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# Editorial to the Topical Collection on Clusters of Galaxies: Physics and Cosmology

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## 1 Clusters of Galaxies in Astrophysics

Clusters of galaxies are large assemblies of galaxies bound together by gravity. Galaxy clusters now are one of the most important cosmological probes to test the standard cosmological models. Constrains on the Dark Energy equation of state from the cluster number density measurements, deviations from the Gaussian perturbation models, the Sunyaev-Zeldovich effect as well as the dark matter profiles are among the issues to be studied with clusters. The baryonic composition of clusters is dominated by hot gas that is in quasi-hydrostatic equilibrium within the dark matter dominated gravitational potential well of the cluster. The hot gas is visible through spatially extended thermal X-ray emission, and it has been studied extensively both for assessing its physical properties and also as a tracer of the large scale

Clusters of Galaxies: Physics and Cosmology
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structure of the Universe. Magnetic fields as well as a number of non-thermal plasma processes play a role in clusters of galaxies as we observe from radioastronomical observations. The goal of the topical collection is to review those processes and to investigate how they are interlinked.

This volume provides an in-depth review of the tremendous theoretical and observational progress that has been made in the recent past. One particularly topical window into cluster physics is provided by the Sunyaev-Zeldovich (SZ) effect. We discuss the implications of the findings of ESA's *Planck* mission on our understanding of cluster gas physics. This is complemented by ever-growing amount of X-ray data by the venerable *XMM-Newton* and *Chandra* satellites that have produced large, high-quality samples of clusters. Also, the *Suzaku* X-ray satellite with its low-background has provided very valuable insights into cluster outskirts. Finally, the *Hitomi* instrument has, during its short life, obtained the first X-ray spectrum of a galaxy cluster with an energy resolution sufficient to detect turbulence.

Clusters of galaxies are not isolated entities in the Universe: they are embedded in the filamentary cosmic web. In the early Universe most of the gas in the web was relatively cool (about 10,000 K) and all the baryons can be accounted for. However, in the present Universe, about half of all the baryons are predicted to be in a warm phase ($10^5$–$10^7$ K) called the Warm-Hot Intergalactic Medium, with temperatures intermediate between the hot clusters and the cool absorbing gas causing the Lyman-alpha forest. In cluster outskirts the connection to these structures can be studied. ESA's *Planck* instrument found an extended bridge of hot gas connecting two clusters of galaxies Abell 399 and Abell 401, shedding light on the 'missing baryons' in the cluster vicinity. These and other aspects of the observations and physics of clusters of galaxies are discussed in the topical collection.

A nice overview of clusters of galaxies with historical connections can be found in a recent paper by L.Rudnick (Physics Today v.72, 1, 46 (2019) doi:10.1063/PT.3.4112).

## 2 Cosmology with Clusters of Galaxies

The evolution of the cluster mass function can be used to test models of hierarchical structure formation and, therefore, to constrain cosmological parameters. Self-similar models of clusters of galaxies predict scaling relations between different observables. In particular, these scaling relations are central to determine the masses of galaxy clusters. In the review by G.W. Pratt, M. Arnaud, A. Biviano et al. in this topical collection the state-of-the art in cluster mass estimation methods is presented in the context of the cosmological parameter analysis. This is particular intriguing in the light of the apparent departure of the observed cluster population from the predicted based on the *Planck* $\Lambda$CDM model. Finally, the prospects for measuring the cluster mass scale with future multi-wavelength surveys is discussed.

## 3 X-Ray Spectroscopy of Galaxy Clusters

Thermal emission dominates the X-ray spectra of clusters of galaxies. However, a range of other physical effects are starting to tell us more about cluster physics. These require high-resolution X-ray spectra and the sophisticated models. Examples for such effects are resonant scattering that affects abundance and turbulence measurements, and charge exchange at the interface of cold and hot gas as well as modified line ratios due to non-thermal electrons. These latest developments in the X-Ray spectroscopy of galaxy clusters is discussed in the review by Gu et al.

## 4 A Millimetre and Submillimetre Probes of the Warm and Hot Universe

Recent impressive progress in centimetre-, millimetre-, and submillimetre-wave studies of clusters of galaxies is due to, both, the Planck satellite and ground-based facilities, such as the Atacama Large Millimeter/Submillimeter Array (ALMA) observatory, the continuum bolometer camera MUSTANG-2 (Multiplexed SQUID/TEC Array at Ninety Gigahertz on the 100-meter Green Bank Telescope) or the millimetre camera NIKA2. The joint analysis with the X-ray data from *XMM-Newton*, *Chandra* and *Suzaku* observatories allows mass estimates and identification of substructures such as shocks, cold fronts. It also yields profiles of the pressure in the intercluster medium by using both the thermal and kinematic SZ effects. The review by T. Mroczkowski et al. showcases some impressive results, like the study of shock-heated gas in the galaxy clusters MACSJ0717.5+3745 and MACSJ0744.8+3927 with extensive multi-wavelength data. Moreover, they present the history, current status and the exciting new directions in this field of the use of SZ effect in cosmological studies.

## 5 Diffuse Radio Emission from Galaxy Clusters

Diffuse radio emission from clusters is an intriguing phenomenon that, so far, has only been observed in a subset of galaxy clusters. The radio emission reveals the presence of cosmic rays and magnetic fields in the intracluster medium. Diffuse radio sources in clusters are classified as radio halos, cluster radio shocks, or revived AGN fossil plasma sources. Radio halo sources can be further divided into giant halos, mini-halos, and possible intermediate sources. With the advent of low-frequency radio interferometers that can perform fast and deep surveys of the sky, the number of known sources has gone up considerably. Van Weeren et al. give an overview of the properties of diffuse cluster radio sources, with an emphasis on recent observational results. Observations of known sources at higher angular resolution have revealed rich structures within the sources, all of which are poorly understood. Van Weeren et al. critically review the classification of the sources and suggest a new naming scheme for radio relics. They also discuss the underlying physical processes that operate in the ICM, the role of relativistic fossil plasma, and the properties of ICM shocks and magnetic fields. The coming years will be exciting as massive amounts of data from the Low-Frequency Array (LOFAR) and other instruments are going to revolutionise the field. The review gives a complete list of diffuse radio sources in clusters to date. As this list is going to evolve quickly, it is linked to an online data base for diffuse cluster sources which is one of the outcomes of the ISSI workshop. This data base is now available on-line under http://galaxyclusters.com and maintained at the University of Hamburg.

## 6 Hot Atmospheres, Cold Gas, AGN Feedback and the Evolution of Early Type Galaxies

The dense, relatively cool gas in the cores of galaxy clusters is cooling via X-ray radiation on timescales much shorter than the cluster ages. Yet, we do not see nearly enough resulting cool gas in the cluster cores. This poses the so-called cooling flow problem and implies that the observed radiative cooling should be offset by some continuous and self-regulating heating mechanism. The current common wisdom is that the energy output from the active galactic nuclei (AGN), found at the centres of almost all cool cores, balances the cooling. It is still unclear how exactly the energy of the AGN outbursts is dissipated in the cooling gas.

A particular interesting setting where this phenomenon can be investigated is the environment of massive galaxies. These systems have cooling gas atmospheres that are surprisingly similar (when scaled) to those in clusters, as well as central radio galaxies / AGN that produce radio lobes and X-ray cavities in the cooling gas. The contribution by Werner et al. reviews the current observational and theoretical understanding of the galactic gas halos. They highlight our view of the interaction between the AGN and the cool gas and its effects on gas cooling and star formation in these systems.

## 7 Gas Motions in the Intra-Cluster Medium

The hot gas filling the galaxy cluster is, to a zeroth approximation, in hydrostatic equilibrium with the cluster's gravitational potential—its thermodynamic pressure supports the gas atmosphere from collapse. Most of the time between the violent cluster-cluster collisions, the kinetic energy of the intracluster gas is a fraction of its thermal energy. However, the gas velocities can provide invaluable information on the current state and geometry of the cluster and shed light on certain physical properties of the intracluster plasma. The review by Simionescu et al. summarises the current state of affairs in measuring the intracluster velocities using direct (Doppler shift of X-ray lines; kinetic Sunyaev-Zeldovich effect) and various indirect methods, and looks to the future instruments.

## 8 The Physics of Galaxy Cluster Outskirts

Clusters grow by accreting the surrounding big and small clusters, groups and galaxies flowing in along the filaments of the vast Cosmic Web. The cluster outskirts is where most of this action is. The cluster central regions are bright and relatively easy to study with the current X-ray instruments, but they are, to a large extent, smooth and hydrostatic. The X-ray brightness drops with radius very steeply, and its very low level in the outskirts (around the "virial radius" and beyond) makes the X-ray emission extremely difficult to study. The contribution by Walker et al. reviews the state of the art in the X-rays, as well as SZ, optical and gravitational lensing studies at this astrophysical frontier, and discusses future instruments.

## 9 Chemical Composition and Enrichment of the Hot Intracluster Medium

The emission lines in the X-ray spectra of clusters of galaxies are produced in the hot, optically thin intra-cluster medium. The ratio between line fluxes and the continuum emission contains the relevant information to deduce the chemical composition of the cluster gas. Because of the deep gravitational well of clusters, they represent a closed box, and their elemental composition is an excellent tracer of the star formation history of the Universe. From abundance measurements of various elements, information on the number of type Ia and core-collapse supernovae, the initial stellar mass function and stellar lifetimes can be derived. The spatial distribution of these elements as well as the abundances for different types of clusters contain the clue to their formation and transport properties. The reviews by Mernier et al. and Biffi et al. highlight the observational and modelling aspects of these chemical enrichment studies, with attention for future X-ray missions and the perspectives for improved modelling.

## 10 Magnetic Field Amplification in Galaxy Clusters and Its Simulation

The non-thermal emission from galaxy clusters carries valuable information about intracluster magnetic fields. The origin of such fields is not well understood, for which, both, numerical as well as physical challenges are to blame. The numerical efforts to simulate the genesis of cosmic magnetic fields are reviewed in Donnert et al. The authors summarise the substantial progress that has been made in recent years with the advent of highly resolved, cosmological magnetohydrodynamics simulations. The simulations follow the structure formation which drives compression and turbulence. These are the drivers that can amplify tiny magnetic seed fields to the microGauss values that are observed in the intracluster medium. The accurate simulation of magnetic field amplification is primarily limited by the range of scales that can be resolved on computational grids. In addition to the numerical challenges, Donnert et al. review a range of physical processes that act on small scales and can lead to the growth of magnetic fields. Finally, they also discuss the applicability of magnetohydrodynamics.

## 11 Shocks and Non-thermal Particles in Clusters of Galaxies

The formation of clusters of galaxies as a part of the large scale structure is accompanied by the supersonic and superalfvenic gas motions which are producing shock waves of a wide range of strengths. The kinetic energy of bulk flows is dissipated into the gas thermal energy and producing non-thermal tails. Cosmological simulations showed that the bulk of the kinetic energy in the cluster volume is dissipated by weak shocks that are associated with major mergers, while the strong accretion shocks dissipate less energy. The cluster gas heating by shocks is accompanied by magnetic field amplification and superthermal particle acceleration. Radio observations of the extended synchrotron emission in clusters of galaxies provides direct evidence of the presence of the non-thermal components (see van Weeren et al. in this collection). However, gamma-ray observations have not provided any conclusive detection of cosmic ray protons in the ICM so far. Accurate estimations of the energy budget in the non-thermal components (cosmic rays and magnetic fields, beside turbulent gas motions) in clusters of galaxies are necessary to allow for precision cosmology using galaxy clusters (see Pratt et al. this topical collection). Detailed models of non-thermal particle acceleration in cluster shocks require multi-scale simulations. At the microscopic, plasma scale which is of the order of the thermal particle gyrodius, *particle-in-cell* codes are used. Models of particle acceleration at the macroscopic scales (which may be more than ten orders larger than the particle gyroradii) can be performed with kinetic models. Then the evolution of cosmic rays in clusters can be modelled with cosmological simulations. Bykov, Vazza, Kropotina et al. review the particle injection and acceleration processes at the microscopic scales in collisionless shocks. Time dependent non-linear kinetic models of particle acceleration by multiple merger shocks with large scale compressible motions of plasma inside the clusters are discussed. The models show that soft cosmic ray spectra containing a noticeable energy density in the super-thermal protons of energies below a few GeV can be produced. These soft spectra are difficult to constrain by gamma-ray observations with the *Fermi observatory*. However, the superthermal tails of the ion population injected by collisionless shocks in the hot intracluster matter can be constrained by the fine high resolution X-ray spectroscopy of Fe ions.

Overall, this collection of papers provides a timely and comprehensive review of the multi-wavelength observations and theoretical understanding of clusters of galaxies in the cosmological context.

Thus, it will be particularly useful to postgraduate students and researchers active in various areas of astrophysics and space science. This collection is based on an international workshop which took place at ISSI Bern during November 20–24 2017 where about forty leading experts in cosmology and physics of clusters of galaxies discussed the issues presented here.

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