters ($\approx 30 – 40\%$) in the extreme ultraviolet or in the soft (1 keV) X-ray band \cite{66}. Since its discovery the properties and origin of the CSE have been subject of debate. CSE has been detected by the Extreme Ultraviolet Explorer and by several X-ray telescopes including the current XMM-Newton. Both the thermal and non-thermal interpretation on the CSE origin have been considered and the issue is still under study.

5 In Conclusion

The wealth of astrophysical information currently available on galaxy clusters can give us a deeper understanding of the Universe we live in. We have entered in a promising era for cosmology with clusters. Today scientists are adopting the multi-frequency approach to carry out cosmological studies since each wavelength contributes a little piece of information which makes sense once the whole puzzle is as-
Assembled. We have come a long way since the times when astronomers were looking for overdensities of galaxies to discover clusters! X-ray observations, optical and infrared observations of the cluster member galaxies and weak lensing of background galaxies by the deep cluster potential are complementary probes of high-redshift clusters. Measurements of the SZE have been used to determine cluster properties such as the gas and total masses, electron temperatures, as well as to constrain the cosmological distance scale \[ 52, 65, 13 \]. The SZE will soon be used as a new band for detecting clusters at high redshift. SZE surveys will be a tremendous source of new information in the near future. In particular surveys like the South Pole Telescope (SPT; \[ 88 \]) or the Atacama Cosmology Telescope (ACT; \[ 63 \]) will produce catalogs of clusters unbiased in redshift. Some of the planned SZE instrumentation is now reality. I am thinking of the Sunyaev-Zel’dovich Array (SZA), an eight-element interferometer which enables one to achieve high sensitivity with respect to single dish observations even for extended low-surface brightness emission. During the commissioning period the SZA demonstrated that it can be used to study distant \( z \geq 1 \) clusters \[ 73 \].

The soon to be flown Planck satellite \[ 9 \] will extend our knowledge of the CMB beyond the limits set by past and present experiments (for instance WMAP). Planck will survey the whole sky and will provide a large dataset of clusters expected to be at \( z > 1 \). Blind SZE surveys in the near future will discover thousands of clusters. Since the SZE signal is independent of redshift the limit of such surveys will be a mass limit. Such cluster surveys can be used to determine cosmological parameters with high precision. The Planck mission will likely lead us to a full comprehension of the CMB temperature anisotropies and it will be crucial as a test of the robustness of the CDM concordance model.

The non-thermal components of clusters of galaxies will be revealed by the future radio telescopes. When arrays like the Square Kilometer Array, SKA \[ 10 \], the Long Wavelength Array, LWA \[ 11 \] or the Low Frequency Array, LOFAR \[ 12 \] will become operational they will reveal new radio halos especially in distant clusters. One can then be able to compare the statistics between the observational data and the expectations from models of cluster and structure formation. The combination of radio and hard X-ray data will be crucial to measure the energy content in the form of relativistic electrons and magnetic field in the ICM. The proposed new generation hard X-ray telescope SIMBOL X \[ 13 \] (a jointly supported Italian-French mission with German participation) which will operate in the 0.5–80 keV, is expected to reveal and map the non-thermal emission in clusters of galaxies.

\[ \text{References:} \]

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\[ 12 \] http://www.lofar.org/
\[ 13 \] http://www.asdc.asi.it/simbol-x/
I believe the time is certainly mature to have a new medium-depth X-ray all-sky survey of clusters carried out with a dedicated satellite with a good point spread function (similar or better than XMM), optimized optics for wide-field X-ray imaging and low background. An all-sky survey, and its associated large sample of clusters, would be crucial to investigate the relationship between X-ray observables and masses. In addition many new clusters at high redshift will be discovered. We need more objects to observe and study. Several ideas for such a survey have been proposed by the scientific community to the various space agencies but none has been approved so far. In the meantime we have to make do with the invaluable archives of both Chandra and XMM-Newton which are providing interesting new results (see among others [29, 77, 96, 7, 16]) and with ongoing X-ray cluster surveys like the X-ray Cluster Survey (XCS; [85]) or the XMM-Large Scale Structure survey (XMM-LSS; [80]). The first will produce a catalog of several thousand serendipitously-detected clusters in over 500 deg$^2$ to beyond $z=1$. See [89] for a recent paper forecasting the constraints on the values of $\Omega_m$, $\sigma_8$, and cluster scaling relations parameters expected from the XCS survey. The second survey, the XMM-LSS, has recently produced a combined analysis of weak lensing and X-ray blind surveys [9]. Meanwhile the continuing program of Chandra and XMM observations will contribute to increase the cluster statistics. The Planck satellite will provide new large datasets of clusters identified through the SZ effect. These will be new targets for the future X-ray observatories like the NASA mission Constellation-X [14] and the ESA mission XEUS [15] that will allow us to carry out more precise studies on the nature and content of the Dark Matter and Dark Energy of the Universe.

6 Further Reading

Additional articles on Cosmology with Clusters not appearing in the Reference section are listed below:

- Borgani, S. & Guzzo, L.: X-ray Clusters of Galaxies as Tracers of Structure in the Universe, Nature, 409, 39–4 (2001)
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14 [http://constellation.gsfc.nasa.gov/]
15 [http://www.rssd.esa.int/index.php?project=XEUS]
discussions with M. Branchesi, L. Feretti, R. Gal, F. Govoni, P. Henry, M. Murgia and B. Tully. I acknowledge partial financial support from contracts ASI-INAF I/023/05/0, 088/06/0 and DA-030.

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