Non-thermal phenomena in colliding galaxy clusters

Titles and Abstracts

Talks

Sources of highest energy cosmic rays, intergalactic magnetic fields, and formation of extended gamma-ray structures

Felix Aharonian (DIAS/Dublin and MPIK/Heidelberg)

The angular, spectral and temporal features of the highest energy protons and accompanying secondary neutrinos and synchrotron gamma-rays propagating through the intergalactic radiation and magnetic fields are described based on the analysis of analytical solutions of the Boltzmann equation obtained in the limit of a small-angle approximation. The perspectives of detection of extended gamma-ray emission from powerful extragalactic cosmic ray accelerators (ZeVatrons), including the ones located at large cosmological distances, are discussed.

A deep radio and X-ray view of cluster formation at the crossroads of filaments

Joydeep Bagchi (The Inter-University Centre for Astronomy and Astrophysics)

Hierarchical models of large-scale structure (LSS) formation predict that galaxy clusters grow via gravitational infall and progressive mergers of smaller virialized halos and their galaxy groups, preferentially at the junction of filaments. Bagchi and his collaborators earlier discovered that diffuse synchrotron radio emission is detectable in an unusual system of large-scale filaments of galaxies extending over several Mpc. The galaxies clearly form an extensive `cosmic-web' like structure around the very rich merging cluster ZwCl~2341.1+0000 at redshift z=0.28. In this presentation I will report on the interesting new results obtained from recent deep radio imaging with GMRT at 150, 240 and 610 MHz and X-ray data obtained by Chandra and XMM-Newton telescopes. I will show that ZwCl~2343.1+0000 is a remarkable system; an unusually massive and complex proto-cluster of galaxies, which is presently under assembly at the crossroads of several filaments; caught in a evolutionary phase far from virialization. Radio maps show both diffuse radio-halo emission all along the optical filaments and two extended regions of `relic' like emission located to the north and south peripheral ends of the central galaxy filament. It is a direct evidence for the acceleration of relativistic electrons to GeV energies extending over scale of >3 Mpc. The supersonic accretion of intergalactic matter on to the central filamentary structure, plus energetics of sub-halo mergers, leads to wide-spread shocks, turbulent flows and acceleration of cosmic ray particles and amplification of weak magnetic fields. Our results give a foretaste of future observations possible in radio and X-ray domains that will open a new window to the large-scale cosmos.

AGN heating in complete samples of galaxy clusters

Laura Birzan (Leiden University)

In the core of many galaxy clusters, giant cavities inflated by the central radio source are present, many with enough feedback 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 of AGN feedback. In order to understand the duty cycle of AGN heating, we use Chandra X-ray data of two complete (flux limited) samples. First, we try to understand the cooling flow/non-cooling flow separation based both on the central cooling time and on the cluster thermal stability. We found that cooling flow clusters are usually thermally unstable and represent 40-60 percent of all clusters. Second, 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\% could have cavities with significant heat, implying a high duty cycle for AGN activity. Lastly, since many clusters of galaxies in our sample are undergoing mergers, we examine how mergers relate to the presence of cooling flows and cavities and to the cavity properties (such as their non-thermal content).

Magnetic fields in the ICM from depolarization analysis

Annalisa Bonafede (Jacobs University)

It is now established that magnetic fields are present in the Intra Cluster Medium of galaxy clusters, as proved by observations of radio halos and radio relics and from the study of the Faraday Rotation Measures of sources located either behind or within clusters. Deep polarization observations of some clusters have been performed in the last years, and the properties of their ICM magnetic field have been constrained. I will present a new study of the intra cluster medium magnetic field aimed at constraining the average properties of the ICM magnetic field in galaxy clusters, and investigating possible differences depending on the cluster thermal and non-thermal properties.

TBD

Marcus Brüggen (Jacobs University)

An introduction to the physics of non thermal components in galaxy clusters

Gianfranco Brunetti (IRA - INAF) - Review

The aim of this review is to use the most recent observational constraints to set up a comprehensive picture of the origin and evolution of relativistic particles in galaxy clusters. I will discuss the most important theoretical aspects and problems, and highlight crucial (theoretical) open questions. The role of future observations in different regions of the electromagnetic spectrum will be discussed.

Cosmological numerical simulations of radio relics in galaxy clusters: insights for future observations

Jack Burns (University of Colorado)

Cosmological shock waves arising from large-scale structure formation are responsible for thermalization of the intracluster medium in galaxy clusters. However, they are also capable of accelerating nonthermal electrons and protons. Here we focus on the acceleration of electrons at shock fronts. This process is thought to be responsible for radio relics, extended radio features in the vicinity of merging galaxy clusters. By combining high resolution Adaptive Mesh Refinement Hydro/N-body cosmological simulations with an accurate shock finding algorithm and a model for electron acceleration, we calculate the expected synchrotron emission resulting from cosmological structure formation. We will show synthetic radio maps and X-ray images of a large sample of galaxy clusters and present luminosity functions and scaling relationships. We find that with upcoming radio telescopes, we expect to see an abundance of radio emission associated with merger shocks in the intracluster medium. By producing observationally motivated statistics, we provide predictions that can be compared with observations to further our understanding of electron shock acceleration and kinematic structure of galaxy clusters.

On the connection between radio halos and cluster mergers

Rossella Cassano (IRA - INAF) - Invited

A radio bimodality is observed in galaxy clusters: a fraction of clusters host giant radio halos while the majority of clusters do not show evidence of diffuse cluster-scale radio emission. Present data clearly suggest that the observed radio bimodality has a correspondence in terms of dynamical state of the hosting clusters. I will report on these evidences in some details and discuss the role of cluster mergers in the generation of giant radio halos and their evolution. Finally I will show expectations on the halo statistical properties in the case where the emitting electrons are re-accelerated by merger-turbulence, and discuss the role of incoming LOFAR surveys.

The curious case of Abell 2256

Tracy Clarke (Naval Research Laboratory)

We present an observational tour of Abell 2256 including detailed radio images of the diffuse halo and relic emission as well as XMM-Newton pressure and temperature maps. Radio maps at GHz frequencies reveal a wealth of total intensity and polarization structures in the system and show spectral steepening across the relic from the NW to the SE. Our new spectral index maps to lower frequencies (330 MHz) reveal a similar spectral trend but show spectral flattening compared to the higher frequency spectrum. We also present new XMM-Newton pressure maps which show a low pressure core co-incident with the radio halo emission, while our temperature maps reveal multiple regions of cool emission.

TBD

Klaus Dolag (MPI for Astrophysics)

Cosmic rays in MHD simulations of galaxy clusters

Julius Donnert (MPA, Garching)

A fraction of Galaxy clusters show large scale diffuse radio emission, so called Radio Haloes. The spectrum of these sources suggest the presence of a population of CR electrons emitting synchrotron radiation in the clusters magnetic field. These electrons are short-lived at the relevant energies and therefore pose a problem regarding the size and morphology of radio haloes. We use MHD simulations of galaxy clusters to study possible models for this radio emission. Assuming purely hadronic models and comparing with observations we are able to constrain the CR proton population in clusters and show possible shortcomings of these models regarding giant radio haloes. Further we give predictions for the expected gamma-ray emission from the corresponding secondary hadronic interactions of CR protons. We will also show preliminary results on the reacceleration of CR electrons in clusters, assuming a magneto-turbulent model.

Non-thermal X-ray emission from galaxy clusters: the contribution of INTEGRAL and future prospects

Dominique Eckert (INAF/IASF-Milano)

Since the first claim of detection 10 years ago, the existence or not of a non-thermal tail in the X-ray spectrum of some galaxy clusters is a long-standing controversy. Since its launch in 2002, INTEGRAL has provided a wealth of data in the hard X-ray energy range, which allowed us to extract high-quality spectra for several well-known clusters. In this presentation, I will summarize the main results (positive: Ophiuchus; negative: Coma, Perseus, A2256) extracted from INTEGRAL data. In view of these new results, I will present the prospects for the future focusing hard X-ray missions (NuSTAR, ASTRO-H), which will have a sensitivity at least two orders of magnitude higher than the current generation in this energy range.

TBD

Luigina Feretti (INAF Istituto di Radioastronomia)

Diffuse radio sources in colliding galaxy clusters

Simona Giacintucci (Harvard-Smithsonian Astrophysical Observatory) - <u>Invited</u>

In this talk, I will present results of the 610 MHz Extended GMRT Radio Halo Survey, an ongoing observational campaign devoted to the study of diffuse radio sources in massive galaxy clusters. The survey, designed to derive the statistical occurrence of giant radio halos and their relation to cluster mergers, revealed the existence of new halos in a number of clusters, and, at the same time, led to the detection of new relics and mini-halos. I will also present results of the GMRT low-frequency follow-up of the new sources found, with emphasis on the discovery of a new population of halos - the ultra-steep spectrum radio halos. Finally, I will discuss the connection between the presence of diffuse emission and the cluster dynamical state, as derived from X-ray and optical observations.

Magnetic field strength and gas temperature connection in galaxy clusters

Federica Govoni (INAF - Osservatorio Astronomico di Cagliari)

Information on the intracluster magnetic fields can be obtained, in conjunction with X-ray observations of the hot gas, through the analysis of the rotation measure (RM) of radio galaxies in the background or in the galaxy clusters themselves.
I will present a work aimed to establish a possible connection between the magnetic field strength and the gas temperature of the intracluster medium. For this purpose we investigated the RM in hot galaxy clusters and we compared these new data with RM information present in the literature for cooler galaxy clusters.

Cluster mergers, shock fronts and radio relics

Matthias Hoeft (TLS, Tautenburg)

Radio relics in clusters are believed to trace shock fronts caused by cluster mergers. Using new high resolution SPH cluster merger simulations we study the properties and the evolution of merger shocks and turbulence in the ICM in detail. We determine the Mach number distribution dS/dM for the large shock fronts (which cause radio relics) and for the shock fronts in the turbulent field. Applying an revised version of the radio emission model described in earlier works we determine the properties of the resulting radio relics and estimate the resulting gamma-ray flux densities. We compare the simulated relics to a recently identified spectacular relic in the cluster CIZA J2242. We discuss in particular if the small width of CIZA J2242 is in agreement with a projected spherical merger shock. Moreover, based on the Mare Nostrum Universe simulation we predict the number of radio relics observable with the Low Frequency Array (LOFAR). We discuss how the number of observable relics depend on the Mach number - radio luminosity relation.

Turbulent flow and stirring mechanisms in the cosmological large-scale structure

Luigi Iapichino (Zentrum für Astronomie der Universität Heidelberg)

Halo mergers and shock waves play a crucial role in the process of hierarchical clustering. Numerical simulations predict that a by-product of cluster formation and virialisation is the injection of turbulence in the cosmic flow. In my talk I will present results from a series of recent works focused on the main stirring mechanisms acting on baryons: minor and major cluster mergers, and curved shocks. Hydrodynamical simulations are the principal investigation tool in this field for theoreticians. In particular I will describe a novel tool for modelling unresolved turbulence in mesh-based simulations, called FEARLESS (Fluid mEchanics with Adaptively Refined Large Eddy SimulationS). Our study of major merger simulations shows a close link between virialisation and turbulence injection. Interesting comparisons between our results and models for cluster radio emission in halos and relics will be drawn.

Turbulence in clusters: a simulation perspective

Tom Jones (University of Minnesota) - Invited

Clusters, especially during mergers, develop strong, large scale motions that one would expect to lead to turbulence, unless dissipation prevents it. Some observational evidence supports the existence of ICM turbulence, including measurements of ICM pressure distributions and Faraday rotation measurements suggesting that ICM magnetic fields are disordered on kpc scales, possible with Kolmogorov power spectra. The properties of nonthermal diffuse radio halos in disturbed clusters may also depend on the existence and behavior of turbulence in these media. Simulations are beginning to address some of the key questions that need to be answered in order to establish how turbulence is likely to develop in these very rarefied media, how the properties of the turbulence depend on the ICM plasma properties and how their observation may illuminate those properties. In my talk I will review the current status of these simulations and their potential impact.

Spectral index studies of the diffuse radio emission in Abell 2256: implications for merger activity

Ruta Kale (Raman Research Institute)

Spectral index studies of radio halos and relics are important to learn about origin and evolution of galaxy clusters. The spectral ages of various regions of radio halos reveal connections to the merging histories of the clusters and the mechanisms of particle acceleration. We present a multi-wavelength analysis of the merging rich cluster of galaxies Abell 2256. We have observed A2256 at 150 MHz using the Giant Metrewave Radio Telescope and successfully detected the diffuse radio halo and the relic emission over an extent ~ 1.2 Mpc^2. Using this 150 MHz image and the images made using archival observations from the VLA (1369 MHz) and the WSRT (330 MHz), we have produced spectral index images of the diffuse radio emission in A2256. These spectral index images show a distribution of flat spectral index ($S \propto \nu^{\alpha}$, α in the range -0.7 to -0.9) plasma in the NW of the cluster centre. Regions showing steep spectral indices (α in the range -1.0 to -2.3) are toward the SE of the cluster centre. These spectral indices indicate synchrotron life times for the relativistic plasmas in the range 0.08 - 0.4 Gyr. We interpret this spectral behaviour as resulting from a merger event along the direction SE to NW within the last 0.5 Gyr or so. A shock may be responsible for the NW relic in A2256 and the Mpc scale radio halo towards the SE is likely to be generated by the turbulence injected by mergers. Furthermore, the diffuse radio emission shows spectral steepening toward lower frequencies. This low frequency spectral steepening is consistent with a combination of spectra from two populations of relativistic electrons created at two epochs (two mergers) within the last ~ 0.5 Gyr. Earlier interpretations of the X-ray and the optical data also suggested that there were two mergers in Abell 2256 in the last 0.5 Gyr, consistent with the current findings.

Re-acceleration of non-thermal particles at weak cosmological shocks

Hyesung Kang (Pusan National University, Korea) and Dongsu Ryu - Invited

We examine the re-acceleration of pre-exisitng cosmic-rays (CRs) via diffusive shock acceleration (DSA) at weak cosmological shocks formed in the intracluster medium during structure formation. Assuming simple models for thermal leakage injection and Alfv'enic drift, we drive analytic solutions for both pre-existing and injected particle populations accelerated in the test-particle regime. Then they are compared with the results from the kinetic DSA simulations. The re-acceleration of pre-existing CRs dominates over the acceleration of injected particles, because the injection is extremely inefficient at weak shocks. We also find Alfv'enic drift reduces the velocity jump across the shock, leading to softer CR spectrum and lower injection and acceleration efficiencies. If the CR pressure is about 5 % of the thermal pressure in the upstream flow, the postshock CR pressure can absorb only a few % of the shock ram pressure for weak shocks with M<~ 3, while it can reach up to 10 % for M~ 4-5, even if the CR injection is inefficient. We also estimate the enhancement factor for the synchrotron radiation from primary electrons re-accelerated at these shocks.

Magnetic reconnection in intracluster medium

Alex Lazarian (University of Wisconsin-Madison) - Invited

I shall discuss the process of magnetic reconnection in turbulent intracluster plasmas. I shall show that the rate of magnetic reconnection is determined by the rate of magnetic stochasticity. The reconnection induces the process of "reconnection diffusion", which allows mixing of hot and cold gas. In addition, I shall discuss another key process that magnetic reconnection induces, which is the First order Fermi acceleration of cosmic rays.

AGNs, small-scale dynamo and magnetic fields in galaxy clusters

Hui Li (Los Alamos National Laboratory) - Invited

X-ray and radio observations of galaxy clusters have revealed a wealth of structures in association with extragalactic radio sources. Structures in the form of large-scale cavities and weak shocks provide a reliable gauge of the energy output of extragalactic radio jets launched by AGNs. Furthermore, they place interesting constraints on the nature of AGN outflows, especially on large scales. We will present 3-D MHD simulations of jets/lobes in the ICM and compare them with ~70 X-ray cavities as well as individual jet/lobe sources. In addition, we will present cosmological MHD simulations of galaxy cluster formation with AGN jets/lobes feedback and its implications for the origin and energetics of the cluster-wide magnetic fields. We demonstrate that the ICM turbulence is excited and sustained by the frequent mergers during the cluster formation. We quantify the available turbulent kinetic energy and nonlinear cascade rates. This turbulence excites a small-scale dynamo process that transports and amplifies the fields originated from the radio jet/lobe system. This process could be the primary process of populating the whole cluster with magnetic fields. We describe the properties of magnetic fields, including their strength, spatial distribution, power spectra and saturation mechanism. These simulations can be compared with observations made by VLA, LOFAR, and E-VLA.

GMRT low frequency follow up observations of diffuse steep spectrum radio emission in galaxy clusters

Giulia Macario (INAF-Istituto di Radioastronomia)

Very recently a couple of galaxy clusters has been found to host diffuse radio halo emission with very steep synchrotron spectra ($\alpha > 1.6$, with $F_\nu \propto \nu^{-\alpha}$), which may be classified as Ultra Steep Spectrum Radio Halos (USSRHs). USSRHs are expected in the re-acceleration model for the origin of cluster radio halos, and are best discovered and studied at low frequencies. I will present preliminary results from new GMRT follow up observations of a number of galaxy clusters at 150 MHz, selected from the GMRT radio halo survey. These clusters are known to host an USSRH or candidate very steep spectrum diffuse emission. This study is aimed to characterize the low frequency spectrum of USSRHs, for comparison with the expectations from the re-acceleration model and for a detailed study of their origin and connection with cluster mergers. Results will be also important in light of the upcoming LOFAR survey observations.

X-ray observations of merger shock fronts

Maxim Markevitch (Smithsonian Astrophysical Observatory) - Review

X-ray observations of shock fronts in merging galaxy clusters provide information on the shock Mach number and velocity, and for well-observed shocks, may constrain the microphysical properties of the intracluster plasma. Combined with radio data, these observations also shed light on the particle acceleration mechanisms and the strength of the magnetic field. Only a few unambiguous shock fronts have been seen in X-rays so far. Curiously, all these weak (M=1.6-3) shocks coincide with edge-like features in their radio halos, where radio data are available. This talk will summarize the current X-ray observations and compare them with radio data.

Study of the spectacular shock wave propagation in the extended and time-dependent gravitational field of RXJ1314.4-2515

Pasquale Mazzotta (Universita' di Roma "Tor Vergata" and Harvard-Smithsonian Center for Astrophysics)

We present a multiwavelength analysis of the merging cluster of galaxies RXJ1314.4-2515. The radio image shows the presence an extended halo in the cluster centerand two Mpc-size relics in the outskirts, one to the east and one to the west. The west relic strongly correlates with the shock front feature perfectly visible in the XMM observation of this cluster. This is the first cluster of galaxies in which such a strong correlation is observed. This observations provide an important support to the shock acceleration models as likely mechanisms behind the formation of the radio relics in clusters. Very interestingly the shock, which seems to propagate with a mach number of 2.5, also presents an M like shape with the nose of the shock slightly tilted inward. Using a specific Hydro N-body simulation we will show in great details the overall dynamic of this object and we will discuss how the observed shape of the front can be simply explained in terms of the variability of the gravitational field of the ongoing cluster merger.

TBD

Brian McNamara (University of Waterloo)

Recent results and future prospects for the detection and characterization of non-thermal emission in galaxy clusters

Silvano Molendi (IASF-Milano/INAF)

In the first part of this presentation I will present a critical review of recent results on non-thermal emission. In the second I will describe future prospects with the upcoming hard X-ray focusing missions with particular emphasis on NuSTAR and NHXM.

New High-Resolution SZ Observations with GBT+MUSTANG

Tony Mroczkowski (University of Pennsylvania)

I will talk about our recent high angular resolution (9'') Sunyaev-Zel'dovich (SZ) effect observations with MUSTANG, a 90 GHz bolometric receiver on the Green Bank Telescope (GBT). MUSTANG has now imaged four massive clusters of galaxies in some of the highest-resolution SZE imaging to date. In three of these clusters, which are mergers, it has revealed complex pressure substructure within the hot intra-cluster gas. In one of these merging clusters, the MUSTANG observation has revealed shocked gas that was previously unknown from the X-ray observations. The one cool-core cluster in our sample shows no significant pressure substructure, and preliminary indications are that it has a steeper than average pressure profile in the core. While SZE observations probe the thermal electron pressure in galaxy clusters, they hold great potential for aiding the interpretation of non-thermal astrophysics, particularly in high-z systems where the merger rate is expected to be higher.

Magnetic field power spectrum in clusters of galaxies

Matteo Murgia (INAF Osservatorio Astronomico di Cagliari) - Review

The existence of magnetic fields associated with the intra-cluster medium in clusters of galaxies is now well established through different methods of analysis. In this talk I will review the recent efforts made through radio observations to measure magnetic field strengths and power spectra and the main issues that have led to our knowledge on magnetic fields in clusters of galaxies.

Gas motions in the outskirts of galaxy clusters

Daisuke Nagai (Yale University)

Gas motions are ubiquitous in galaxy clusters forming via accretion and merging, and these gas motions play important roles in shaping thermodynamic properties of the intracluster medium (ICM). In this talk, we will present analysis of gas motions and thermodynamic structure of the ICM using high-resolution Eulerian cosmological simulations of sixteen simulated clusters.

We show that the gas motions contribute up to 5%-30% of the total pressure support with contribution increasing with cluster-centric radius and for dynamically active clusters. The non-thermal pressure provided by these gas motions is, however, not accounted for in hydrostatic estimates of the total mass profile and would lead to systematic underestimate of the cluster mass. We demonstrate explicitly for the first time that accounting for support from gas motions recovers the true mass profiles of clusters. We also discuss the prospects of measuring gas motions in clusters with the upcoming Astro-H mission equipped with the high spectral resolution quantum X-ray calorimeter.

Furthermore, we present detailed comparisons of our simulated galaxy clusters to recent Suzaku X-ray measurements of cluster outskirts. The simulated ICM temperature profiles are consistent with observations. However, the gas density is overestimated due to significant gas clumping, causing the flattening of the observed entropy profiles by Suzaku. Our work highlights that detailed understanding of gas clumping is critical for studying the thermodynamic structure of the ICM in the outskirts of clusters.

Non-thermal phenomena in merging clusters of galaxies as observed with Suzaku and to be with ASTRO-H

Kazuhiro Nakazawa (University of Tokyo) - Invited

Non-thermal phenomena are rather common in clusters of galaxies as evidenced by the diffuse radio emission. However, radio emission only provides the population of GeV electrons multiplied by the poorly understood intra-cluster magnetic field. Detection of Inverse-Compton (IC) X-rays is important because it can resolve this degeneracy. Observational results of a prototypical merging cluster Abell 3667 with Suzaku shows there is no strong IC X-rays in this cluster (Nakazawa et al. 2009) and provided rather high magnetic field lower-limit of ~2 uG in its north-west radio relic. Analysis using XMM-Newton (Finoguenov et al. 2010) and Suzaku re-analysis (Akamatsu et al. 2010) shows evidence of shock heating around the relic, further increasing the lower limit of the magnetic field. I will also provide perspective of coming hard X-ray facilities, ASTRO-H HXI and SGD in particular, as a powerful tool to detect possibly localized non-thermal and/or very hot component from clusters of galaxies.

Evolution of shocks and shock-injected turbulence in the formation of galaxy clusters embedded in Mpc scale filaments

Surajit Paul (IUCAA, India) + L. Iapichino (ITA, Heidelberg), F. Miniati (ETH, Zurich), J. Bagchi (IUCAA, India), K. Mannheim (ITPA, Wuerzburg)

Hierarchical growth of massive structures like cluster of galaxies, Mpc filaments release enormous amount of energy through mutual interactions. These events are associated with production of Mpc-scale shocks and injection of considerable amount of turbulence, affecting the non-thermal energy budget of the ICM. In order to study this thoroughly we performed a set of cosmological simulations using the hydrodynamical code Enzo. Our study analyzes the formation of clusters undergoing major mergers, the growth of filaments, the propagation of merger shocks and their interaction with the filamentary cosmic-web surrounding the clusters. This shock-filament interaction is shown to produce peripheral structures remarkably similar to giant non-thermal radio arcs observed in Abell 3376 and Abell 3667 clusters. One of the most relevant results of this work is the finding of a relatively long timescale (about 4 Gyr) for turbulence decay in the centre of major merging clusters. This time scale is substantially longer than typically assumed in the turbulent re-acceleration models, invoked for explaining the statistics of observed radio halos.

TBD

Vahé Petrosian (Stanford University)

Cosmic ray transport in galaxy clusters: implications for radio halos

Christoph Pfrommer (HITS) - Invited

I will review hydrodynamical simulations on the evolution of galaxy clusters in a cosmological environment. I will particularly emphasize the rich astrophysics of non-thermal processes such as cosmic rays (CRs), magnetic fields, shocks and turbulence. Going beyond simulations, I will discuss how the interplay of CR propagation and turbulent advection selects a bimodal spatial distribution that is characteristic for the dynamical state of a cluster. As a result, strongly turbulent, merging clusters should have a more centrally concentrated CR energy density profile with respect to relaxed ones with very subsonic turbulence. This translates into a bimodality of the expected diffuse radio and gamma ray emission of clusters. Thus, the observed bimodality of cluster radio halos appears to be a natural consequence of the interplay of CR transport processes, independent of the model of radio halo formation, be it hadronic interactions of CR protons or re-acceleration of low-energy CR electrons.

The galaxy cluster A2255 and the origin of its radio halo

Roberto Pizzo (ASTRON)

A2255 is a nearby and rich galaxy cluster. X-ray and optical investigations revealed that it has recently undergone a major merger. As a result, spectacular extended diffuse features are detected in the radio domain at its center (halo) and at its periphery (relics). A2255 is the first cluster in the literature for which has been detected highly polarized filamentary emission, presumably associated with the central radio halo. To investigate its origin, we performed multi-frequency observations of the cluster with the Westerbork Synthesis Radio Telescope (WSRT). The data have been processed through RM-synthesis allowing the first successful RM tomography of a galaxy cluster. The results reveal the nature of the polarized filaments and their location within the cluster. Their magneto-ionic properties suggest that they should lie at the cluster periphery and that their central location is due to projection effects. Their morphology and high polarization favor an association with relics rather with a radio halo.

The dynamic core of HCG 62: AGN outburst and merger

David Rafferty (Leiden University)

We report on an analysis of new Chandra data of the galaxy group HCG 62, well known for possessing AGN cavities in its ICM. With the new data, a factor of three deeper than previous Chandra data, we re-examine the energetics of the cavities and determine new constraints on their contents. We confirm that the ratio of radiative to mechanical power is less than 10-4, among the lowest of any known cavity system, implying that the relativistic electrons in the lobes can supply only a tiny fraction of the pressure required to support the cavities. This finding implies additional pressure support in the lobes from heavy particles or thermal gas, and we place new constraints on the presence of thermal gas in the cavities. Lastly, we report additional evidence for a recent merger in the surface brightness, temperature, and metalicity structure of the ICM.

Galaxy clusters at gamma-ray energies – status and prospects

Olaf Reimer (University of Innsbruck) - Invited

Whereas the presence of relativistic electrons in galaxy clusters is clearly indicated by the presence of diffuse halos and relics at radio wavelengths, the existence of relativistic protons is most directly probed through high-energy gamma-ray emission produced as result of collisions of cosmic ray protons with non-relativistic protons in the intracluster medium. Besides utilizing capable instruments like the Fermi Gamma-ray Space Telescope and the 3rd generation Imaging Atmospheric Cherekov Telescopes, the quest for detection of the first galaxy cluster at GeV or TeV energies is still ongoing. I'll review the observational status, discuss implications regarding the non-thermal particle content of galaxy clusters and magnetic fields in the ICM. It appears that the volume-averaged relativistic-hadron-to-thermal energy density ratio is determined to less than <5%-10% in a variety of GeV and TeV observations. I'll conclude with an outlook for the ongoing Fermi mission, and prospects for the recently upgraded Cherenkov Telescope arrays, as well as the CTA observatory.

A radio approach to the cool core-non cool core dichotomy

Mariachiara Rossetti (IASF-Milano INAF)

From the point of view of X-ray astronomers, galaxy clusters are usually divided into two classes: "cool core" (CC) and "non-cool core" (NCC) objects. The origin of this dichotomy has been subject of debate in recent years, between "evolutionary" models (where clusters can evolve from CC to NCC, mainly through mergers) and "primordial" models (where the state of the cluster is fixed "ab initio" by early mergers or pre-heating). I will show that in a representative sample (clusters in the GMRT Radio halo survey with available X-ray data), none of the objects hosting a giant radio halo can be classified as a cool core, using different indicators.This result suggests that the main mechanisms which can produce the ingredients to start a large scale synchrotron emission (most likely mergers) are the same that can destroy CC or prevent their formation and therefore strongly supports "evolutionary" models of the CC-NCC dichotomy.

Diffuse emission in clusters: tracers of cluster mergers. Recent results and prospects for LOFAR.

Huub Röttgering (Leiden Observatory)

Radio observations of clusters are important to understand the impact of shocks and mergers on the general evolution of clusters. In the last two years we have embarked on a large project to elucidate the relation of the diffuse radio relics and properties of the ICM. In this talk we will first discuss results on studies of individual clusters including ZwCl 2341.1+0000, MACS J0715.5+3745 and Abell 2256. The radio observations presented all show how that shocks produced in cluster mergers are clearly related to the presence of diffuse radio emission. We then present results from a study of a sample of relics. Using this sample, we found clear relations between the various properties of the relics (the Mach number of merger shocks as traced by the radio spectral index, projected distance from the cluster center and the radio power).

In the second part of the talk I will briefly review the status of LOFAR, a new radio telescope that is currently being commissioned. First results on nearby clusters will be shown.

Shocking news from cluster accretion

Lawrence Rudnick (University of Minnesota) - Invited

I present recent results on the Coma Cluster from the WSRT (90cm) and GBT (20cm), which change our view of the underlying dynamics. We show that the relic source is much larger than previously seen, its faint extension giving a total size of approximately 2 Mpc. The relic bounds a similarly sized column of galaxies which are infalling to Coma, and is therefore likely an "infall shock," generated in the pre-merger stage. On the western edge of the halo there is a clear radio/X-ray shock, likely driven by sub-groups emerging from their first encounter with the cluster.
I will also present some shocking results on a radio-discovered cluster with a number of surrounding "shocklets," a possible connection in Coma between the relativistic plasma and the dark matter, and some mildly shocking comments about rotation measures.
The cluster work has been led by Bolton Fellow Shea Brown, and with the assistance of Minnesota undergraduate Jeffrey Lemmerman. The RM work is led by Minnesota grad Damon Farnsworth. Support for this work comes from a U.S. NSF grant, AST-0908688, and from an NRAO GBT student fellowship.

Simulations of LSS, shocks, and non-thermal effects

Dongsu Ryu (Chungnam National University) - Review

Shock waves form in the intergalactic medium (IGM), as a consequence of accretion, merger, and turbulent motion, as well as outflow from galaxies. They not only heat gas but also govern nonthermal processes through the acceleration of cosmic rays, production of magnetic fields, and generation of vorticity. Yet, the nature of such cosmological shocks, especially those outside cluster cores, remains largely unknown, because observation is still scarce. On the other hand, simulations for the formation of the large-scale structure (LSS) of the universe have revealed the properties of cosmological shocks. In this talk, I will review the recent progress in simulations of LSS focusing on shocks and their roles on nonthermal processes.

Measuring turbulence in clusters using XMM-Newton RGS

Jeremy Sanders (University of Cambridge, Institute of Astronomy) - Invited

Using the Reflection Grating Spectrometers on XMM-Newton it is now possible to constrain or measure the turbulence in the intracluster medium of some galaxy clusters. Examining a deep observation of Abell 1835 we were able for the first time to limit the line-of-sight, non-thermal, velocity broadening to 274 km/s. This is made possible because

Abell 1835 has a compact bright cool core, so that the instrumental broadening is small and its X-ray emission lines are strong. We build on this work to examine the RGS spectra of 62 clusters, groups and ellipticals from the XMM archive to measure or constrain the amount of turbulence. We find five objects with better than 500 km/s broadening. In addition we model the instrumental broadening of the spectra. After subtracting this contribution we find at least 15 of the sources with less than 20 per cent of the thermal energy density in turbulence, and two sources with evidence for turbulence.

Observations of hard X-rays from clusters and cluster mergers

Craig Sarazin (University of Virginia) - Invited

Clusters of galaxies often host radio halo and/or radio relic sources, which so far have only been found in clusters which are undergoing mergers. I will describe some recent X-ray observations of merging clusters with radio halos and relic. The results from Suzaku Hard X-ray Detector (HXD) spectra of Coma, Abell 3667, and several other merging clusters will be described. Swift-BAT observations of Coma and a larger sample of clusters will be discussed. Abell 3667 is the archetype of a merging cluster with radio relics. The NW radio relic is the brightest cluster relic or halo known, and is believed to be due to a strong merger shock. Recently, we observed the NW relic region with XMM. We find a sharp X-ray surface brightness discontinuity at the outer edge of the radio relic, and a significant drop in the hardness of the X-ray emission at the same location. This discontinuity is consistent with a Mach number 2 shock moving at 1200 km/s associated with the merger. Kinetic energy is being dissipated in this shock at a rate of ~2e45 erg/s. If this shock has accelerated the relativistic electrons in the radio relic, then the efficiency of electron acceleration is ~0.2%. Shock acceleration at the outer edge of the relic and radiative losses as the electrons are advected away from the shock can explain the rapid steepening of the radio spectral index with distance from this edge of the relic. Alternatively, the surface brightness discontinuity and hardening of the X-ray spectrum might be due to Inverse Compton (IC) emission from the relic. In this case, the magnetic field in the relic is about 3 muG. Since the observed X-ray excess from the relic is an upper limit to IC emission, this yields a lower limit on the relic magnetic field of >= 3 muG. This is a remarkably strong magnetic field at this large projected distance (2.2 Mpc) from the cluster center, but is consistent with Faraday rotation through the relic observed towards two background radio galaxies.

Modelling the magnetised ICM: from microscale physics to global dynamics

Alexander Schekochihin (R. Peierls Centre for Theoretical Physics, U. of Oxford) - Invited

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Metal enrichment and star formation due to environmental effects

Sabine Schindler (University of Innsbruck)

During the collision of galaxy clusters galaxies are exposed to an ICM with higher density and higher relative velocity. Therefore environmental effects like ram-pressure stripping are particulary strong in these periods. We present new simulations of ram-pressure stripping and its influence on metal enrichment and star formation. We also present ICM metallicity distributions and metallicity-temperature relations in merging and non-merging clusters.

The intracluster magnetic field power spectrum in relaxed galaxy clusters from rotation measure studies

Valentina Vacca (INAF - Osservatorio Astronomico di Cagliari)

The goal is to constrain the magnetic field power spectrum in relaxed, cool core, galaxy clusters by comparing Faraday rotation measure images of central radio galaxies with the expectations of 3-dimensional numerical simulations.

The dicotomy between merging and non merging objects

Franco Vazza (Jacobs University Bremen) - Invited

I will present an overview of the differences found between merging and relaxed objects in a large set of massive galaxy clusters simulated in a fully cosmological context, and focusing on important features connected to non-thermal phenomena: 1) shock waves; 2) turbulent motions; 3) acceleration of relativistic particles; 4) formation of radio relic emission; 5) irregularities in the large scale distribution of thermal component and in the X-ray emission.

Observational properties of radio sources in galaxy clusters: current knowledge and open questions

Tiziana Venturi (INAF, IRA) - Review

In this talk I will review our knowledge of the observational properties (i.e. size, morphology, radio spectra) of the continuum emission of diffuse radio sources in galaxy clusters, i.e. mini-halos, radio halos and relics, as well as extended radio galaxies. Observed and intrinsic properties of diffuse cluster radio sources will be discussed in connection with the cluster dynamical status, and statistical trends will be shown and very briefly compared to the expectations from theoretical models for the formation of such sources. Finally, I will highlight the main questions which still remain open or unclear.

Diffusive shock acceleration in the galaxy cluster CIZA J2242.8+5301

Reinout van Weeren (Leiden University)

We have discovered an extraordinarily long and narrow radio relic in the northern periphery of merging galaxy cluster CIZA J2242.8+5301 at a redshift of 0.19. The source has a clear spectral index gradient perpendicular to its long axis, with the spectral index steepening from -0.6 to -2.0 across the narrow relic towards the cluster centre. Polarization properties point to a highly aligned magnetic field and magnetic field vectors are aligned parallel to the relic. The very narrow relic width of about 50 kpc allows us to constrain the magnetic field strength to about 5-7 microG, without resorting to equipartition arguments. Throughout the cluster, additional diffuse emission is found with a total extent of about 3

Mpc. The observations presented for this relic constitute strong evidence for the existence of diffusive shock acceleration induced by a cluster merger.

Swift/BAT search for non-thermal emission in HIFLUGCS clusters

Daniel R. Wik (NASA Goddard Space Flight Center)

Detections of diffuse inverse Compton (IC) emission at hard X-ray energies have typically been controversial and/or of low significance. Consistency of the existing limits and detections may be possible only for very extended IC spatial distributions. To test this idea, we apply a method to characterize extended, hard X-ray emission from the Swift BAT survey. Spatially coincident spectra from XMM-Newton and Swift are jointly fit to simultaneously constrain both thermal and nonthermal components, but no significant IC spectral component is seen in any of the clusters in the sample. For the Coma cluster, our upper limits exclude the most recently detected IC fluxes, regardless of the IC spatial distribution. Spectra from all clusters are summed, to enhance marginal IC emission possibly present in many clusters, but no aggregate nonthermal excess is found, although a hint of an excess is seen in the radio halo/relic subset.

Gas turbulent motions in galaxy clusters

Irina Zhuravleva (MPA Garching)

We discuss different possibilities to constrain ICM turbulence in galaxy clusters using bright X-ray lines. Numerical simulations are used to find the most appropriate description of the velocity field power spectrum, constrain the anisotropy of gas motions and calibrate the contribution of the turbulent motions to the pressure support. The impact of the velocity field on the surface brightness distribution and on the spectral shape of strong X-ray lines, modified by the resonant scattering, is evaluated via radiative transfer calculations. The uncertainties in deriving the properties of the velocity field are critically evaluated. We in particular find that the amplitude of radial motions is most important for resonant scattering, while tangential motions only weakly affect the scattering.

Testing the connection between radio mini-halos from core gas sloshing with MHD simulations

John ZuHone (Harvard-Smithsonian Center for Astrophysics)

A number of cool-core clusters are marked by the presence of "radio mini-halos": diffuse, low surface-brightness radio emission that roughly extends over the core region. In the turbulent acceleration scenario for radio halos, such emission would result from reacceleration of relativistic electrons from turbulence driven by mergers, but mini-halos are often associated with clusters which show few signs of recent merging. However, these same clusters show evidence for sloshing of the cool core gas in X-rays, and the radio emission has been shown to be coincident with the cold fronts that are the signature of such sloshing. Turbulent generated by the sloshing motions may provide the necessary ingredient. We have performed MHD simulations of gas sloshing in galaxy clusters using the FLASH code in order to determine the effectiveness of such a mechanism. We show that turbulent motions are indeed generated by such sloshing motions and present preliminary results on the corresponding spectrum of radiation emitted by particles accelerated by this turbulence.

Posters

A521. Multiple shock heating of a merging cluster atmosphere

Hervé Bourdin (Dipartimento di Fisica; Università di Roma 'Tor Vergata')

A521 is an X-ray luminous an massive galaxy cluster located at z=0.247, showing a very irregular morphology at X-ray and optical wavelengths and thus presenting a complex dynamical state. Moreover, this cluster hosts a radio halo with very steep spectral index (Brunetti et al., 08), as well as a radio relic (Ferrari et al., 06; Giacintucci et al., 06). We present the analysis of a recent and deep XMM-Newton observation of A521. At the interface between the two major cluster components, we evidence a cross shape feature with high entropy, delimited with cold fronts. Interestingly, this feature appears as spatially correlated with the radio halo emission. In this interacting cluster we further evidence the release of two shock fronts, one of which being located to the Eastern cluster outskirt, and intercepting the electron acceleration region revealed by the radio relic.

Riding the wake of a merging cluster

Rebecca Canning (Selwyn College. Institute of Astronomy)

The Chandra X-ray observation of the galaxy cluster Abell 2146 (Russell et al. 2010) has revealed the supersonic passage of a subcluster through the cluster centre producing two Mach 2 shock fronts and a gas structure similar to the bullet cluster (Markevitch et al. 2002). We report on integral field unit observations of the brightest cluster galaxy located behind one of the shock fronts and in the wake of the ram pressure stripped core. Crawford et al. (1999) have detected the optical emission line gas surrounding the brightest cluster galaxy. The galaxy has a large H alpha luminosity above 10^{42} erg s^{-1} and a large star formation rate (200 solar masses per year, O'Dea et al. 2008). The unique location of the BCG behind the shock front and offset from the X-ray cool core allows us to investigate the effect of turbulence behind the shock and disruption of the cooling core on the cool 10^4 K gas in the system.

Low frequencies in New Mexico: the Long Wavelength Array Station One and the EVLA Low Band Upgrade

Tracy Clarke (Naval Research Laboratory)

The Long Wavelength Array (LWA) is a new digitally steerable radio telescope which operates in the frequency range of 10 to 88 MHz. The full LWA instrument will consist of 53 phased array "stations" which are distributed over a region with a maximum baseline of roughly 400 km in the state of New Mexico. Each station will consist of 256 pairs of dipole-based antennas. The signals can be formed into 4 beams with separate tunings and pointings. The output beams are transported to a central location for high-resolution aperture synthesis imaging with mJy sensitivities and arcsecond resolution. We present details of the commissioning of the first station (LWA1) which has all 256 dipole antennas in place. The station is located near the core of the NRAO EVLA, and is expected to be fully operational in early 2011. We also present details of a new initiative to equip the EVLA with broadband low frequency receivers which cover the spectrum between 50 and

436 MHz. The EVLA system will initially access the 68 to 86 MHz and 230 to 436 MHz sub-bands by working with the existing 74 and 330 MHz feeds, respectively. The improved bandwidth and system temperature, coupled with the power of the EVLA WIDAR correlator, will significantly enhance the performance in both bands. This new EVLA system also has the potential to expand the power of the initial LWA stations through combining signals within the EVLA correlator.

Supermodel analysis of the soft and hard excesses in the Coma cluster

Roberto Fusco-Femiano (IASF-Roma/INAF), M.Bonamente, M.Orlandini and A.Lapi

The Supermodel is a powerful tool to determine the thermal contribution by the hot intracluster plasma which is crucial for the analysis of the soft and hard excesses. In the Coma cluster the intracluster gas density and temperature profiles are obtained by the Supermodel analysis of X-ray observables, namely the XMM-Newton temperature profile (Snowden et al 2008) and the ROSAT brightness distribution (Mohr et al 1992).

For the soft excess we move in the scenario that one or more filaments (WHIMs) projected onto the cluster are responsible for the soft X-ray emission in addition to the intracluster contribution. We show that the width of the soft spectrum in the energy range 0.2-0.5 keV is a formidable thermometer to measure the temperature of the filament(s). The temperature is in the interval (3.5-6.5)x 105 K (99% c.l.) considering an average metallicity of 0.1Z_solar.

For the hard excess the Supermodel analysis confirms the previous BeppoSAX/PDS analysis of Fusco-Femiano et al (2004). A recent joint Suzaku/XMM-Newton analysis (Wik et al 2009) reports an upper limit of ~6 x 10-12 erg/cm2/s for the nonthermal flux for an average gas temperature of 8.45 keV. However, they also report an excess of nonthermal radiation at a confidence level above 4sigma for an XMM-Newton average temperature of 8.2 keV in the Suzaku/HXD-PIN FOV in agreement with the PDS analysis of Fusco-Femiano et al and therefore in disagreement with that of Rossetti & Molendi (2004). Besides, when the smaller size of the HXD-PIN FOV with respect to that of the PDS FOV and the higher temperature of 8.45 keV used by Wik et al are taken into account, the Supermodel analysis of the PDS spectrum gives a nonthermal flux consistent with the above upper limit of Suzaku.

Sunyaev-Zeldovich maps of two merging galaxy clusters

Cathy Horellou (Onsala Space Observatory) and the APEX-SZ collaboration

We present Sunyaev-Zeldovich (SZ) maps at 870 micron and 2 mm of two merging galaxy clusters: Abell 2744, a massive galaxy cluster at redshift 0.31 that shows multiple evidence of merging activity (including a radio halo), and MS1054-0321, at redshift 0.8. Two bolometer cameras were used on the APEX telescope, a 12 meter antenna in northern Chile: LABOCA (a 295-element array, angular resolution of 19.5 arcsec) and ASZCA (a 330-element array, one-arcminute resolution). With careful treatment of the data it is possible to quantify the size of the hot plasma distribution, to measure the Compton parameter, and to detect deviations from the X-ray surface brightness distribution.

Discoveries of low frequency extensions to the relic in Abell 4038

Ruta Kale (Raman Research Institute)

Low frequency observations of radio halos and relics are playing a major role in advancing our knowledge of non-thermal phenomena in galaxy clusters. Our low frequency (150, 235 and 606 MHz using the GMRT) study of the relic in A4038 has revealed a whole new story. A new steep spectrum (spectral index ~-2.5) component that forms an extension of the earlier known relic is discovered. Also a plume having low surface brightness and steep spectrum is suspected toward the northwest of the main source. These new low frequency observations have revealed more than twice the extent of the radio relic that was known from earlier studies at 1.4 GHz. A model fit to the integrated spectrum of the relic in A4038 is consistent with an adiabatically compressed cocoon of spectral age 300 million years. We present the radio images of A4038 and the model fit in this poster. The interpretation of these results and implications of it will be discussed.

A statistical investigation of clusters radio emission: role of AGNs

Joseph Lanoux (CESR), Etienne Pointecouteau, Martin Giard

The radio emission in the direction of galaxy clusters is mainly due to individual AGNs emission, and to the intracluster medium (ICM) non-thermal emission. The AGNs population in clusters is correlated to the overall halo properties. However, this is not well understood beyond the impact of the central AGN, which is often found to be the prominent feedback feature. The overall population of AGNs likely impacts the evolution of galaxy clusters properties. In order to better understand this relation (which will also leads to constraints on non-thermal ICM emission for lower mass systems), we are conducting a statistical analysis of the radio emission in the direction of a large number of X-ray clusters. By means of their number counts and stacked radio emission, we are investigating the evolution of the fraction of AGN and of their radio luminosities with respect to the cluster mass and redshift, aiming to constrain their imprints on the cluster physical properties.

Probing gas dynamics in cluster mergers through the SZ effect

Siddharth Malu (Raman Research Institute)

We present 12mm observations of the bullet cluster from the Australia Telescope Compact Array; in particular, a high angular resolution measurement of the substructure in Sunyaev-Zel’dovich Effect (SZE). We report the first discovery of multiple compact SZ features in a galaxy cluster, as also their peculiar displacement from the X-ray brightness centres. None of these SZ feature centres corresponds to any bright spot in X-ray, optical or lensing maps. This implies that the gaspressure distribution differs significantly from the distributions in gas emission measure, galaxy and dark matter distributions. This has implications for the gas physics and evolution in the cluster merger event. SZE displaced from X-ray centres implies that modeling cluster dynamics is non-trivial; our observations indicate that our current lack of understanding cluster merger astrophysics may be a limitation in modeling cluster SZE contribution to small-angle CMB anisotropy and the cause for difficulties in reconciling recent observations of such anisotropy with structure formation models.

Radio relics observable with LOFAR

Sebastian Nuza (AIP) and Matthias Hoeft (TLS)

The Low Frequency Array (LOFAR) will operate in the frequency range 30 - 240 MHz. Due to the steep spectra of radio relics LOFAR is excellently suited to search for relics. We predict the number of relics observable with LOFAR. To this end we estimate the relic luminosity function based on the Mare Nostrum Universe simulation. We discuss how the predicted number depends on model assumptions for the
magnetic field strength in radio relics.

Shocks and Cavities from Multiple Outbursts in the Galaxy Group NGC 5813: A Window to AGN Feedback

Scott Randall (Harvard-Smithsonian Center for Astrophysics)

We present results from new Chandra, GMRT, and SOAR observations of NGC5813, the dominant central galaxy in a nearby galaxy subgroup. The system shows clear signatures from three distinct outbursts of the central AGN, with three pairs of roughly collinear cavities. The inner two cavity pairs are each associated with elliptical shock fronts with measured temperature jumps and Mach numbers of M~1.7 and M~1.5 for the inner and outer shocks, respectively. Such clear signatures from three distinct AGN outbursts in an otherwise relaxed system provide a unique opportunity to study AGN feedback and outburst history. The mean power of the two most recent outbursts varies by an order of magnitude, indicating that the mean jet power varies significantly over long ($\sim 10^7$ yr) timescales. The total energy output of the most recent outburst is also less than the total energy of the previous outburst, which may be a result of the lower mean power, or may indicate that the most recent outburst is ongoing. We directly measure the local heat input into the ICM at the shock fronts, and show that the shock heating balances radiative cooling of the gas locally. The outburst interval implied by both the shock and cavity ages ($\sim 10^7$ yr) indicates that in this system shock heating alone is sufficient to balance radiative cooling close to the central AGN, which is the relevant region for regulating feedback between the ICM and the central SMBH.

Public Lecture

Exploring the Cosmos from the Moon

Jack Burns (University of Colorado at Boulder)

The Moon is a unique platform for fundamental astrophysical measurements of gravitation, the Sun, and the Universe. Lunar Laser Ranging of the Earth-Moon distance provides extremely high precision constraints on General Relativity and alternative models of gravity. Lacking a permanent ionosphere and, on the farside, shielded from terrestrial radio emissions, a low frequency (<100 MHz) radio telescope on the Moon will be an unparalleled observatory for probing myriad cosmic phenomena from the Sun to galaxy clusters to the very early Universe. Crucial stages in the acceleration of high energy particles near the Sun, which will be harmful to astronauts exploring beyond the Earth’s immediate environs, can be imaged and tracked with the lunar radio telescope. The evolution of the Universe during and before the formation of the first stars, black holes, and quasars can be traced for the first time with a farside low frequency radio array. Extended radio structures produced by colliding galaxy clusters can similarly be imaged with such a powerful array of telescopes. The NASA Lunar Science Institute at the Ames Research Center recently funded a multi-university center dedicated to the study of Astrophysics from the Moon and headquartered at the University of Colorado. In this talk, I will describe how future observatories on the Moon will explore some of the most exciting problems in astronomy and astrophysics.