# Galaxy Clusters as Giant Cosmic Laboratories

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# ABSTRACT BOOK

**Oral Communications and Posters**

Edited by

Jan-Uwe Ness

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# Chapter 1

# Invited Speakers

### Simulations to calibrate clusters for cosmology

Stefano Borgani[1]
[1] *University of Trieste & INAF*

In my talk I will overview recent results obtained from the analysis of cosmological hydrodynamical simulations of galaxy clusters, aimed at calibrating them as tools for precision cosmology. Among the different applications that simulations find in this context I will discuss: calibration of the effect of baryons on the halo mass function, quantification and origin of violation of hydrostatic equilibrium, comparison between X-ray and weak-lensing masses, robustness of scaling relations of different mass proxies against cluster mass.

### Comparison of Obervations and Simulations of galaxy clusters

Klaus Dolag[1]
[1] *University Observatory Munich, Germany*

Upcoming astronomical surveys and instruments like Planck, SPT, PanStars, DES, Euclid, LOFAR, eRosita and many more will need a theoretical counterpart in form of simulations which follow the formation of cosmological structures in so far unaccomplished detail, taking into account enough physical and also briefly show the role of other virtual telescopes like SkyLense, which allows to produce mock optical observations including weak and strong lensing signals. processes to allow a self consistent comparison to observations at multiple wavelength and throughout the entire epoch of structure formation. I will report on preliminary results from a recent simulation campaign, where we followed the formation of cosmological structures in so far unaccomplished detail, performing a large set of cosmological, hydrodynamical simulations covering up to $Gpc^3$ volumes, taking into account enough physical processes (star- formation, chemical enrichment, AGN feedback) to allow a self consistent comparison to observations at multiple wavelength. This partially needs to be done by virtual observations. I will also introduce a novel virtual X-ray observatory designed to obtain synthetic observations from hydro-numerical simulations, named PHOX.

## The Herschel view of clusters of galaxies

Alastair Edge[1]
[1]*Durham University, Durham, UK*

I will review Herschel results on clusters of galaxies concentrating on the properties of the central cluster galaxy. In particular, I will focus the link between the FIR atomic cooling flows ([OI] and [CII]) with other tracers of the cold molecular gas phase in cluster cores and how the FIR dust continuum correlates to the associated star-formation. I will summarise the prospects for other Open and Key Projects and how Herschel results can set the agenda for future ALMA and JWST observations.

## Cluster mass profiles from X-ray observations: present constraints and limitations

Stefano Ettori[1]
[1]*INAF Osservatorio Astronomico di Bologna*

The distribution of the gravitating and baryonic mass in galaxy clusters is the key ingredient to use these structures as astrophysical laboratories and cosmological probes. I'll review the methods used to recover the gas and total mass profiles for galaxy clusters from X-ray observations. I'll discuss some of the limitations affecting the X-ray analysis. I'll illustrate how the estimates of the gas mass fraction and of the mass concentration can be used as robust cosmological tools.

### Cluster masses from weak lensing measurements

Henk Hoekstra[1]
[1] *Leiden Observatory*

The cluster mass is a key observable, however most methods to determine this require assumptions about the dynamical state of the cluster and the three-dimensional distribution of matter. The cluster potential also deflects light rays from background galaxies, leading to small systematic alignments in the shapes of these sources, an effect called weak gravitational lensing. By measuring this signal it is possible to map the projected matter distribution directly and measure masses.

In recent years weak lensing has become an important way to calibrate other mass proxies, although the 3d structure of the clusters complicates things. In this talk I will describe the technique and the observational challenges that need to be overcome and present some recent results that provide a flavor of what is to come as ever larger samples of clusters are studied.

### Multiwavelength Constraints on Scaling Relations and Substructure in a Sample of 50 Clusters of Galaxies

Andisheh Mahdavi[1], Henk Hoekstra[2], Arif Babul[3], Chris Bildfell[3], Tesla Jeltema[4], J. Patrick Henry[5]
[1] *San Francisco State University*
[2] *Leiden University*
[3] *University of Victoria*
[4] *UC Santa Cruz*
[5] *University of Hawaii, Manoa*

We describe results from the JACO/CCCP project, which seeks to determine the detailed physical properties of gas and dark matter in a sample of 50 clusters of galaxies. Using CFHT weak gravitational lensing data, combined analysis of Chandra and XMM-Newton data, and in a few cases Sunyaev-Zel'dovich observations from multiple interferometers, we determine the distribution of gas and dark matter, assuming hydrostatic equilibrium where necessary. We find that gas mass is the lowest scatter estimator of weak lensing mass at $r_{500}$ (the log slope is 1, implying that clusters of this mass range have the same baryon fraction). The intrinsic scatter in the observable-lensing mass relation is $15+/-7\%$ for gas mass, $20\% \pm 6\%$ for $Y_X$, and $35\% \pm 8\%$ for temperature. The last two scatters decrease when measured at $r_{2500}$. We confirm and extend our earlier finding that hydrostatic masses are systematically low when compared with weak lensing masses, most likely due to nonthermal pressure support. We find that the best measures of the degree of deviation from equilibrium are the central entropy (or equivalently, the central cooling time), the BCG-to-X-ray peak offset, and the centroid shift variance.

### Metals in clusters of galaxies observed with Suzaku and XMM-Newton

Kyoko Matsushita[1], Eri Sakuma[1], Kosuke Sato[1], Toru Sasaki[1], Takuya Sato[1]
[1] *Tokyo University of Science*

We derived the abundance profiles of O, Mg, Si, S and Fe in the intracluster medium (ICM) of several clusters and groups of galaxies up to about 0.3 $r_{180}$ with Suzaku and those of Fe in 28 nearby brightest clusters of galaxies up to 0.3-0.5 $r_{180}$ with XMM. At 0.1–0.5 $r_{180}$, clusters have relatively flat Fe abundance profiles with a small scatter. In these regions, the O/Fe and Mg/Fe ratios are consistent to the solar ratio, but some systems show a hint of enhancement of O/Fe and Mg/Fe ratios. Since metals have been synthesized in galaxies, the ratios of metal mass in the ICM to the total light from galaxies in clusters or groups are key parameters in investigating the chemical evolution of the ICM. The iron-mass-to-light ratios (IMLR) of clusters and groups of galaxies were measured from 0.2 to 0.5 $r_{180}$, and out to $r_{180}$ of the Hydra A cluster. The IMLR increase toward outer regions. These results indicate that the metal-enrichment process in these clusters has been universal, and a significant amount of Fe is synthesized at a very early stage in cluster formation.

### The X-ray Scaling Properties of Galaxy Clusters

Ben Maughan[1]
[1] *University of Bristol*

The scaling relations between cluster properties present an intersection between the study of clusters as cosmic laboratories and as cosmological probes. Scaling relations offer cheap observational estimates of cluster masses, but only if we understand how feedback processes in clusters influence the shape and scatter of the scaling relations. I will present results from our X-ray studies of three complementary samples that shed new light on the details of the scaling relations: an archival sample of 114 clusters covering $0.1 < z < 1.3$ which allows us to dissect the cluster population based on cooling and morphology; a statistically complete sample at $0.15 < z < 0.3$ which allows us to investigate selection biases and to utilise full hydrostatic masses; and a new X-ray study of a sample of weak lensing selected clusters which enables us to view selection bias from a different perspective.

## AGN Feedback in Clusters

Brian McNamara[1]
[1] *U. Waterloo, Ontario Canada*

I will review the evidence for AGN feedback in clusters, groups, and galaxies. I will show that radio AGN are driving large-scale outflows of metal-rich gas throughout the hot atmospheres of clusters. Recent studies have shown that AGN feedback was operating in clusters when the Universe was half its present age. Apparently, the excess entropy in hot atmospheres was deposited by radio AGN over time, rather than during an early ”preheating” epoch. Large cooling flows were less prevalent at z=0.4 than they are today.

## X-ray and Optical Observations of High Redshift SPT Selected Galaxy Clusters

Joseph Mohr[1], for the SPT Collaboration
[1] *Ludwig-Maximilians University, Scheinerstrasse 1, 81679 Munich GERMANY*

Rare, high mass clusters at high redshift serve as important probes of cosmology and useful laboratories for studies of structure evolution. The SPT SZE survey can cleanly select clusters with $M_{200} > 3 \times 10^{14} M_{\odot}$, regardless of their redshift. With the recent completion of the optical/IR followup over 750 deg$^2$ of the survey, the characteristics of this population are now clear. The population of $S/N > 5$ ($> 4.5$) SPT clusters is contaminated at $< 5$pct ($\sim$20pct) through SZE selection alone. In combination with OIR followup the purity reaches $\sim$100pct. Roughly 20pct of the SPT clusters lie at $z > 0.8$, producing a sample of approximately 35 systems over the follow-up complete survey region and an expected sample of over 100 of these systems over the full 2500 deg$^2$ SPT survey. Initial cosmological analyses relying on X-ray mass calibration at lower redshift provide constraints consistent with existing non-cluster studies. However, the real cosmological power of this sample can only be realized through improved mass calibration. We are pursuing additional mass measurements using XMM-Newton and Chandra observations, VLT velocity dispersions and HST+VLT weak lensing. These XMM-Newton observations also provide a new window on processes like AGN feedback and star formation that drive the evolution of the intracluster medium.

## AGN feedback in clusters: the feedback cycle

Paul Nulsen[1]
[1] *Harvard-Smithsonian Center for Astrophysics*

While high resolution X-ray observations have made a strong empirical case for radio mode AGN feedback in clusters, detailed understanding of the feedback cycle remains poor. I will discuss routes by which outburst energy is transferred to the intracluster medium and what is known about their relative importance. I will also discuss how AGN at cluster centres may be fuelled by cooled or cooling intracluster gas to close the feedback loop. Future observations will extend our understanding of the functioning and significance of AGN feedback for the formation and evolution of galaxy clusters.

## Galaxy cluster detections in the PLANCK Survey

Etienne Pointecouteau[1], the Planck Collaboration
[1] *IRAP (Université de Toulouse/CNRS)*

The Planck nominal mission of more than two surveys of the whole sky is now completed and to be released to the public in early 2013. From the first all-sky survey, we have released an early SZ sample of 189 clusters detected via the Sunyaev-Zel'dovich effect with high signal-to-noise and is highly reliable, and since presented the detection of about 35 new clusters found by Planck. The Planck collaboration is engaged in massive identification and follow-up programs of its SZ sources at X-ray, optical, and SZ wavelengths. Dedicated cluster studies are also conducted by the consortium. I will briefly review and summarise the Planck collaboration early SZ results, and further present and details new Planck results on clusters from the nominal mission: new SZ detections, ongoing follow-up programs, constraints on SZ scaling relations, structural studies, etc.

## LOFAR surveys of the radio sky: probing shocks and magnetic fields in galaxy clusters

Huub Röttgering[1]
[1] *Leiden Observatory, Leiden, the Netherlands*

Radio observations of clusters are important to understand the impact of shocks and mergers on the general evolution of clusters. In the last years we have embarked on a large project to elucidate the relation of diffuse radio sources in clusters and properties of the ICM. In this talk we will first discuss results from studies of individual clusters including the spectacular 'sausage' and 'toothbrush' clusters. We then present results from radio observations of a sample of clusters. Also assisted by simulations, we then show how many parameters of merging clusters can be constrained (mass ratio, impact parameter, orientation).

In the last part of the talk I will briefly review the status of the pan-European radio telescope LOFAR, the Low Frequency Radio Array. First results on nearby clusters will be shown.

## A Fully Self-Consistent Picture of Galaxy Cluster Abundances and Optical, X-ray, and SZ Scaling Relations at z=0.2

Eduardo Rozo[1]
[1] *University of Chicago*

In the early Planck results series of papers, the Planck collaboration argued that the SZ-optical scaling relation appeared to be in conflict with expectations based on X-ray galaxy clusters. We demonstrate how this tension can be resolved, resulting in a fully self-consistent picture of galaxy clusters where any two scaling relations can be combined to predict a third. Moreover, we demonstrate that the optical and X-ray abundances of galaxy clusters are consistent with each other, and consistent with cosmological expectations for a WMAP7 cosmology.

### The thermal and dynamical state of cluster cores

Jeremy Sanders[1]
[1] *University of Cambridge, Cambridge, UK*

Modern X-ray telescopes, such as XMM-Newton and Chandra, have revolutionised our understanding of the cores of galaxy clusters. For example, the spectral resolution of the XMM-RGS instruments have allowed us to see individual emission lines from gas at various temperatures, while Chandra's spatial resolution has allowed us to locate where this material is. I will discuss recent work where we used deep XMM-Newton observations to measure in detail the temperature structures in cluster cores, finding a close balance between heating and cooling rates. A new possibility, we found recently, is to use XMM-RGS to place tight limits on the gas motions in the cores of galaxy clusters by measuring line widths. I will also discuss new advances in this area to improve these results and connect to what we can learn about the turbulent state of clusters by looking for pressure and density fluctuations in images and spectral maps.

### The origin of the chemical elements in cluster cores

Jelle de Plaa[1]
[1] *SRON Netherlands Institute for Space Research*

Metals play a fundamental role in ICM cooling processes in cluster cores through the emission of spectral lines. But when and how were these metals formed and distributed through the ICM? The X-ray band has the unique property of containing emission lines from all elements from carbon to zinc within the $0.1-10$ keV band. Using XMM-Newton, the abundances of about 12 elements are studied, which contain valuable information about their origin. Most elements were formed in type Ia and core-collapse supernovae, which have very different chemical yields. Massive stars and AGB stars also contribute by providing most of the carbon and nitrogen in the ICM. Because feedback processes suppressed star formation in the cluster centre, the element abundances allow us to directly probe the star formation history of the majority of stars that are thought to have formed between $z=2-4$. The spatial distribution in the core and the evolution with redshift also provide information about how these elements are transported from the member galaxies to the ICM. I review the current progress in chemical enrichment studies of the ICM and give an outlook to the future opportunities provided by XMM-Newton's successors, like Astro-H.

# Chapter 2

# Dynamical and thermal structure of galaxy clusters and their ICM

## Observing simulated galaxy clusters: the prospects of velocity diagnostics of the ICM

Veronica Biffi[1], Klaus Dolag[3], Hans Boehringer[2]
[1] *Max Planck Institute for Astrophysics, Garching, Germany*
[2] *Max Planck Institute for Extraterrestrial Physics, Garching, Germany*
[3] *University Observatory Munich, Munich, Germany*

Non-thermal motions in the intra-cluster medium (ICM) are believed to play a non-negligible role in the pressure support to the total gravitating mass of galaxy clusters. Future X-ray missions, such as Astro-H and Athena, will allow us to directly detect the signature of these motions from high-resolution spectra of the ICM. I will present here a study on a set of clusters extracted from a cosmological hydrodynamical simulation, devoted to explore the role of non-thermal velocity amplitude in characterising the cluster state and the relation between observed X-ray properties. To this goal, we apply the X-ray virtual telescope PHOX to generate mock observations of the simulated clusters. From the synthetic spectra we extract luminosity and temperature, and we accurately estimate the gas velocity dispersion from the broadening of heavy-ion (e.g. Fe) emission lines in the high-resolution spectra. Since luminosity is a quantity very well measured in X-ray and temperature is closely related to the total cluster mass, which is the most fundamental property to characterise the system, we explore the $L_X - T$ relation in combination with the ICM velocity diagnostics. This offers a promising way to identify disturbed clusters in addition to the commonly used morphological classification.

## Exploring the dynamics of A194

Akos Bogdan[1], Ralph Kraft[1], William Forman[1], Christine Jones[1], Randall Scott[1], Ming Sun[2], Christopher O'Dea[3], Eugene Churazov[4], Stefi Baum[3]
[1] *Smithsonian Astrophysical Observatory*
[2] *Department of Astronomy, University of Virginia*
[3] *Rochester Institute of Technology*
[4] *Max-Planck-Institut für Astrophysik*

Based on Chandra and ROSAT observations we investigated the poor cluster Abell 194, which hosts two luminous radio galaxies, NGC547 (3C 40B) and NGC541 (3C 40A). We demonstrated the existence of a large X-ray cavity at the southern part of the cluster formed by the giant southern radio lobe arising from 3C 40. Using the parameters of the hot ICM, the extent and location of the cavity, we estimated the total work of the AGN, the age of the cavity, and the total cavity power. Furthermore, in the Chandra images of NGC545 and NGC541 we detected sharp surface brightness edges, identified as merger cold fronts, and extended tails. Using the pressure ratios between inside and outside the cold fronts, we estimated that NGC545 and NGC541 are moving with transonic velocities. The low radial velocities of these galaxies relative to the mean radial velocity of Abell 194 imply that their motion is oriented approximately in the plane of the sky. Based on these and earlier observations, we concluded that NGC547 is in the center of Abell 194 and NGC545 and NGC541 are falling through the cluster. These suggest that Abell 194 is undergoing a major cluster merger event.

### Turbulence measurements in two giant elliptical galaxies

Jelle de Plaa[1], Irina Zhuravleva[2], Norbert Werner[3], Jelle Kaastra[1,4], Eugene Churazov[2,5], Randall Smith[6], Ton Raassen[1], Yan Grange[1]
[1]*SRON Netherlands Institute for Space Research*
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[3]*KIPAC Stanford University*
[4]*Astronomical Institute, Utrecht University*
[5]*Space Research Institute (IKI), Moscow*
[6]*Harvard-Smithsonian Center for Astrophysics, Cambridge*

Turbulent pressure is thought to contribute significantly to the total pressure in the hot intracluster medium. Due to the limited spectral resolution of current X-ray observatories, it is very difficult to detect turbulence directly from line broadening and quantify this important pressure term. There are, however, other methods to estimate the level of turbulence. We study the effect of resonant scattering on Fe XVII lines in deep XMM-Newton RGS spectra of two giant elliptical galaxies. In the spectra, we find significant differences in Fe XVII line ratios between the galaxies, which are explained by a difference in the level of turbulence. Combined with information from deep Chandra images, we discuss the magnitude differences and the origin of the turbulence in these objects.

### The gas distribution in galaxy cluster outer regions

Dominique Eckert[1]
[1]*ISDC Data Center for Astrophysics, Geneva, Switzerland*

Cluster outskirts are the regions where the transition between virialized cluster gas and accreting material from the large-scale structure occurs. I will present an analysis of a large sample of nearby clusters with ROSAT/PSPC, taking advantage of the large field-of-view of this instrument, to trace the behavior of the intracluster gas out to the virial radius. Detailed comparison between data and three different sets of numerical simulations will be shown. I will also present the mean azimuthal scatter profiles in our sample to quantify the deviations from the assumption of spherical symmetry. The implications of these results on our knowledge of the state of the gas in cluster outskirts (clumping, hydrostatic equilibrium) will be discussed.

### Cold Fronts in Groups and Clusters and their dynamical state in the optical

Fabio Gastaldello[1], Laura Di Gesu[1], Matteo Messa[1], Simona Ghizzardi[1], Elke Roediger[2], Mariachiara Rossetti[1], Dominique Eckert[3], Silvano Molendi[1], David Buote[4], Philip Humphrey[4]

[1] *INAF-IASF Milan*
[2] *Jacobs University Bremen*
[3] *ISDC Geneva Observatory*
[4] *University of California Irvine*

Cold fronts are found both in merging and in cool core relaxed clusters. In merging clusters cold fronts mark the discontinuity among the merging dense subcluster and the less dense surrounding ICM. In relaxed clusters cold fronts are likely induced by minor mergers that produce a sloshing mechanism of the low entropy gas in the core. For a sample of clusters we combine the existence of a cold front with indicators of dynamical activity in the optical: presence of substructure and peculiar velocity of the BCG. We extend this comparison to the few sloshing cold fronts in X-ray bright groups currently known, showing the tantalizing implications for the evolution of disk galaxies in the group environment.

### X-ray and dynamical properties of the DAFT/FADA cluster sample

Loic Guennou[1], Florence Durret[2], Christophe Adami[1], Gastao B. Lima Neto[3]

[1] *Observatoire Astronomique Marseille Provence, France*
[2] *Institut d'Astrophysique de Paris, France*
[3] *Instituto Astronomico e Geofisico, Sao Paulo, Brazil*

We have undertaken the DAFT/FADA survey with the double aim to obtain constraints on dark energy based on weak lensing tomography and to have homogeneous and high quality data for a sample of 91 massive clusters in the redshift range [0.4,0.9] with HST data previously available. We have studied the XMM-Newton data available for 42 of these clusters to derive their X-ray temperatures and luminosities, and to search for substructures. This was coupled with a dynamical analysis for the 26 of these clusters having at least 30 spectroscopic galaxy redshifts in the cluster. We propose to present preliminary results on the coupled X-ray and dynamical analyses of these clusters.

### Extending measures of the ICM to the outskirts: facts, myths and puzzles.

Silvano Molendi[1]
[1] *IASF-Milano INAF*

Over the last decade our understanding of cluster cores has improved dramatically: the same cannot be said of cluster outer regions. In this presentation I will review some of the better known results that have been reported for cluster outskirts trying to distinguish between those than can be trusted and those that should be viewed with some skepticism. On the basis of this division, I will highlight the truly important open issues that can and should be addressed in the next few years. I will close by describing the key feature required of an X-ray experiment to achieve dramatic improvements in the characterization of cluster outskirts.

### Bulk motion measurements in clusters of galaxies using XMM-Newton and ATHENA

Jukka Nevalainen[1]
[1] *University of Helsinki*

I will present preliminary results of bulk motions in A2256 cluster of galaxies as measured with XMM-Newton EPIC instruments. I will discuss the results in the context of the recent Suzaku findings. I will also present the expected quality of the bulk motion measurements with the proposed ATHENA (Advanced Telescope for High Energy Astrophysics) mission. ATHENA contains an X-ray microcalorimeter spectrometer XMS which would make a huge improvement in high resolution (dE $\sim$ 1 eV) X-ray astronomy. In addition to its factor of 100-1000 increase in the effective area compared to current high resolution instruments, it would for the first time enable spatially resolved high spectral resolution X-ray measurements. In the talk I will discuss how these technological advances would improve the measurements of the dynamics of the large scale structure in the form of bulk motions in clusters of galaxies.

## X-ray study of clusters at the outer edge and beyond

Takaya Ohashi[1], Hiroki Akamatsu[1], Yoh Takei[2]
[1] *Tokyo Metropolitan University*
[2] *ISAS/JAXA*

We first report on recent Suzaku results on cluster outer regions. Significant temperature jumps have been confirmed for a number of radio relics, including those in A3667, A3376 and CIZA J2242.8+5301. This confirms that the radio relics generally correspond to shock fronts with the Mach numbers around 3. Relaxed clusters show a systematic temperature drop down to about 1/4 of the central levels at the virial radii, with entropy profiles deviating from the simulated curve around the virial radius. This suggests that the gas is out of simple equilibrium in the outer edge regions. We are proposing DIOS, characterized by a wide-field ($\sim$ 50 arcmin) array of microcalorimeters combined with 4-reflection X-ray optics, for the studies of cluster outer regions and their connection with WHIM filaments. DIOS will be able to measure the detailed thermal and dynamical properties of the gas accreting onto clusters from the filaments.

## Challenging the merging/sloshing cold front paradigm with a new XMM observation of A2142

Mariachiara Rossetti[1], Dominique Eckert[3], Fabio Gastaldello[2], Silvano Molendi[2], Simona Ghizzardi[2], Sabrina De Grandi[4]
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[4] *Osservatorio astronomico di Brera*

A2142 is the first cluster in which cold fronts were observed. Two striking surface brightness discontinuities are visible even to an untrained eye in Chandra images and the pressure profiles are almost continuous across them, providing textbook examples of cold fronts. However, A2142 does not fit within the now dominant scenario, that describes cold fronts either as the edges of merging subclusters or as the cool cores "sloshing" in the potential well of their host cluster.

I will present results from a new deep XMM-Newton observation of this cluster, showing details on the distribution of the thermodynamic quantities and metal abundance in the inner region. I will also provide the first evidence for a third surface brightness discontinuity, located at almost 1 Mpc distance from the cluster center. The temperature measurements across the discontinuity exclude the shock front hypothesis for the nature of this feature and are consistent with a cold front.

Combining this observation, published optical data and preliminary results on the radio band, I will discuss the dynamical state of A2142, showing the peculiar position of this object in all the usual classifications of galaxy clusters (sloshing/merging, relaxed/disturbed, radio quiet/radio halo).

**Shock fronts, electron-ion equilibration and ICM transport processes in the merging cluster Abell 2146**

Helen Russell[1], Brian McNamara[1], Jeremy Sanders[2], Andy Fabian[2], Paul Nulsen[3]
[1] *University of Waterloo*
[2] *University of Cambridge*
[3] *Harvard-Smithsonian Center for Astrophysics*

Shock fronts generated by galaxy cluster mergers provide a key tool for studying the cluster gas. However, unambiguous detections of merger shock fronts are rare and only a few examples have been found to date. Our new 400ks observation of Abell 2146 reveals detailed structure associated with a major merger event including a Mach $M = 2.3$ bow shock ahead of the dense, ram pressure stripped subcluster core and the first known example of an upstream shock in the ICM ($M = 1.6$). By measuring the electron temperature profile behind each shock front, we determine the timescale for the electron population to thermally equilibrate with the shock-heated ions. We find that the temperature profile behind the bow shock is consistent with the timescale for Coulomb collisional equilibration and the postshock temperature is lower than expected for instant shock-heating of the electrons. We have also investigated the suppression of transport processes in the ICM by calculating the width of each shock front and the subcluster contact discontinuity. The upstream shock in particular is remarkably narrow over its 440kpc length. We calculate a best-fit width of only $6 \pm 4$kpc, which is significantly narrower than the estimated mean free path.

**Temperature, entropy, and mass profiles to the virial radius of galaxy clusters with Suzaku**

Kosuke Sato[1], Kyoko Matsushita[1], Nobuhiro Okabe[2], Kazuya Ichikawa[1], Takuya Sato[1], Motokazu Takizawa[3], Yutaka Fujita[4], Kazuhiro Nakazawa[5], Noriko Yamasaki[6], Shin Sasaki[7]
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[3] *Yamagata University*
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[5] *University of Tokyo*
[6] *ISAS/JAXA*
[7] *Tokyo Metropolitan University*

We studied the temperature, entropy, and mass profiles of the intracluster medium in the Hydra A (3 keV), Abell 1246 (6 keV), and a few clusters and around the cluster outskirts beyond the virial radii with Suzaku. The observations showed the temperature drop from the central to the outer region around r200 region of the clusters by 60%, and the radial temperature profile had a weak directional dependence. The derived entropy profiles have a flatter slope compared to that of the numerical simulation, particularly in r>r500. We also found that the radial ratios of the entropy from cluster observations with Suzaku to the expected values from the simulation have a similar slope index. This would suggest a universality that all the clusters have passed similar evolution processes. We also discuss the temperature dependence, which corresponds to the system size, of the derived entropy and baryon fraction derived from calculated gas mass and total mass under the assumption of hydrostatic equilibrium, to the virial radius.

## Exploring the outskirts of the galaxy clusters Abell 2029, PKS 0745-191 and the Centaurus Cluster to the virial radius

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We present Suzaku observations of the outskirts of the galaxy clusters Abell 2029 and PKS 0745-191, which have been studied with good azimuthal coverage out to the virial radius and beyond. Measurements of galaxy clusters to the virial radius are important for understanding the physics of cluster formation and accretion, and for calculating more accurate cluster masses which are needed for using clusters as cosmological probes. Abell 2029 demonstrates a significant deviation away from spherical symmetry, suggesting merger activity which has disturbed the ICM along one direction. We use new background pointings of PKS 0745-191 to improve the accuracy of the background modelling and resolve the problems with the original observation made in George et al. 2009. For both clusters the entropy profile is found to flatten off in the outskirts below the predicted values assuming purely gravitational structure formation, suggesting that in the outskirts around the virial radius the ICM is out of hydrostatic equilibrium. We present preliminary results for the Centaurus cluster whose outskirts have been explored for the first time, and whose large angular extent (due to its closeness) allows the ICM to be probed in more detail.

## Studying the properties of galaxy cluster morphology estimators

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X-ray observations reveal a variety of galaxy cluster morphologies. This indicates that the fraction of clusters showing structure does not satisfy the assumption of hydrostatic equilibrium and spherical shape, which are needed to determine cluster masses from X-ray data. It is thus important for the understanding of cluster properties as well as for cosmological applications to mark such clusters. Two methods to do so are power ratios (P3/P0) and center shifts (w) which trace asymmetries of the gravitational potential. We studied the effect of Poisson noise and background which can severely influence the power ratio and center shift measurements in detail using a large sample of simulated X-ray cluster images and improved the method to correct for these effects. This enables us to study the evolution of substructure over a large redshift range where photon statistics vary substantially. Based on a visual study of simulated cluster images, we present structure boundaries to divide samples into relaxed, mildly disturbed and disturbed objects and discuss a new morphology estimator: the peak of the P3/P0 profile to better identify merging clusters. The analysis methods were applied to 80 observed galaxy clusters, finding 10% disturbed, 65% mildly disturbed and 25% relaxed objects.

**Probing the Microphysics of the Intracluster Medium with Cold Fronts in the ICM**

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Many X-ray observations of galaxy clusters reveal the presence of sharp, discontinuities in the surface brightness of the X-ray emitting gas. Spectral analysis of these features shows that the colder gas is on the brighter side, hence they have been dubbed cold fronts. These features arise naturally in simulations from major mergers of galaxy clusters and cool-core gas sloshing in the gravitational potentials of relaxed galaxy clusters. Most, if not all, cold fronts appear to be remarkably resilient to the effects of fluid instabilities and thermal conduction. Using magnetohydrodynamics simulations of the intracluster medium including viscosity and thermal conduction, we will show how simulations of the formation of cold fronts in clusters can shed light on the microphysical properties of the thermal gas in the ICM.

# Chapter 3

# Non-thermal processes in clusters

### Discovery of the first radio halo in a new Planck cluster confirmed by XMM Newton

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We present the discovery of the first $\sim$ Mpc size source of diffuse non-thermal radio emission- a giant radio halo- in the galaxy cluster PLCK G171.94 − 40.65 at z=0.27. PLCK G171.94 − 40.65 is a hot (T$\sim$ 10 keV), massive, and luminous galaxy cluster discovered by the Planck through the Sunyaev-Zel'dovich effect and confirmed by the XMM Newton observations. The Giant Metrewave Radio Telescope (GMRT) 235 MHz and the NRAO VLA Sky Survey 1.4 GHz data revealed the $\sim$ Mpc size giant radio halo in this cluster. The integrated radio spectrum of the radio halo is quite steep with a slope $\alpha = 1.6 \pm 0.3$. The X-ray surface brightness and temperature maps with the XMM Newton data show that the cluster is hot and has a disturbed morphology indicative of a recent merger. These properties are consistent with the expectations of the turbulent re-acceleration model and support the causal connection between cluster mergers and radio halos.

### CIZA J2242.8+5301: The galaxy cluster with the strongest merger shock

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Radio relics are Mpc-scaled, steep-spectrum synchrotron sources that are most likely produced by particle acceleration at merger shock waves. CIZA J2242.8+5301 is a merging cluster which hosts a spectacular double radio relic. The northern relic has a clear bow-like shape, a length of 2 Mpc, and a width of only 50 kpc. Using *XMM-Newton* data, we found evidence for a shock of Mach number $3.7 \pm 1.5$ at the northern relic – the highest ever detected in a cluster merger – which confirms the remarkable nature of this object. X-ray images also reveal a complex ICM morphology: a strongly elongated overall shape, a bright arc located 0.25 Mpc away from the center, and a fainter arc coincident with part of the inner edge of the northern relic. Additionally, there is indication of a surface brightness discontinuity near the southern relic, and of possible symmetrical inner shocks that do not cause detectable radio relics. We also present preliminary results from a 200-ks *Chandra* exposure of the cluster, and discuss all our findings in the context of recent results from numerical simulations. With upcoming interferometers, the joint analysis of radio and X-ray data will open a new era of studying galaxy cluster outskirts.

### X-ray Observations of Shocks and Radio Emission in Abell 3667, Abell 665, Abell 2061, and the Cygnus-A Cluster


Craig Sarazin[1], Alexis Finoguenov[2,3], Daniel Wik[4], Tracy Clarke[5], Ming Sun[6], Kazuhiro Nakazawa[7], Frederica Govoni[8], Valentina Vacca[8], Kevin Pimbblet[9], Yutaka Fujita[10]

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XMM-Newton, Suzaku, and radio observations of the northwest merger shock in Abell 3667 will be presented. The radio relic has a sharp outer edge which agrees with the position of the shock. X-ray observations indicate that the merger shock Mach number is about 2. Comparing the radio emission to the shock properties implies that approximately 0.2% of the dissipated shock kinetic energy goes into accelerating relativistic electrons. This is also an order of magnitude smaller than the efficiency of shock acceleration in many Galactic supernova remnants, which may be due to the lower Mach numbers of cluster merger shocks. The X-ray and radio properties indicate that the magnetic field strength in the radio relic is about 3 $\mu$G, which is a very large field at a projected distance of $\sim$2.4 Mpc from the center of a cluster. The radio spectrum is relatively flat at the shock, and steepens dramatically with distance behind the shock. This is consistent with radiative losses by the electrons and the post-shock speed determined from the X-ray properties.

Time permitting, the X-ray and radio properties of the merger shocks in the clusters Abell 665, Abell 2061, and Cygnus-A will be summarized.


### A Multi-wavelength Look on Cluster Radio Haloes


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Giant radio haloes in galaxy clusters provide the best evidence that ultra-relativistic particles (cosmic rays) and magnetic fields exist over Mpc scales. Despite being critical for a complete understanding of cluster growth through mergers, their powering mechanism remains unclear. Theoretical models of radio halo origin have so far been based on X-ray selected cluster samples, with X-ray luminosities being used as a proxy for cluster mass. I will show what happens when clusters are selected based on their Sunyaev-Zel'dovich (SZ) effect instead, which provides a relatively unbiased mass estimate based on the total thermal energy content. The result is a distinctive mass scaling for the radio halo power which can be used to differentiate between simple theoretical models. In addition, the segregation between radio halo and radio quiet systems becomes much less pronounced. I will discuss the implications for this reduced "bi-modality" of radio halo clusters, and present the first correlation results for a complete SZ-selected sample obtained via stacking of NVSS radio maps.

# Chapter 4

# Cluster mass determination

## A simple recipe for estimating masses of elliptical galaxies and clusters of galaxies.

Natalya Lyskova[1], Eugene Churazov[1]
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We discuss a simple and robust procedure to evaluate the total mass/the circular velocity speed profile of massive elliptical galaxies and clusters of galaxies. The method only relies on information about the optical surface density and the projected velocity dispersion profiles of tracers and therefore can be applied even in case of poor or noisy observational data. Stars, globular clusters or planetary nebulae can be used as tracers for mass determination of ellipticals and galaxies for clusters. The proposed procedure first was tested on a sample of cosmological simulations of individual galaxies and galaxy clusters and then applied to real observational data. Independently the total mass profile was derived from the hydrostatic equilibrium equation for the gaseous atmosphere. Mismatch in mass profiles obtained from optic and X-ray data is used to estimate the non-thermal contribution to the gas pressure and/or to constrain the distribution of tracer's orbits.

## Galaxy cluster mass profiles

Gabriel Pratt[1]
[1]*CEA-Saclay*

I will discuss in detail the structural properties of the mass profiles determined from the hydrostatic X-ray and weak lensing approaches, and their impact on total mass estimate using a sample of 50 galaxy clusters, including 19 from LoCuSS and 31 from REXCESS. X-ray data are available for all systems, and I will describe the clear dependence of the mass profile shape, as determined from NFW model fits, on global parameters such as the dynamical state as defined by X-ray morphology. For the 19 LoCuSS systems, both X-ray and weak lensing mass profiles are available. At $R_{500}$ the X-ray masses are $\sim 20$ per cent *larger* than the weak lensing masses, completely at odds with expectations. The offset is driven by the most morphologically disturbed systems, and will I show how factors such as mass concentration and X-ray - BCG offsets affect the mass ratios. I will discuss the impact of this on mass-observable calibrations with particular emphasis on the SZ signal from Planck, and what steps need to be taken in order to improve mass measurement comparisons.

Part of this work was undertaken by the Planck Collaboration.

## Individual mass determination of the HIFLUGCS Clusters

Gerrit Schellenberger[1], Thomas Reiprich[1], Lorenzo Lovisari[1]
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Clusters of galaxies are the most massive gravitationally relaxed systems in the universe, so the observed cluster mass function is a sensitive probe of cosmological parameters. The greatest challenge in measuring the cluster mass function is obtaining sufficiently accurate mass estimates.

We are in the process of deriving the mass function by the determination of the individual masses for the 64 objects of the HIFLUGCS sample using high quality data from Chandra. By studying the two dimensional cluster shape we can obtain more accurate masses and investigate the presence of substructures and the consequent impact on the determination of the cosmological parameters. Furthermore we show significant and systematic differences between all instruments (XMM EPIC and Chandra ACIS) in determining the cluster temperatures in specified regions and we quantify the uncertainties for the resulting masses.

## Clustering algorithm: Sensitivity of mass determination using Abell 3581

Susan Wilson[1]
[1] *North-West University, South Africa*

Study of galaxy clusters has gained impetus with huge amount of multi-wavelength data becoming online. They are important as they provide a way to study galaxy formation and evolution as well as large-scale structure in the Universe. In order to understand the environment and various processes within clusters, we need to characterize these clusters. The richness of the cluster is a crucial parameter that needs to be determined. At the same time this allows us to determine other properties such as velocity dispersion, size and mass. This task is not an easy one and has many possible ways to do so. In this poster a comparison between various methods for clustering are analyzed. Using virtual observatory tools possible candidates are selected and then the KMM algorithm is used to test for multi-modality in the groups to determine the final possible member candidates. Other Gaussian Mixing Model (GMM) algorithm is tested for comparison. Another method used is that of hierarchy, which relies on catalogs and papers as used by Simbad is also compared. The preliminary results obtained are compared against literature values.

**Improved strong lensing mass reconstruction in galaxy clusters with a non-parametric method**

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We present an improved version of the WSLAP code for lensing reconstruction. The code implements a new constrain derived from the luminosity of the galaxies in the cluster that greatly improves the mass reconstruction. The method is tested with simulations and soon will be applied to real data.

# Chapter 5

# Cluster scaling relation with emphasis on X-rays

### The fundamental plane of clusters of galaxies

Mauro D'Onofrio[1]
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We present the luminosity profiles of the 76 clusters of galaxies of the WINGS survey (Fasano et al. 2006). From these light profiles we derived the effective radii and effective surface brightnesses of all clusters. These data, coupled with the available velocity dispersions measured by Cava et al. (2009), were used for the analysis of the Fundamental Plane of clusters of galaxies. The resulting FP was also compared with that observed for early-type galaxies and for globular clusters.

We show that the inner regions of clusters of galaxies are well virialized structures likely dominated by dark matter (DM). Finally, we provide a method based on the FP analysis that gives the ratio between the amount of DM and the stellar masses of our clusters.

### Evolution of the X-ray luminosity-temperature relation from the XCS first data release

Matt Hilton[1]
[1] *University of Nottingham*

We present a measurement of the evolution of the X-ray luminosity–temperature ($L-T$) relation since $z \approx 1.5$ using a sample of 211 serendipitously detected X-ray selected clusters with spectroscopic redshifts drawn from the *XMM* Cluster Survey first data release (XCS-DR1). This is the first study spanning this redshift range using a single, large, homogeneous cluster sample. After binning the sample into three redshift bins, we find no evidence for evolution in the slope or intrinsic scatter of the relation since $z \approx 1.5$, finding both to be consistent with previous measurements at $z \approx 0.1$; however, the evolution of the normalisation of the relation is seen to evolve negatively with respect to the self-similar expectation. We discuss the implications of this result for heating models of the intracluster medium, in the context of hydrodynamical simulations from the Millennium Gas Project. We also present the results of a complimentary study of the $L-T$ relation at low redshift, using a subsample of XCS-DR1 clusters cross-matched with the SDSS optical and FIRST radio surveys.

## X-ray properties of Fossil Groups

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Fossil groups (FGs) are galaxy systems with masses and X-ray halos comparable to those of groups and clusters of galaxies, but whose optical light is dominated by a single, large elliptical galaxy surrounded by much fainter companions. Their early assembly leaves enough time for intermediate-luminosity galaxies to merge and makes FGs the oldest and most relaxed galaxy systems. Thus, FGs are the ideal environment to study the link between galaxy evolution and IGM. We will present an homogeneous analysis of the global X-ray properties of 7 FG. The results of this analysis will seed light on the presence of absence of cool cores in FG, the heating mechanisms and the metal enrichment history of the IGM and their scaling relations.

## Scaling relations with a complete sample of galaxy groups

Lorenzo Lovisari[1], Thomas Reiprich[1]
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Galaxy clusters are an attractive tool to constrain cosmological parameters and well-determined scaling relations between X-ray observables and cluster mass give us a precious diagnostic to study the thermodynamical history of the intra-cluster medium (ICM). Scaling relations have been investigated extensively for galaxy clusters, however the question of whether these relations hold true also for galaxy groups remains unsettled. We are in the process of improving the accuracy of scaling relations using a complete sample of 22 groups to study if there is a systematic difference between clusters and groups and the influence of non-gravitational physics on low-mass systems.

By combining this sample with the HIFLUGCS creates a master sample of 86 groups and clusters ranging over more than three orders of magnitude in luminosity. This large leverage will directly allow us to place tight constraints on cosmological parameters.

# Chapter 6

# AGN feedback in clusters

## The Duty Cycle of Radio Mode Feedback

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In the cores of many galaxy clusters, giant cavities inflated by the central radio source are present, many with enough energy to balance the central cooling. However, it is not clear how often such AGN feedback occurs, or whether all systems in which cooling is expected (i.e., cooling flows) have evidence for AGN feedback. In order to understand the duty cycle of AGN heating, we use Chandra X-ray data of two complete (flux limited) samples. We identify cooling flow clusters in these samples and find they represent approximately 60 percent of all clusters. We simulate X-ray images of these cooling flows to determine how much cavity power could be hidden in existing Chandra data, and we find that 60–100 percent could have cavities with significant energy, implying a high duty cycle for AGN activity. Lastly, we identify a radio luminosity cut-off for the central radio source above which only sources in cooling flows are found, implying a connection between the central radio source and the cooling flow, as expected if AGN feedback is operating.

## X-ray and Optical Observations of the X-ray Gas Rich, Early type Galaxies NGC4342 and NGC4291

William Forman[1], Akos Bogdan[1], Irina Zhuravleva[2], Eugene Churazov[2], J. Christopher Mihos[3], Paul Harding[3], Ralph Kraft[1], Paul Nulsen[1], Qi Guo[4], Christine Jones[1]
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We discuss X-ray and optical observations of two early-type galaxies, NGC4342 and NGC4291 that host unusually massive supermassive black holes (SMBH) compared to their relatively low stellar masses. We argue, from the X-ray observations, that both galaxies have large dark matter halos and that it is the stellar masses that are too small for their measured SMBH masses as predicted by the SMBH-stellar mass relation. We infer, from deep optical observations of NGC4342 and the presence of the dark matter halos in both galaxies, that the low stellar masses could not arise from tidal stripping effects. Instead, we suggest that the unusually large SMBH's in these two galaxies have dramatically suppressed star formation. In addition, we discuss the X-ray observations of NGC4342 which show the galaxy corona interacting with a larger gas system in the distant outskirts of the Virgo Cluster, most likely associated with the W′ group, dominated by NGC4365, at a distance of about 23 Mpc.

### Solving the Cooling Flow Problem through Mechanical AGN Feedback

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Unopposed radiative cooling of plasma would lead to the cooling catastrophe, a massive inflow of condensing gas, particularly manifest in the cores of clusters. The last generation X-ray telescopes, Chandra and XMM, have radically changed our view on baryons, indicating AGN heating as the balancing counterpart of cooling. In this work, I investigate the engine of the self-regulated heating. I argue that the mechanical feedback, based on massive subrelativistic outflows, is the key to solving the cooling flow problem, i.e. dramatically quenching the cooling rates for several Gyr without destroying the cool-core structure. Using a modified version of the 3D hydrocode FLASH, I show that bipolar AGN outflows can further reproduce fundamental observed features, such as buoyant bubbles, weak shocks, metals dredge-up, and turbulence. The latter is an essential ingredient to drive nonlinear thermal instabilities, which cause the formation of extended cold gas, a residual of the quenched cooling flow and, later, fuel for the feedback engine. Compared to clusters, groups and galaxies require instead a gentler mechanical feedback, in order to avoid catastrophic overheating. I will present the merits and flaws of the key hydrodynamic models, with a critical eye toward observational concordance.

### Heating gas perpendicular to the jet direction

Avishai Gilkis[1], Noam Soker[1]
[1] *Technion. Israel*

With a 2.5D hydrodynamic code we show that gas perpendicular to the jet direction is efficiently heated. The heating is mainly via mixing by vortices generated by the shocked jet material. In addition, some of the gas from the equatorial plane is entrained by the jets and carried to large distances. That collimated jets can efficiently heat the ICM in all directions strengthens the AGN-feedback model. We use non-relativistic jets with a wide opening angle, such that a pair of bubbles similar to those observed is formed. In addition to inflating the bubbles and mixing the ambient gas, the vortices also excite sound waves in the ICM.

**The environmental impact of powerful radio galaxies in groups and clusters**

Martin Hardcastle[1]
[1] *University of Hertfordshire, UK*

There is a good deal of observational evidence that powerful radio galaxies can have a significant energetic impact on their host groups and clusters. However, even with combined radio and X-ray information, it is often difficult to get a quantitative estimate of the energy provided by the AGN or its dynamical state. I will present the current best picture, backed by observational evidence, for the dynamics of powerful classical double (FRII) radio sources in groups and clusters, and will show with the help of numerical modelling how their energetic impact can (and cannot!) be estimated from observable parameters.

**Low frequency radio maps for the REXCESS cluster sample**

Susanne Roswitha Heidenreich[1]
[1] *University of Southampton, Southampton, United Kingdom*

We present new low-frequency radio maps for 28 clusters taken from the Representative XMM-Newton Cluster Structure Survey (REXCESS). The REXCESS sample (Boehringer et al. 2007) consists of 33 local (z¡0.2) clusters fully sampling the cluster X-ray luminosity function, and its lack of bias with respect to cluster dynamic state makes it ideal for investigating the relationship between cluster properties and AGN populations. Our 610-MHz radio maps were obtained using the Giant Metrewave Radio Telescope (GMRT), and will be used to examine the different types of radio outburst, their relation to global cluster properties, and their influence on cluster heating. Here we present the new radio maps and some preliminary science results.

### Strong constraints on the applicability of the Bondi accretion process to AGN feedback

Shlomi Hillel[1], Noam Soker[1]
[1] *Technion, Israel*

We argue that one of the basic assumptions of the Bondi accretion process, that the accreting object has zero pressure, does not hold for many active galactic nuclei (AGNs), and hence the Bondi accretion cannot be used there. We show that the winds of the stars that are orbiting the super massive black hole (SMBH) exert a ram pressure larger than that in the hot medium surrounding the SMBH. Adding to other problems the Bondi accretion process has in explaining feedback in cooling flow clusters, this claim renders the Bondi accretion a problematic process for AGN feedback in cooling flow clusters.

### Radio loud AGN: is there a link between luminosity and cluster environment?

Judith Ineson[1], Judith Croston[1], Martin Hardcastle[2], Ralph Kraft[3], Daniel Evans[4], Matt Jarvis[2]
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Understanding how the properties of radio-loud AGN outbursts relate to the cluster environments in which they occur is a crucial question for AGN feedback models. Studies using flux-limited samples suggest that FRII radio galaxies inhabit different environments at low and medium redshifts, and that local FRI sources inhabit different environments from FRII sources. This complex interdependence between an AGN and its environment needs to be disentangled: did all radio-loud AGN inhabit richer environments at earlier epochs, or do radio-loud AGN of a given luminosity always inhabit similar environments? I will present first results from the Chandra ERA (Environments of Radio-loud AGN) Large Project, designed to address this problem by characterising the environments of a sample of 25 radio-loud AGN at z $\sim$0.5, covering three decades of radio luminosity. I will explain how our systematic environmental study at a single epoch has allowed us to determine the relationship between radio luminosity and cluster environment for the first time. I will also compare our results with samples at different epochs, allowing us to gain a detailed picture of the environmental characteristics of radio-loud AGN from z $\sim$1 to the present day.

## Fundamental parameters of FRII radio galaxies and their impact on groups and clusters' environments

Anna Kapinska[1], Phil Uttley[2]
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Radio galaxies and quasars are among the largest and most powerful single objects known and are believed to have had a significant impact on the evolving Universe and its large scale structure. Since their jets inject significant amounts of energy into the surrounding medium the knowledge of the fundamental properties (such as kinetic luminosities, lifetimes and the central densities of the environments) of these sources are crucial for understanding AGN feedback in galaxy clusters. Here, we explore the intrinsic and extrinsic fundamental properties of Fanaroff-Riley II (FRII) objects. We construct multidimensional Monte Carlo simulations using semi-analytical models of FRIIs time evolution and complete, flux limited radio catalogues to create artificial samples of radio galaxies. The method allows us to set better limits on the confidence intervals of the intrinsic and extrinsic fundamental parameters. Furthermore, we investigate the total power produced and injected to the clusters' environments by populations of FRIIs at various cosmological epochs ($0.0 < z < 2.0$). We find these estimates to be strikingly robust despite the strong degeneracy between the fundamental parameters. Such a result points to a compelling indicator of the scale of AGN feedback in groups and clusters of galaxies.

## The Role of AGN Feedback in Strong Lensing Predictions

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When distant galaxies lie near the centres of massive galaxy clusters, they can be gravitationally lensed to appear as giant arcs in the sky. There has long been a discrepancy between observations and $\Lambda$CDM predictions of strong lensing features and the typical angular scale that separates them. We investigate the role of baryonic physics implemented in cosmological simulations in affecting the outcome. Recent state-of-the-art simulations have provided a sample of 20-30 relaxed massive clusters ($M > 2 \times 10^{14} \mathrm{M}_\odot$) at z=0.25 and z=0.5 in WMAP7 cosmology. These clusters, originally modelled with dark matter only, have been re-simulated with various subsets of baryonic processes including: metallicity-dependent cooling, star-formation, galactic winds and AGN feedback. We present the strong lensing properties of this cluster sample, with surprising consequences for the arc statistics problem.

### Investigating Radio Jets along the Fanaroff-Riley Divide as Measures of Cluster Environment and Feedback

Tamela Maciel[1]
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Determining the nature of the Fanaroff-Riley dichotomy in radio galaxy jets remains key to understanding AGN and the role they play in galaxy evolution and cluster feedback. To better understand this divide, we wish to determine the strength of environmental influence compared to intrinsic source properties. An essential step is to have a systematic study of radio sources along the critical FRI/FRII divide, but despite many years of study, this goal still remains. To directly study this regime, a sub-sample of 302 radio galaxies from the CoNFIG catalogue (Gendre et al. 2010) have been selected between a luminosity band spanning the FR divide ($10^{24} - 10^{26}$ W Hz$^{-1}$ sr$^{-1}$ at 1.4 GHz) for detailed analysis of morphology and jet evolution. A systematic investigation of intrinsic jet properties as well as the richness of the surrounding environment is underway, with focus on the characteristics of the exceptional high-luminosity FRIs and low-luminosity FRIIs. The result is a statistically significant and well-defined sample to address long-standing questions on the relationship between radio jets and galaxy/cluster dynamics.

### Active and star-forming galactic nuclei in WINGS

Paola Marziani[1], Mauro D'Onofrio[2], Daniela Bettoni[1], Giovanni Fasano[1], Bianca M. Poggianti[1], collaboration WINGS
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We analyzed the spectra collected under the wide-field nearby galaxy clusters survey (WINGS) to reveal emission lines in cluster galaxies. After removing stellar emission with dedicated population synthesis models we found evidence for faint emission line activity in a sizable number of cluster galaxies. Diagnostic diagrams were used to define or at least constrain the origin of the emission line activity. Cross-correlation with radio and X ray survey data was also used for the identification of “true” active nuclei. We report preliminary results on incidence and basic properties of the active and star forming galaxies we identified.

### The Influence of Cooling and Feedback on Cluster Pressure Profiles

Simon Pike[1], Scott Kay, Rick Newton[1]
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The intracluster medium is a heated plasma that is approximately in hydrostatic equilibrium, and forms the major contribution to the SZ effect. The SZ effect can be used to investigate the scaling relation between the $Y$ parameter, which is a volume integral over the pressure of the gas, and cluster mass. It is therefore important to investigate how gas physics within the cluster might affect the pressure profile, and therefore its $Y$ parameter. In my talk I will show preliminary results from a new set of 30 high-resolution hydrodynamical simulations, spanning a mass range of $10^{14}$ to $10^{15}$ $h^{-1}\mathrm{M}_{\odot}$. These simulations are being used to investigate how the gas physics, especially cooling and feedback from active galactic nuclei, affects the pressure profile and the SZ $Y$ parameter.

### On the role of AGN feedback on the baryon content of galaxy clusters

Susana Planelles[1]
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The global baryon content of the largest galaxy clusters is expected to accurately trace the matter content of the universe and, therefore, it can be used to reliably determine the matter density parameter $\Omega_m$. However, this fundamental assumption is challenged by the growing evidence from optical and X-ray observations that the total baryon mass fraction increases towards rich clusters.

In this context, we investigate the dependence of stellar, hot gas, and total baryon mass fractions as a function of cluster mass. To do so, we study the baryon mass fraction in a set of hydrodynamical simulations of galaxy clusters performed using the Tree+SPH code GADGET-3. These clusters have been re-simulated using various subsets of baryonic processes including radiative cooling, star formation, galactic winds and AGN feedback. We investigate the dependence of the baryon fraction upon the different models of baryon physics and we discuss the consequences of these results in the context of determining the cosmic matter density parameter.

## Initial Results from a Very Deep Chandra Observation of the Galaxy Group NGC 5813

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Results from a deep (650 ks) Chandra observation of the galaxy group NGC 5813, the deepest Chandra observation of a galaxy group core to date, will be presented. This unique system shows three pairs of collinear cavities in the intragroup medium (IGM), each pair associated with an elliptical outburst shock front. It is therefore ideal for studying AGN feedback and the outburst history of the central AGN. Measurements of the shock heating at each shock front show that shocks alone are enough to offset radiative cooling of the gas indefinitely, within at least the central 26 kpc. The internal energy of the cavities is not required, and is likely deposited in the IGM at larger radii. This demonstrates that shock heating can play an important role in the AGN feedback process, particularly at smaller radii, close to the central AGN.

## Inflating chain of X-ray deficient cavities with a continuous jet

Michael Refaelovich[1], Noam Soker[1]
[1]*Technion, Israel*

We show that with a single episode of jet-launching it is possible to explain a chain of X-ray deficient cavities as seen for example at the Hydra A cluster. The key physical process is the formation of multiple vortices by vortex shedding and other instabilities. We explore the parameter space for which such a chain is obtained. The calculations are performed with a 2.5D hydrodynamic code including gravity. The multiple vortices, and especially vortex shedding, might be another channel for the jets to deposit energy into the intra-cluster medium.

## The cold feedback mechanism

Noam Soker[1]
[1] *Technion, Israel Institute of Technology, Haifa, Israel*

I will present new results of the cold feedback mechanism in cooling flows. I will discuss new results on the way the feedback is maintained between the cooling gas and the heating process by jets. A substantial fraction of the cold gas is ejected back in jets. I will present new 2D hydrodynamical simulations of such slow massive jets and the bubbles they inflate. These simulations resolve very clearly the vortexes that are developed in the bubble inflation process. I will emphasize the crucial role played by vortexes in determining the morphology of the bubbles and in heating the gas in all direction.

## Triggering of AGN Feedback

Mark Voit[1]
[1] *Michigan State University*

Feedback from a central active galactic nucleus appears to be resupplying the energy radiated from cluster cores and preventing overproduction of stars in the central galaxy. However, much about this process remains mysterious. For example, somehow the accretion rate on parsec scales in the vicinity of the central engine is tuned to match the intracluster cooling rate on scales of tens of kiloparsecs. My talk will discuss the observational evidence pointing to the conditions for triggering feedback in galaxy cluster cores, the roles of conduction and thermal instability in regulating that feedback, and new Enzo simulations of conductive galaxy clusters.

## Chapter 7

# Chemical composition of the ICM

**Metal jumps across sloshing cold fronts: the case of A496**

Simona Ghizzardi[1], Sabrina De Grandi[2], Silvano Molendi[1]
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[2] *INAF-OABrera, Merate(Lc), Italy*

Cold-fronts in cool-core clusters are thought to be induced by minor mergers and to develop through a sloshing mechanism. While temperature and surface-brightness jumps have been measured in many systems (Ghizzardi+2010), a detailed characterization of the metal abundance across the discontinuity is only available for a handful of objects. This is a limitation as the metal distribution in a sloshing ICM can provide information on enrichment and metal mixing processes. Within the sloshing scenario, we expect the central cool and metal rich gas to be displaced outwards into lower abundance regions, thus generating a metal discontinuity across the front, as already observed in Centaurus, Perseus and 2A0335+096. We analyzed a long (120ksec) XMM-Newton observation of A496 to study the metal distribution and its correlation with the cold-fronts and thermodynamical gas properties. We find Fe and Si discontinuities across the two main cold-fronts located 75 kpc North-East and 120 kpc South of the peak. The metals follow the temperature and entropy distributions in a spiral-like pattern similar to the one predicted by numerical simulations. We present our results and discuss in details implications on the sloshing process and on the metal enrichment and mixing mechanisms.

**X-ray Measurement of the Elemental Abundance at the Outskirts of the Perseus Cluster with Suzaku**

Shutaro Ueda[1], Kiyoshi Hayashida[1]
[1] *Dept of Earth and Space Science, Graduate School of Science, Osaka University*

The X-ray emission of the Perseus cluster was extensively observed with *Suzaku* beyond its virial radius. The initial result from the northwest and the east arm observations suggest non-uniformity of the intra cluster mediums (ICM) as presented in Simionescu et al. 2011. They also reported the metal abundance (commonly defined for all the elements) of the ICM was approximately 0.3 solar over the observed regions. In this paper, we focus on the elemental abundance ($Z$) of various elements at the outskirts ($\sim$1.3 Mpc, $\sim$0.75 $r_{200}$) including all data obtained after their report. The X-ray spectra extracted for 5 annulus regions from 10' to 60'($\sim$1.3 Mpc). The temperature of ICM smoothly decreases from 6 keV to 4 keV in the regions. The $Z_{\rm Fe}$ is uniformly distributed throughout the regions. Even in the outermost (50'$-$60') region, the $Z_{\rm Fe}$ is determined to be $0.254^{+0.078}_{-0.067}$ solar. The abundance of lighter elements, Mg, Si, and S, are of importance for the origin of the ICM at the outskirts. We find $Z_{\rm Mg}$ is distributed roughly 0.6 solar and the upper limit of $Z_{\rm S}$ is 0.2 solar in the regions. These results verify the abundance differences among elements in the outskirts of the ICM.

# Chapter 8

# Comparison of X-ray, SZE and optical observations of clusters

### Mergers and AGN Outbursts in Planck SZ and X-ray Selected Cluster Samples

Christine Jones[1], Stephen Murray[2], Kevin Fogarty[1], Nabila Aghanim[3], Monique Arnaud[4], Gabriel Pratt[4], Pasquale Mazzotta[5], Iacopo Bartalucci[5], Herve Bourdin[5], et al.
[1] *Harvard Smithsonian Center for Astrophysics*
[2] *Johns Hopkins University*
[3] *University of Paris South*
[4] *Centre d'Etudes de Saclay*
[5] *University of Rome, Tor Vergata*

We compare the cluster morphology including merger properties and the effects of AGN outbursts in X-ray flux limited and Planck SZ selected cluster samples. This study shows the higher frequency of AGN outbursts and lower occurrence of major mergers in X-ray selected cluster samples compared to SZ selected samples. In addition, we show the analysis of recent X-ray observations of Planck clusters undergoing major mergers.

### A Comparison of X-ray, Radio, and Lensing Results with GBT+MUSTANG Observations of the Sunyaev-Zel'dovich Effect

Tony Mroczkowski[1], Mark Devlin[2], Simon Dicker[2], Erik Reese[2], Alex Young[2], Brian Mason[3], Charles Romero[4], Craig Sarazin[4], Jon Sievers[5], Jack Sayers[6]
[1] *JPL/Caltech*
[2] *University of Pennsylvania*
[3] *NRAO*
[4] *University of Virginia*
[5] *Princeton*
[6] *Caltech*

We present recent high angular resolution (9") Sunyaev-Zel'dovich effect observations with MUSTANG, a 90-GHz bolometric receiver on the 100-meter Green Bank Telescope. MUSTANG is now imaging a sample of clusters with complementary Chandra X-ray observations, HST optical observations that probe the mass distribution through strong and weak lensing, radio observations that probe the non-thermal component of the intra-cluster gas, and lower resolution SZE observations that can recover larger scales. The MUSTANG observations, which will be used to assess the impact of substructure on SZE scaling relations, are some of the highest resolution SZE images to date, and are revealing complex pressure substructures in intermediate redshift clusters. Combined, these observations reveal complicated cluster dynamics, which must be understood in order to use clusters as cosmological probes.

**The simulated SZ-richness relation**

Luca Porcelli[1], Peter Thomas[1], Chris Short[1], Scott Kay[2]
[1] *University of Sussex, Brighton, UK*
[2] *The University of Manchester, Manchester, UK*

We explore the simulated Sunyaev-Zel'dovich versus cluster richness (Y500-N200) relation using results from the Millennium Gas simulation.

The simulation uses the Guo (2011) semi-analytic model to follow the growth of galaxies and their associated central black holes. Feedback from supernovae and active galactic nuclei are then used to determine the entropy history of the intracluster medium. Thus, we are able to follow the joint evolution of both the galaxies and the thermal history of the ICM. We compare with recent results from Planck.

**The Evolution of the Y-M scaling relation in MUSIC clusters**

Federico Sembolini[1], Marco De Petris[2], Gustavo Yepes[1], Luca Lamagna[2], Barbara Comis[2], Stefan Gottlöber[3]
[1] *Universidad Autonoma, Madrid, Spain*
[2] *Università La Sapienza, Rome, Italy*
[3] *Leibniz-Institut für Astrophysik, Potsdam, Germany*

We study the baryon properties and the Y-M scaling relation of MUSIC, currently the largest dataset of high resolution gasdynamical simulated galaxy clusters (more than 700 objects). All the MUSIC clusters have been simulated with both radiative and non-radiative physics. They were extracted from two large cosmological N-body simulations: MareNostrun and MultiDark. We find that Sunyaev-Zeldovich scaling relations of this dataset are in good agreement with the self similar hypothesis. An improved determination of the scatter in the mass estimates has been possible due to the large number of clusters in our dataset. We also check the validity of commonly used assumptions in the determination of the scaling relations, namely a constant gas fraction for all clusters and a fixed critical overdensity at different redshifts. Therefore, our results reinforce the use of self-similar scaling relations for cosmological tests and observational studies.

### Mass and shape of Abell 1689

Mauro Sereno[1]
[1] *Politecnico di Torino, Italia*

Accurate determinations of mass of galaxy clusters are crucial probes but we have often to deal with either biased mass measurements or precise determinations of very peculiar clusters. A better understanding of intrinsic shapes plays a major role. We consider how the shape of the intracluster medium can be inferred by combining X-ray photometry and spectroscopy with the measurement of the SunyaevZeldovich effect. Together with gravitational lensing, we can get unbiased estimates of mass and concentration and probe the hydrodynamical properties of the cluster. The method has been applied to Abell 1689.

### The 2XMMi/SDSS Galaxy Cluster Survey

Ali Takey[1], Axel Schwope[1], Georg Lamer[1]
[1] *Leibniz-Institut für Astrophysik Potsdam (AIP), 14482, Potsdam, Germany*

We present a catalogue of X-ray selected galaxy clusters and groups from the 2XMMi/SDSS Galaxy Cluster Survey. The survey is a search for galaxy clusters detected serendipitously in observations with XMM-Newton in the footprint of the Sloan Digital Sky Survey (SDSS). The main aims of the survey are to identify new X-ray galaxy clusters, investigate their X-ray scaling relations, identify distant cluster candidates, and study the correlation of the X-ray and optical properties.

In this talk, we describe the basic strategy to identify and characterize the X-ray cluster candidates that currently comprise 1180 objects selected from the second XMM-Newton serendipitous source catalogue (2XMMi-DR3). We present the optically confirmed cluster sample that includes about 550 clusters with estimation of the redshifts from the SDSS data, covering redshift range from 0.05 to 0.75. We also describe the automated method that used to reprocess the XMM-Newton X-ray observations, determine the optimum source extraction radius, generate source and background spectra, and derive the temperatures and luminosities of the optically confirmed clusters. L-T relation and X-ray-optical relations will be presented.

# Chapter 9

# The evolution of the cluster population with redshift

### Detection and characterisation of the first Planck high-z candidates

Inés Flores-cacho[1], on behalf of the Planck Collaboration
[1]*IRAP (Université de Toulouse/CNRS)*

With its unprecedented ability to scrutinise the sub-millimetre to centimetre full sky, the *Planck* satellite is uniquely suited to search for the progenitors of clusters of galaxies. The forming massive halos at $z > 1 - 2$ are expected to host massive galaxies with high star formation rates. Clustered in the growing potential well that is being stablished, these galaxies are within *Planck*'s reach via their sub-millimetre emission. These sources are identified in the survey using a new method tuned to detect the rarest and brightest sub-millimetre cold sources on the sky, given the extremely high cumulative brightness that arises from several clustered galaxies or the drastically enhanced brightness of a lensed galaxy in the Planck beam.

I will describe the detection method and show the results on the first five confirmed *Planck* high redshift sources: lensed systems with $2.7 < z < 5.2$ also detected by SPT and/or Herschel observations; a high redshift ($z = 1.5$) proto-cluster identified by Spitzer; and a newly detected Planck source, 17p732, a potential concentration of galaxies at $z = 1.7$ with follow-up observations with Herschel, VLT/XSHOOTER and IRAM. I will discuss the prospects for these objects to have heated their gaseous atmosphere, and thus, to possibly be detectable in X-rays with XMM-Newton.

### The smaller the better: X-ray groups as cosmic laboratories

Stefania Giodini[1]
[1]*Leiden Observatory*

Galaxy groups provide the skeleton of the cosmic web and provide the building blocks for the most massive structures in the universe. Deep X-ray surveys have opened a new observational window enabling the detection of large samples of galaxy groups. Primers for such work are the sample of X-ray detected groups in the COSMOS and CFHTLS fields. These samples span a large range in total mass and redshift. I will show how X-ray observations complemented with a large multi-wavelength data set enables to understand the role of galaxy groups in the assembly of visible matter. In particular I will focus on the properties of the galaxy distribution (e.g. galaxy stellar mass function) and their evolution in X-ray galaxy groups and how they compare to predictions from recent semi-analytical models. Furthermore I will show newly determined X-ray/weak lensing scaling relations for CFHTLS groups.

**Search for Galaxy-ICM Interaction in Rich Clusters of Galaxies**

Liyi Gu[1], Naohisa Inada[2], Saori Konami[3], Tadayuki Kodama[4], Kazuhiro Nakazawa[1], Madoka Kawaharada[5], Kazuo Makishima[1]
[1] *University of Tokyo*
[2] *Nara National College of Technology*
[3] *Tokyo University of Science*
[4] *National Astronomical Observatory of Japan*
[5] *Institute of Space and Astronautical Science*

In a rich cluster of galaxies, hundred of member galaxies swim in the intra-cluster hot plasma with transonic speed. Since the moving galaxies carry their own inter-stellar plasma, they may interact with the cluster plasma in form of ram pressure and/or magnetohydrodynamic turbulence. Such interaction will gradually transfer energy and momentum from galaxies to the cluster plasmas. Hence, the plasmas will be heated against radiative loss, while the stellar component is expected to become more and more concentrated towards cluster center.

To verify this conjecture, we studied the "optical-light vs. ICM-mass ratio" profile for a sample of 34 relaxed clusters with z=0.1-0.9. Using optical data obtained with the UH88 telescope and X-ray data with XMM-Newton and Chandra, we calculated the radially-integrated optical luminosity profiles and projected ICM mass profiles, respectively. We found that the light-to-ICM ratio profiles drop more steeply outwards in low redshift clusters. According a K-S test, the evolution is significant at >90% confidence level. By assessing systematic errors and biases, we found none of them is significant against the observed evolution. Furthermore, other astrophysical effects, e.g., dynamical friction, are estimated to be insufficient to explain the observation. This result provides important support for galaxy-plasma interaction scenario.

**Sunyaev-Zel'dovich Clusters in Millennium Gas Simulations**

Scott Kay[1], Peter Thomas[2], Christopher Short[2]
[1] *The University of Manchester, Manchester, United Kingdom*
[2] *University of Sussex, Brighton, United Kingdom*

New surveys at radio wavelengths, exploiting the Sunyaev-Zel'dovich effect, are expected to detect thousands of new clusters, many of which will be at high redshift. Of fundamental interest is how their measured SZ Y parameter correlates with mass, as this enables the data to be used for cosmological parameter estimation. In this talk, I will present results from the large-volume Millennium Gas cosmological simulations, where the simulated cluster populations have been used to investigate gas pressure profiles and the $Y-M$ relation, as well as their dependence on redshift and cluster physics. I will include new results from our latest simulation, a large (10 billion particle) run that contains a novel prescription for stellar and AGN feedback using input from one of the latest semi-analytic galaxy formation models. I will also cover related issues such as projection effects from large-scale structure and the effect of hydrostatic bias on the $Y-M(Y_{\mathrm{X}})$ relation.

## GAMA Survey: SFR, metallicity, and stellar mass relationships in clusters of galaxies

Maritza Arlene Lara-Lopez[1]
[1]*Australian Astronomical Observatory, Epping, Australia*

The star formation rate (SFR), stellar mass and metallicity are among the fundamental parameters of galaxies. A comprehension of the interplay of those properties as well as its environmental dependence will give us a general picture of the physics and feedback processes ongoing in clusters of galaxies. We studied the relationships and environmental dependencies between the SFR, stellar mass, and gas metallicity for more than 200 galaxies in clusters up to redshift 0.35 using GAMA (Galaxy And Mass Assembly), a spectroscopic survey with data taken with the 3.9m Anglo-Australian Telescope (AAT). Using a control sample of more than 28,000 star-forming field galaxies, and a subsample of isolated galaxies in GAMA, we found evidence for an increment in the SFR and a decrement of the gas metallicity for galaxies in clusters.

## Galaxy Transformation in the Major merger Abell 2744

Matt Owers[1], Warrick Couch[2], Paul Nulsen[3], Scott Randall[3]
[1]*Australian Astronomical Observatory*
[2]*Swinburne University of Technology*
[3]*Harvard-Smithsonian Center for Astrophysics*

The most extreme form of structure formation in the Universe occurs when two massive clusters of galaxies merge to form a single entity. This violent event vigorously rearranges the environment of the residing galaxies and simulations suggest that this process may result in an enhancement in the cluster specific mechanisms driving galaxy transformation. We have been studying the complicated cluster Abell 2744 using the powerful combination of AAOmega multi-object spectroscopy, Chandra X-ray spectroimagery and deep, multi-band HST ACS imaging. The AAOmega and Chandra data reveal a Bullet-like major merger in the core region with a merger axis tilted well out of the plane of the sky, together with an interloping minor merger. The HST imagery reveals several jellyfish galaxies which harbour trails of star forming blobs which extend some 30kpc from the galaxies. Two such galaxies are spatially coincident with a shock-affected region observed in the Chandra data, indicating that the high pressure merger environment may be significantly affecting these galaxies. In this talk, I will discuss how the major merger in Abell 2744 may have contributed to the rise of these rare jellyfish galaxies.

**CL0024 as seen by the Galaxy Cluster Evolution survey (GLACE)**

Ricardo Pérez-Martínez[1], Miguel Sánchez-Portal[2], Jordi Cepa[3,4], Irene Pintos[3], Ana Pérez-García[3]
[1]*INSA / XMM SOC*
[2]*INSA / HSC*
[3]*IAC*
[4]*Universidad de la Laguna*

The Galaxy Cluster Evolution survey (GLACE) is aimed to study the evolution of emission line galaxies in clusters across the cosmic time. It takes advantage of OSIRIS (first light instrument of GTC) tunable filters to scan $H\alpha$/[NII], $H\beta$, [OII]3727and [OIII]5007 in search of star formation activity and/or AGNs in clusters in three different redshift windows ($\sim 0.40$, $\sim 0.63$ and $\sim 0.86$), providing a unique view of the evolution of cluster galaxies along such redshift range. Moreover, the OSIRIS large field of view ($8\times 8$ $arcmin^2$) together with GTC large collective area ($D \sim 10m$) make it possible to detect SFR $\sim 2M\odot$ up to 2 $Rvir$. We present here the first results of the program together with a brief description of this novel technique focusing in the cluster CL0024+1654 ($z \sim 0.39$) and relating our findings with RX J1257.2+4738 ($z \sim 0.86$) and A2219 ($z \sim 0.23$, from a previous study with CAFOS at CAHA, also in tunable filter mode).

**The DPOSSII distant compact groups of galaxies: evidence of cluster-induced group evolution**

Emanuela Pompei[1], Angela Iovino[2]
[1]*European Southern Observatory*
[2]*INAF; Osservatorio astronomico di Brera-Milano*

Compact groups of galaxies are defined as dense, isolated, small associations of galaxies on the sky. Until recently, they were thought to be mostly nearby- Universe objects and pretty much a freak of nature.

Recently extensive multi-wavelength surveys and deep pointed observations have shown that not only compact groups exist at higher redshift, up to z=0.3, but also that they seem to have some effect in the evolution of the clusters and vice-versa. Several distant clusters of galaxies resemble an association of groups, and even in the nearby Universe significant substructure is observed, like, for example in the Coma cluster, or in Virgo, where a compact group has been found in the vicinity of the cluster center.

Finally groups and compact groups found in the vicinity of clusters show systematically higher mass and velocity dispersion than those found in the field, constituting a good proof of the hierarchical growth of structures in the Universe.

This is observed also in distant (z$\sim$0.2) compact groups; the results of our spectroscopic survey will be presented in this poster paper.

### Deep Chandra observation of the galaxy cluster WARPJ1415.1+3612 at z=1: an evolved cool-core cluster at high redshift

Joana Santos[1], Paolo Tozzi[2], Piero Rosati[3], Mario Nonino[2], Gabriele Giovannini[4]
[1] *ESAC/ESA*
[2] *INAF-Trieste*
[3] *ESO*
[4] *INAF-Bologna*

Galaxy clusters are dynamical environments hosting complex astrophysical phenomena, that provide us with a wealth of information on the intricate processes that shape the cosmic large-scale structure and galaxy evolution. The so-called cool-core phenomenon, where an AGN heats the otherwise radiatively cooling cluster plasma, involves the X-ray emitting intracluster medium, the brightest cluster galaxy, cold molecular gas, and the central radio AGN.

In this talk we present a detailed investigation of the ICM of the cluster WARPJ1415.1+3612 at z=1.03. Using the deepest (370 ksec) Chandra observation of a distant cluster, we studied the properties of the cluster cool-core. Our analysis shows a temperature drop towards the cluster core of about half of the global ICM temperature, and probably the highest metallicity peak ever observed in galaxy clusters.

Using a multiwavelength dataset comprising radio VLA data, optical GEMINI-GMOS spectroscopy and imaging from HST and SUBARU, we traced a connection between the central galaxy and its interactions with the hot plasma.

These data unambiguously demonstrates that at z=1, a cool core cluster has ICM properties similar to the ones of local cool-cores and our analysis is the first detailed study of the feedback process in a cool-core at such high-redshift.

### XCS: present status and latest results

Pedro Viana[1]
[1] *Centro de Astrofísica da Universidade do Porto*

The *XMM* Cluster Survey (XCS) is a serendipitous search for galaxy clusters using all publicly available data in the XMM-Newton Science Archive. Our recent first data release (XCS-DR1) contains 503 optically confirmed groups and clusters, among which 255 new to the literature and 356 new X-ray discoveries. We will provide an update on XCS-DR1 and describe the properties of the systems found so far. Focusing on the 17 fossil groups/clusters identified with the help of the Sloan Digital Sky Survey, we will show that brightest galaxies in these systems have stellar populations and star-formation histories which are similar to normal brightest cluster galaxies, but their stellar masses are significantly larger and correspond to a much bigger fraction of the total group/cluster optical luminosity. We will also highlight the 15 clusters expected to be also detected by the *Planck* satellite, characterize the expected overlap between the final XCS and *Planck* cluster catalogues, and discuss joint applications of the XCS and *Planck* data. Finally, we expect to be able to present preliminary constraints on the values of $\sigma_8$ and $\Omega_m$, derived from XCS data, and compare them with our previous forecasts.

**Redshift evolution of the radio luminosity function inside galaxy clusters**

Martin Sommer[1], Kaustuv Basu[1,2], Florian Pacaud[1], Frank Bertoldi[1], Heinz Andernach[3,1]
[1] *Argelander-Institut fuer Astronomie, Universitaet Bonn, Bonn, Germany*
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[3] *Universidad de Guanajuato, Guanajuato, Mexico*

Understanding the properties of the radio emitting galaxies in cluster environments is not only important for galaxy evolution studies, but also for the current X-ray and Sunyaev-Zel'dovich (SZ) effect cluster surveys where their non-thermal emission is regarded as a "contaminant" which can bias the mass-observable scaling relations. Of particular concern is the impact of radio contamination on the high-z clusters detected through SZ, as those high-z clusters carry the maximum leverage in constraining the dark energy equation of state. Two things make up the study of the evolution of radio galaxies: A) their number density evolution inside the cluster volume, and B) the change in their spectral energy density with redshift. Concerning the first component, we have obtained the first statistically significant measurement of the redshift evolution of the 1.4 GHz radio luminosity function (RLF) inside galaxy clusters. The results, obtained using archival radio, X-ray and optical data, show a strong increase in the volume averaged radio luminosity with redshift. I present the details of this measurement and discuss some potential implications.

# Chapter 10

# Galaxy clusters as cosmological probes

## Measuring the scatter in the mass richness relation for galaxy clusters using the correlation function

Julia Campa[1], Juan Estrada[2]
[1] *CIEMAT-SPAIN*
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Clusters of galaxies are becoming a powerful tool to constrain cosmological parameters. This has motivated the design of a new wide-area cluster surveys at mm, optical/near infrared, and X-ray wavelengths. These surveys will have the potential to find hundreds of thousands of clusters.

The ability to constrain the cosmological parameters from the evolution of galaxy clusters counts is limited by the knowledge of the cluster mass. Accurate constraints require a precise model relating observables to total mass. We present a method to constrain the scatter in the mass observable relation by making use of the bias measured in the cluster correlation function. Since our goal will be to constrain the scatter in maxBCG cluster sample of optically selected clusters from SDSSS and in the future Dark Energy Survey cluster sample, in this work the observable will be the richness.

First we will study the bias in halos on a past lightcone using N-body simulations to study the errors that come from Halo Model prediction. Finally we assign richness to dark matter halos in the simulation to test our method. We compare the bias measured in clusters with the model and describe the results for the scatter measurements.

## Cosmological tests with Galaxy Clusters from ROSAT to eROSITA

Gayoung Chon[1], Hans Boehringer[1]
[1] *Max-Planck-Institut für extraterrestrische Physik, Garching, Germany*

Galaxy clusters are ideal tracers of the large-scale matter distribution and the growth of cosmic structures in the Universe. Therefore they can be used as sensitive probes to test cosmological models. X-ray observations provide an efficient way of detecting and characterising galaxy clusters. Based on the first all-sky X-ray survey from the ROSAT mission we compiled a flux limited catalogue of galaxy clusters that we use to assess the abundance and clustering of galaxy clusters and apply these results to constrain cosmological parameters. This cluster survey is most sensitive to constrain the matter density of the Universe and the amplitude of dark matter density fluctuations. The upcoming eROSITA All-Sky X-ray Survey is expected to be about 30 times deeper than the survey of ROSAT. This data set will in particular allow us to trace the redshift evolution of the galaxy cluster population which will provide tight constraints on the properties of Dark Energy. We provide forecasts of the potential of the eROSITA mission.

### Distant Galaxy Clusters in a Deep XMM-Newton Observation

Arjen de Hoon[1], Georg Lamer[1], Axel Schwope[1], Rene Fassbender[2], Hans Boehringer[2], Martin Muehlegger[2], Mike Lerchster[2]
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[2]*MPE, Garching, Germany*

Within the XMM-Newton Distant Cluster Project (XDCP), we highlight a deep ($\sim$ 250 ks) archival XMM-Newton observation, targeting the AGN LBQS J2212-1759. We find 9 extended sources, of which 5 are confirmed to be emission from galaxy clusters, either from previous publications or through our own spectroscopic campaign. We identify 3 distant clusters at $z \geq 1$ in the field, of which 2 are new spectroscopically confirmed discoveries. 2 extended sources could not be identified. We present (1) X-Ray analyses of the extended sources, (2) results from optical spectroscopic follow-up, (3) galaxy overdensity maps derived from deep CFHT-LS data, and (4) implications for cosmology based on this single $\sim 0.2$ square-degree field.

### Galaxy populations in rich and poor environments

Heidi Lietzen[1], Elmo Tempel[2,3], Pekka Heinämäki[1], Pasi Nurmi[1], Maret Einasto[2], Enn Saar[2]
[1]*Tuorla Observatory, University of Turku, Finland*
[2]*Tartu Observatory, Estonia*
[3]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

Several studies have shown that properties of galaxies depend on their environment. Galaxies in dense environments are more often elliptical, have lower star-formation rate, are more luminous, and are more likely to host a radio-loud active nucleus than galaxies in low-density environments. It has not yet been known if these properties of galaxies are fully determined by the local, group-scale environment or if the larger scales also affect their evolution. In the latest study of our research group, we have analyzed statistical properties of galaxies on two different scales of environment: the group scale and the supercluster scale. We have found that galaxies in groups of equal richness are more often star-forming in void regions than in superclusters. The group richness required to quench star-formation in the majority of galaxies is higher in the void regions. This means that galaxy populations depend on the large-scale environment independently of the group scale. Our result may be interpreted as evidence for an assembly bias in groups: the evolution of galaxies is enhanced or suppressed by their large-scale environment. In other words, galaxies in voids developed later than galaxies in superclusters.

**How many strong gravitational lenses are there in the sky?**

Jesús Vega[1], David Valls-Gabaud[2], Gustavo Yepes[1]
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Context: Strong lensing is one of the most direct probes of the mass distribution in galaxy clusters. It can be used to constrain the density profiles and to measure the mass of the lenses. The distribution of Einstein radii near the upper limit should probe the probability distribution of the largest mass concentrations in the universe. Moreover, the abundance of strong lensing events can be used to constrain the structure formation and the cosmological parameters.

Aims: The main purpose of the project is to compare predictions with observations in order to decide if they are in agreement or if a change needs to be done at either the cosmological models or the observational methods.

Methods: We generate a number of Monte-Carlo realisations of dark halos according to a mass function based on the LambdaCDM model. The shape of every halo is assumed to be spherical. To assess the cosmic variance, each realisation of dark halos is then constructed by computing the expected number of dark halos, and generating an integer number from the Poisson distribution with the mean. We take this semi-analytic approach to predict the distribution of Einstein radii for different solid angles.

**Probing High-Redshift Galaxies through Cluster Lensing**

Wei Zheng[1]
[1] *Johns Hopkins University, Baltimore, USA*

The Hubble Multi-Cycle Treasury Program CLASH provides our best view of 25 clusters in 16 broad bands. We report our discoveries of $z>7$ galaxies in some of these fields. Thanks to the lensing effect, we are able to reach the faint optical fluxes in the sources' restframe, Combing with the Spitzer/IRAC data, we estimate the age and star-formation history of these young galaxies. Some of the galaxies candidates are bright enough for future spectroscopic followup observations.

# Name Index