Structure in Clusters and Groups of Galaxies in the Chandra Era

July 12-14, 2011
Boston, Massachusetts
Boston Doubletree Guest Suites
Hosted by the Chandra X-Ray Center

Chandra X-Ray Center

Smithsonian Astrophysical Observatory

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This Chandra science workshop is sponsored by the Chandra Directors Office (CDO) at the Chandra X-ray Center (CXC), part of the Smithsonian Astrophysical Observatory in Cambridge, MA.

Tuesday July 12

8:45 - 9:00 Opening Remarks

I. Cluster Structure Since 2000, What Has Chandra Seen and How Has it Changed Our Views?

9:00 - 9:30 Craig Sarazin
Chandra's Clear View of the Structure of Clusters

9:30 - 9:45 William Forman
A Shock Model for the the Outburst from the Supermassive Black Hole in M87

9:45 - 10:00 Elizabeth Blanton
Sloshing, Shocks and Bubbles in the Cool Core Cluster Abell 2052

10:00 - 10:30 Poster Microtalks

10:30 - 11:00 Break and Poster Viewing

II. Cluster and Group Physics - Gas Dynamics, Transport Properties, Outstanding Questions

11:00 - 11:30 Eugene Churazov
X-ray Surface Brightness Fluctuations and ICM Physics

11:30 - 11:45 Jelle de Plaa
Turbulence Measurements in Two Giant Elliptical Galaxies

11:45 - 12:00 Jeremy Lim
Velocity Field of the Optical Nebula at the Center of the Perseus Cluster

12:00 - 12:15 Takayuki Tamura
Discovery of Gas Bulk Motion in the Galaxy Cluster Abell 2256 with Suzaku

12:15 - 12:30 Helen Russell
Revealing the ICM transport properties with a deep Chandra observation of A2146

12:30 - 2:00 Lunch and Poster Viewing

III. Observational Overview to AGN Feedback

2:00 - 2:30 Megan Donahue
AGN Feedback and Cluster Environment

2:30 - 2:45 Ewan O'Sullivan
AGN Feedback in Galaxy Groups: A Combined X-ray/Low-Frequency Radio View

2:45 - 3:00 Scott Randall
The Role of Shock Heating in AGN Feedback

3:00 - 3:15 Myriam Gitti
AGN feedback is Mechanical? Evidence for Massive Outflows in Hydra A

3:15 - 3:30 Julie Hlavacek-Larrondo
AGN Feedback in Highly-Luminous Clusters of Galaxies

3:30 - 3:45 Aneta Siemiginowska
3C186: A Luminous Quasar in the Center of a Strong Cooling Core Cluster at $z > 1$

3:45 - 4:15 Break and Poster Viewing

IV. Theory of Feedback/Numberical Simulations

4:15 - 4:45 Debora Sijacki
Cosmological Simulations of AGN Feedback in Groups and Clusters: Implementation, Results and Uncertainties

4:45 - 5:00 Daisuke Nagai
Exploring the Cosmic Melting Pot in the Virialization Region of Galaxy Clusters

5:00 - 5:15 Yuan Li
Simulating the Cooling Flow of Cool-Core Clusters

5:15 - 5:30 Bill Mathews
Using Cluster Gas Fractions to Estimate Total BH Mechanical Feedback Energy

5:30 - 5:45 Brian Morsony
AGN and their Environments

Wednesday July 13

V. Observational Overview

9:00 - 9:30 Alexey Vikhlinin
Substructures in Galaxy Clusters

9:30 - 9:45 Matthias Ehle
X-raying the Mach Cones of Virgo Cluster Spiral Galaxies

9:45 - 10:00 Ryan Johnson
Sloshing Gas In a Flux Limited Sample of Chandra Clusters

10:00 - 10:15 Brendan Miller
Supermassive Black Hole Activity in Field and Cluster Early-Type Galaxies

10:15 - 10:30 Irina Zhuravleva
Velocity Field in the ICM: Observational Signatures and Constraints

10:30 - 11:00 Break and Poster Viewing

VI. Simulations

11:00 - 11:30 Klaus Dolag
Magnetic Fields, Turbulence and Cosmic Rays in Galaxy Clusters

11:30 - 11:45 Mateusz Ruszkowski
MHD Simulations of Ram Pressure Stripping in Late Type Galaxies

11:45 - 12:00 Konstantinos Gourgouliatos
Evolution of Rising Magnetic Cavities and UHECR Acceleration

12:00 - 12:15 John ZuHone
The Physics of Gas Sloshing in Clusters of Galaxies

12:30 - 2:00 Lunch and Poster Viewing

VII. Masses, Baryons and Metals (Part 1)

2:00 - 2:30 Norbert Werner
Baryons in the Outskirts of the Nearest Brightest Galaxy Clusters

2:30 - 2:45 Fabio Gastaldello
Cold Fronts in Groups and Clusters and their Dynamical State in the Optical

2:45 - 3:00 Viral Parekh
Substructure in Galaxy Clusters Identification through Six Morphology Parameters

3:00 - 3:15 Eric Miller
Probing the Outskirts of Clusters with Chandra, Suzaku and XMM

3:15 - 3:30 Matthew Fleenor
Advantages at Multi-Wavelengths: A Pre-Processed Galaxy Group within a Cluster

3:30 - 4:00 Break and Poster Viewing

VIII. Masses, Baryons and Metals (Part 2)

4:00 - 4:30 David Buote
Galaxy, Group and Cluster Mass Profiles from Small Scales out to the Virial Radius

4:30 - 5:00 Christine Jones
Planck SZ Selected Cluster Samples Compared with X-ray Selected Samples

5:00 - 5:15 Akos Bogdan
The Curious Case of NGC 4342, an Optically Faint but Gas-Rich Early-Type Galaxy

5:15-5:30 Philip Humphrey
Tracing the Gas to the Virial Radius (R_{100}) in a Galaxy Group

5:30 Reception with Music and Cash Bar

Thursday July 14

XI. Multiphase Gas in Clusters and Groups

9:00 - 9:30 Alastair Edge
The Cold Gas in Cluster Cores - So Much Progress in the Chandra Era!

9:30 - 9:45 Michael McDonald
The Origins and Ionization Mechanisms of Warm Filaments in Cool Core Clusters

9:45 - 10:00 Lawrence Rudnick
All Mixed Up – Relations Between Cluster Thermal and Non-Thermal Plasmas

10:00 - 10:15 Edmund Hodges-Kluck
X-shaped Radio Galaxies as Probes of Radio-Mode AGN Feedback

10:15 - 10:30 Nimisha Kantharia
Radio Signatures of Ram Pressure Sweeping in Low Galaxy Density Environs

10:30 - 11:00 Break and Poster Viewing

X. Conference Summary/Panel Discussion

11:00 - 12:30 Megan Donahue

12:30 - 1:30 Bag Lunch and Poster Removal

Presenters

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Posters

- Esra Bulbul - *High Resolution XMM-Newton Spectroscopy of a Cool Core Cluster Abell 3112*
- Alberto Doria - *The X-Ray Cavity System and Radio Mini-Halo in the Galaxy Cluster RBS 797*
- Edmund Douglass - *The Galaxy Cluster Environment of Wide Angle Tail Radio Sources*
- Damon Farnsworth - *Nonthermal Excess at Cluster Peripheries*
- Deborah Haarsma - *Brightest Cluster Galaxies in Non-Cool Core Clusters*
- Quyen Hart - *The Evolution of Radio Galaxies in Coma Cluster Progenitors*
- William Hawley - *Heating and Chemical Enrichment in the Core of the Antlia Cluster*
- Marie Machacek - *Sloshing, Stripping, Bubbles and Shocks in the NGC5846 Galaxy Group*
- Christopher O'Dea - *AGN Feedback in the Cool Core Cluster A2597*
- Mahadev Pandge- *Detailed Investigation of X-Ray Cavities in a Poor Cluster cD Galaxy NGC 6338*
- Lukasz Stawarz - *On the High-Energy Non-Thermal Emission Generated in the Intracluster Medium.*
- Adam Tomczak - *A Census of Mid-Infrared Selected AGN in Massive Galaxy Clusters at* $0 < z < 1.3$
- Joshua Wing - *Substructure in Galaxy Clusters Identified by Double-lobed Radio Sources*

Sloshing, Shocks, and Bubbles in the Cool Core Cluster Abell 2052

Elizabeth Blanton
Boston University

We present results from a very deep (∼650 ksec) Chandra X-ray observation of Abell 2052, as well as archival VLA radio observations. The data reveal exquisite detail in the inner parts of the cluster, including bubbles evacuated by the AGN's radio lobes, compressed bubble rims, filaments, and loops. Two concentric shocks are seen, and a temperature rise is measured for the innermost one. On larger scales, an excess surface brightness spiral feature is detected. The spiral has cooler temperatures and higher abundances than its surroundings, and is likely the result of sloshing gas initiated by a previous cluster-cluster or sub-cluster merger. Initial evidence for previously unseen bubbles at larger radii related to earlier outbursts from the AGN is presented.

The Curious Case of NGC 4342, an Optically Faint but Gas-Rich Early-Type Galaxy

Akos Bogdan
SAO

Based on Chandra observations, we performed a comprehensive analysis of NGC 4342, an optically faint early-type galaxy in the outskirts of the Virgo cluster. This galaxy hosts an unusually bright ($L_X \sim 10^{40}$ erg/s), hot ($kT \sim 0.56$ keV) X-ray corona. However, the low stellar mass of NGC 4342 should not be sufficient to gravitationally bind such a significant amount of hot gas. Therefore, NGC 4342 is a truly unique and curious object. With a tenuously bound, but bright corona, NGC 4342 is "the canary of the coal mine" for sensing the presence of external gas in its local environment. Our goal is to understand the origin and nature of the unusually large gas mass surrounding NGC 4342, and measure the properties of the external medium producing the observed gas distortions.

High Resolution XMM-Newton Spectroscopy of a Cool Core Cluster Abell 3112

Esra Bulbul
Center for Astrophysics

XMM-Newton and Chandra observations have revealed that some physical mechanisms act as an inhibitor to prevent cool gas to infall onto central cD galaxies. Understanding what happened to the cool gas in cooling flow clusters was one of the prime problems in extragalactic astrophysics until analysis of the XMM-Newton RGS spectra showed that they do not, in fact, cool beyond a temperature about one-third of the virial temperature. We examine high signal to noise XMM-Newton RGS and EPIC observations to determine the physical characteristics in the cool core and outskirts of the nearby rich cluster A3112. The lack of any Fe XVII and Fe XVIII lines in the RGS spectra confirms the absence of any cool gas. This disproves the theory that strong soft excess emission has a thermal origin.

Galaxy, Group, and Cluster Mass Profiles from Small Scales to the Virial Radius

David Buote
UC Irvine

I will discuss several recent results from our group on mass profiles obtained from X-rays: (1) a new relationship between the slope of the total mass profile and the stellar half-light radius in massive elliptical galaxies, (2) evidence that the elliptical galaxy NGC 720 resides in a modest Milky-Way–size halo containing the cosmic fraction of baryons, (3) results of a combined X-ray and stellar dynamics study of the group-scale Virgo galaxy NGC 4649 to quantify the amount of non-hydrostatic support of the gas, and (4) a systematic study of the biases arising from spherically averaging intrinsically ellipsoidal galaxy clusters.

X-ray Surface Brightness Fluctuations and ICM Physics

Eugene Churazov
MPA/IKI

Chandra angular resolution provides exquisitely detailed X-ray images of nearby clusters and groups. Substructure seen in these images reflects the complexity of ICM physics, including thermal conduction, viscosity, magnetic fields, perturbations in gravitational potential and presence of gas motions. The results of the analysis of few brightest clusters are presented.

Turbulence Measurements in Two Giant Elliptical Galaxies

Jelle de Plaa
SRON Netherlands Institute for Space Research

Turbulent pressure is thought to contribute significantly to the total pressure in the hot intra-cluster 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.

Magnetic Fields, Turbulence and Cosmic Rays in Galaxy Clusters

Klaus Dolag
MPA

In galaxy clusters, non-thermal components such as magnetic field, turbulence and high energy particles keep a record of the processes acting since early times till now. These components play key roles by controlling transport processes inside the cluster atmosphere and therefore have to be understood in detail. Although including them in simulations is extremely challenging as the structures in and around clusters are quite complex and span a very large dynamic range in scales, it allows us to put constrains on turbulence and the presence of cosmic rays in galaxy clusters by comparing in detail the induced radio emission in these simulations with observations.

AGN Feedback and Cluster Environment

Megan Donahue
Michigan State University

I will review the evidence for a link between the intracluster gas in the core of the host cluster or group and the activity exhibited by the AGN in the central bright galaxy. The presence of luminous radio activity appears to require low-entropy, X-ray emitting gas, either in the form of a cluster-scale cool core or a more compact, galaxy-scale corona. The large fraction of X-ray luminous clusters whose brightest cluster galaxies are also radio galaxies (and emission-line systems) implies that the relationship is common and relatively long-lived.

The X-Ray Cavity System and Radio Mini-Halo in the Galaxy Cluster RBS 797

Alberto Doria
University of Bologna

We present a study of the cavity system in the galaxy cluster RBS 797 based on Chandra and VLA data. The Chandra data reveal a cool core and a higher metallicity along the cavity direction. This could be due to the AGN outburst, which lifts cool metal-rich gas from the center along the lobes orientations, as seen in other systems. We found indications of cool cavity rims surrounding the cavities. Likely, the 1.4 GHz radio emission, expanding, have displaced the gas compressing it into bright cool arms. Finally we show that the large scale radio emission detected with our new VLA observations may be classified as a radio mini-halo powered by the cooling flow (cf), as it nicely follows the trend P_{radio} vs. P_{cf} predicted by the re-acceleration model.

The Galaxy Cluster Environment of Wide Angle Tail Radio Sources

Edmund Douglass
Boston University

Due to their frequent association with galaxy clusters and their connection to ICM ram pressure, wide angle tail (WAT) radio sources have proven to be reliable tracers of high-density environments, as well as indicators of cluster dynamical activity. In an effort to perform a coherent study of the X-ray properties of WAT clusters, we have assembled a sample of 10 WAT systems from within the Chandra archive. We find that the clusters display both merger signatures and evidence of cool/high-Z gas near the WAT host galaxy, suggesting a possible relation between WAT formation and perturbed cool cores. To understand WAT-hosting systems with respect to general cluster properties, we compare the results with those of an identical analysis of an archival sample of WAT-less CC and NCC clusters.

The cold gas in cluster cores - so much progress in the Chandra Era!

Alastair Edge
University of Durham (UK)

In the past 12 years the observational constraints on the amount of cold gas present in the cores of clusters and groups have changed radically. I will review the past, current and future observations of this illusive phase, with particular emphasis on the role of Chandra.

X-Raying the Mach Cones of Virgo Cluster Spiral Galaxies

Matthias Ehle
ESA/ESAC, XMM-Newton SOC

The detailed comparison between HI observations and simulations of ram-pressure stripped Virgo Cluster spiral galaxies allows a construction of a 3D view of their orbits within the hot intracluster medium. The velocities and Mach numbers derived provide simple Mach cone geometries for the studied galaxies. With XMM-Newton we searched for hot gas within the Mach cones of selected Virgo Cluster spiral galaxies: NGC 4569, NGC 4388, and NGC 4501. Low-resolution maps show extraplanar diffuse extended X-ray emission. In NGC 4569 the hot gas from a galactic superwind fills the entire Mach cone. Hot gas tails in NGC 4388 and NGC 4501, situated within their Mach cones, are most likely due to the mixing of the stripped galactic ISM and the hot ICM of the Virgo Cluster.

Nonthermal Excess at Cluster Peripheries

Damon Farnsworth
University of Minnesota

Using confusion subtracted Green Bank Telescope observations at 1.4 GHz we have discovered that most of the diffuse synchrotron emission in two galaxy clusters is missing in the existing interferometer images. A2142 ($z = 0.09$), a mini-halo cluster with a sloshing cool core, now displays a > 1 Mpc giant radio halo spanning an X-ray cold front offering a view of physical conditions in the very different environs on either side. The radio relic in A1367 ($z = 0.02$) extends $\sim$400 kpc in our GBT observations ($> 4\times$ the extent previously observed). This suggests that a significant fraction of the relativistic plasma in cluster environs is undetected. Probing the relationship between the thermal and nonthermal cluster gas is crucial to understanding the associated shock/accretion/merger processes.

Advantages at Multi-Wavelengths: a Pre-Processed Galaxy Group within a Cluster

Matthew Fleenor
Roanoke College (VA)

We utilize multi-wavelength data to confirm an infalling galaxy group embedded within the cluster Abell 3128 (z = 0.05). While previous analyses of the merging complex highlighted primarily the optical or the x-ray wavelengths, a more complete picture results from the inclusion of moderate-resolution radio (1.4 GHz) photometry of the extended emission. Specifically, the directionality of two, head-tail radio galaxies corroborates the picture of an infalling group with an advancing front of mildly shocked gas (M $\sim$ 1.25). Optical spectroscopy also supports the efficiency of pre-processing within the group environment since the group members are highly evolved and yet foreign to the cluster ($t_{merge} < 1$ Gyr).

A Shock Model for the the Outburst from the Supermassive Black Hole in M87

William Forman
Smithsonian Observatory

We present new results from our analysis of the 500 ksec Chandra observation of M87. The observations show a clear shock and extensive filamentary structure which is closely related to the radio emission. We derive the energy, age, and duration of the outburst that produced the 13 kpc radius shock. With a simple model for the main outburst, we can estimate the fraction of energy deposited in M87's atmosphere and the fraction that is carried away by the weak shock. We show that the deposited energy is comparable to that radiated by M87's cooling atmosphere. We discuss the importance of AGN feedback, seen in M87, for the evolution of galaxies.

Cold Fronts in Groups and Clusters and their Dynamical State in the Optical

Fabio Gastaldello
INAF IASF-Milano, UCI

Cold fronts are found both in merging and in cool core relaxed clusters. In merging clusters cold fronts mark the discontinuity among the merging 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 groups currently known. We present A 2028 which shows the unique combination of a corona close to a cold front constraining in principle the stripping of coronae and the velocity field creating cold fronts.

AGN Feedback is Mechanical? Evidence for Massive Outflows in Hydra A

Myriam Gitti
INAF-OABo / SAO

Our detailed Chandra study of the Hydra A cluster indicates the presence of multiphase gas along soft filaments. We estimate that $10^{11} M_{\odot}$ of low-entropy material has been dredged up by the rising lobes from the central 30 kpc to the observed current position of ~ 100 kpc. The outflow amounts to a few hundreds $M_{\odot}$/yr, which is comparable to the inflow rate of the cooling flow. The energy required to lift the cool gas is $\sim 2 \times 10^{60}$ erg, which is comparable to the work required to inflate the cavities and is $\sim 25\%$ of the total energy of the large-scale shock. Uplift provides a significant channel for the dissipation of outburst energy. The AGN feedback in Hydra A is acting not only by directly heating the gas, but also by removing a substantial amount of potential fuel for the SMBH.

Evolution of Rising Magnetic Cavities and UHECR Acceleration

Konstantinos Gourgouliatos
Purdue University

GN jets produce low density cavities in clusters of galaxies. Stability requires the presence of magnetic fields. We find self-consistent analytical structure of cavities containing large-scale electromagnetic fields and plasma expanding self-similarly. These solutions have no surface currents and, thus, are less susceptible to resistive decay, while they can be confined by a uniform pressure without deformation. If the adiabatic index of the plasma within the cavity is $\Gamma > 4/3$, the expansion leads to the sudden formation of large-scale current sheets. We demonstrate that the ensuing explosive reconnection of the magnetic field can accelerate UHECRs.

Brightest Cluster Galaxies in Non-Cool Core Clusters

Deborah Haarsma
Calvin College

In Haarsma et al 2010, we investigated Brightest Cluster Galaxies (BCGs) and core gas in the REXCESS representative sample of 31 galaxy clusters. We detected a correlation between the central stellar density of the BCG and the central gas density of the cluster, but only for non-cool core clusters. We suggested that the same process that sets the central entropy in non-CC clusters also determines the central stellar density of the BCG, and that this underlying physical process could be mergers. We are now testing whether the correlation is present in a sample of 75 clusters from the Archive of Chandra Cluster Entropy Profiles (ACCEPT, Cavagnolo et al 2009) that have optical data in the Sloan Digital Sky Survey. This work is supported by the Michigan Space Grant Consortium.

The Evolution of Radio Galaxies in Coma Cluster Progenitors

Quyen Hart
CASA, CU-Bolder (and Regis University)

The Evolution of Radio Galaxies in Coma Cluster Progenitors Abstract: Evolutionary studies of cluster radio galaxies provide a snapshot of AGN activity, which can affect the thermal history of the ICM. Guided by cosmological simulations, we select 22 clusters between $0.2 < z < 1.2$ that are predicted to end with X-ray properties similar to the Coma Cluster, a prototypical massive cluster in the present epoch. We use new and archival VLA L-band radio maps to identify cluster radio galaxies at P$> 5 \times 10^{23}$ W/Hz. Contrary to previous studies, we find significant evolution of the radio luminosity function of cluster radio galaxies with higher-power radio galaxies situated in lower-temperature clusters at earlier epochs. Our results suggest a 9-10 fold increase in the heat injected into high-z clusters by AGN compared to the present epoch.

Heating and Chemical Enrichment in the Core of the Antlia Cluster

William Hawley
Harvard University

The dynamical processes responsible for heating and chemical enrichment of the ICM depend upon the environment and thus the cluster's evolutionary stage. These processes create distinct X-ray signatures in the hot cluster gas. We use a 53 ks XMM exposure of the core of the Antlia cluster, a galaxy cluster in an intermediate merger stage without a cool core, to study the transport of energy and metals throughout the ICM. We construct density, temperature, pressure, entropy and abundance maps to identify gas motions and heat flows, relate these motions to metal abundance ratios and gradients, and test simple models for chemical enrichment and heating of the Antlia cluster gas.

AGN Feedback in Highly-Luminous Clusters of Galaxies

Julie Hlavacek-Larrondo
University of Cambridge

Highly-luminous cool core clusters of galaxies ($L_X > 10^{45}$ erg/s) require extreme feedback from their central AGN in order to offset cooling of the ICM. For a typical BH mass ($10^9 M_\odot$), these AGN must be operating at high enough Eddington rates that they should be radiatively efficient. We would therefore expect to see an X-ray point source. We present a sample of such clusters for which there is NO evidence of a nuclear X-ray point source. Using Chandra, we derive upper limits of the nuclear luminosities and identify a range of possible explanations as to why these objects appear to be so radiatively-inefficient, each of which carries significant implications for the origin and operation of jets, including the possibility that these BHs are significantly more massive ($\gg 10^9$ $M_\odot$).

X-shaped Radio Galaxies as Probes of Radio-Mode AGN Feedback

Edmund Hodges-Kluck
University of Maryland

"X"-shaped Radio Galaxies (XRGs) are radio galaxies with a second pair of lobes ("wings") in addition to the double-lobed radio morphology. The wings are long and faint (having no jet) and are symmetric about the nucleus, thereby forming an "X" shape. The origin of XRGs is debatable (SMBH merger vs. hydrodynamic lobe deflection), but regardless they are interesting probes of radio-mode feedback because XRGs illuminate a pair of "dead" radio lobes which interact with the surrounding intracluster medium. Since dead radio galaxies are notoriously rare, a radio/X-ray study could provide constraints on models of AGN feedback wherein dead radio galaxies play a significant role. I will present a few "proof of concept" objects.

Tracing the Gas to the Virial Radius (R_{100}) in a Galaxy Group

Philip Humphrey
University of California, Irvine

We present a Chandra and Suzaku study of the fossil group/ poor cluster RXJ1159+5531. The Chandra data reveals a round, relaxed morphology, while the combination of flat surface brightness profile, high luminosity and optimal distance allow the ICM to be detected to the virial radius ($R_{100} = 1.1$Mpc) in a single Suzaku field. We measure the gas over $\sim$3 orders of magnitude in radius. With 4 data-bins beyond $0.5R_{200}$ and good azimuthal coverage (>30%), we find no evidence that the entropy profile flattens at large scales ($>R_{500}$). The baryon fraction within R_{100} is consistent with the Cosmological value (0.15 ± 0.02). This contrasts sharply with recent results for Virgo and Perseus, indicating that substantial gas clumping cannot be ubiquitous, at least in highly evolved clusters.

Sloshing Gas In a Flux Limited Sample of Chandra Clusters

Ryan Johnson
Denison University

In this talk I will present a flux limited sample of galaxy clusters observed with Chandra which exhibit sloshing gas in their cores. This work confirms that sloshing is indeed common in cool core clusters, as it should be based on the persistence of the resulting morphology and the frequency of interactions which may initiate it. With a particular emphasis on comparing the morphological traits of the sloshing gas with those predicted by simulations, I will describe how gas sloshing may be used to constrain the merger histories of galaxy clusters on an individual basis, as well as constrain the build up of structure over cosmic times.

Planck SZ Selected Cluster Samples Compared with X-ray Selected Samples

Christine Jones
SAO

The Planck all sky ESZ cluster catalog provides arguably the most complete set of massive clusters in the $z < 0.5$ Universe. We compare the Planck ESZ cluster sample with flux limited samples of X-ray selected clusters to determine how samples selected through these two techniques may be biased. We also examine the overall properties of these cluster samples (including X-ray luminosities and gas temperatures) and characterize the fraction of merging and cool core clusters in the ESZ and X-ray cluster catalogs.

Radio Signatures of Ram Pressure Sweeping in Low Galaxy Density Environs

Nimisha Kantharia
National Centre for Radio Astrophysics

Gas stripping mechanisms such as ram pressure sweeping are commonly observed in rich clusters of galaxies which contain substantial matter in the ICM and velocity dispersion is high. The signs on radio emission that are commonly attributed to ram pressure are asymmetric and swept up features in the gas disk. Such features have also been observed in galaxies in small groups and outskirts of clusters where X-ray emission shows the hot ICM has low densities but difficult to attribute them to ram pressure stripping. Generally mechanisms which can aid ram pressure are proposed: tidal interaction or winds due to star formation. In this paper, we review results obtained from radio observations of a few systems and discuss these in context of physical mechanisms active in such systems.

Relativistic Particle Population and Magnetic Fields in Clusters of Galaxies

Doron Kushnir
Weizmann Institute of Science

We derive constrains on the cosmic ray (CR) population and magnetic fields (MF) in clusters of galaxies, based on: 1. The correlation between the radio and the X-ray luminosities: the former emitted by synchrotron of secondary electrons in a strong MF, $>\sim 3$ muG; In the core, the CR energy is $\sim 10^{-3}$ of the thermal energy; The source of CR is the accretion shock (AS), which accelerate CR with efficiency $>\sim 1\%$. 2. The HXR luminosity: emitted by IC of CMB photons by electrons accelerated in AS with efficiency $>\sim 1\%$. The constrains imply that gamma-ray emission from secondaries will be difficult to detect with existing/planned instruments. However, the extended emission from primary electrons might be detected by future HXR (NuStar, Simbol-X) and gamma-ray observations (Fermi, HESS, VERITAS).

Velocity Field of the Optical Nebula at the Center of the Perseus Cluster

Jeremy Lim
University of Hong Kong

The optical nebulae at the centers of cool-core clusters may trace streamlines due to cooling flows and/or AGN activity. Here we present the velocity field of the entire optical nebula at the center of the Perseus cluster. The velocity field allows us to better disentangle the different structures that make up this nebula and test models for how these structures are produced. For example, we find that the velocity fields of the pairs of horseshoe-like filaments associated with the north-western and southern X-ray cavities differ in important aspects from the model where they comprise vortices behind rising bubbles.

Simulating the Cooling Flow of Cool-Core Clusters

Yuan Li
Columbia University

In an attempt to better understand the cooling flow problem of galaxy clusters, we simulate the onset of the cooling instability of the hot gas in the center of cool-core clusters using Enzo, an adaptive mesh refinement (AMR) code. The 3D simulation setup is such that the initial gas density profile matches the observations of Perseus Cluster with an NFW dark matter potential. We find that the cooling instability happens globally, causing the temperature to drop and the density to increase within $r \sim$ a few tens of pc. The amount of cold gas remains in good agreement with observations when the gas inflow is strong enough to potentially trigger feedback that stifles the cooling flow.

Sloshing, Stripping, Bubbles and Shocks in the NGC 5846 Galaxy Group

Marie Machacek
SAO

The NGC 5846 galaxy group shares many properties with highly evolved 'fossil' groups, yet its ICM is far from relaxed. We use a 120 ks Chandra exposure to study bulk gas motions, induced by galaxy interactions, and 'bubble' evolution, driven by AGN activity in the dominant galaxy NGC 5846. From analyses of X-ray surface brightness, gas density and temperatures, we find features consistent with 'sloshing', and constrain gas velocities and the orbit of the perturber. From X-ray bubbles, we estimate the duty cycle and outburst energies for NGC 5846's AGN. Knotty substructure is found in the inner bubbles. We argue that the properties of the inner bubbles are consistent with the recent passage of a shock. We also show gas stripping from a cE galaxy NGC 5846A, as it plummets towards NGC 5846.

Using Cluster Gas Fractions to Estimate Total BH Mechanical Feedback Energy

Bill Mathews
University of California, Santa Cruz

The total mechanical feedback energy received by clusters of mass $4 - 11 \times 10^{14} M_{sun}$ exceeds 10^{63} ergs and mean feedback luminosity 10^{46} erg/s. This can be estimated by comparing gas density profiles in idealized adiabatic clusters evolved to zero redshift with entropy and gas fraction profiles in clusters of the same mass. Feedback energy, stored as potential energy in the cluster gas, can be estimated by comparing the PE within the same gas mass in adiabatic and observed atmospheres which have expanded considerably. The total feedback energy far exceeds energy gained by supernovae or lost by radiation. Less than 1% of the feedback energy is deposited within the cooling radius, but the time-averaged mass inflow from cooling is nicely offset by outflow due to feedback expansion.

The Origins and Ionization Mechanisms of Warm Filaments in Cool Core Clusters

Michael McDonald
MIT

We present results from a survey of 33 cool core clusters and groups covering nearly three orders of magnitude in mass aimed at explaining the presence and morphology of warm, ionized gas in the cool cores of galaxy clusters. Using the Maryland-Magellan tunable filter we have taken a census of these mysterious Halpha filaments with unprecedented depth and resolution. These data have been supplemented with new and archival X-Ray, UV, near-far IR, mm, and radio imaging and spectroscopy. Armed with the most detailed picture of the warm gas in cool cores to date, we investigate several possible mechanisms for both producing the observed morphologies and ionizing the cool gas. Our results offer exciting new constraints, both quantitative and qualitative, for the latest models of clusters.

Supermassive Black Hole Activity in Field and Cluster Early-Type Galaxies

Brendan Miller
University of Michigan

Initial results from a Large Chandra Program targeting highly sub-Eddington supermassive black hole activity in local early-type field galaxies are provided. This is a comparison study to the AMUSE-Virgo project, which examined 100 Virgo early-types. The field galaxies presented here may show a modest tendency toward higher nuclear X-ray luminosities at a given black hole mass, with a "downsizing" trend of relatively higher Eddington ratios in lower mass objects consistent with that found for Virgo. X-ray luminosity is found to scale with optical bulge luminosity similarly (again with a marginal offset) for field and cluster galaxies. The potential influence of the large-scale environment upon low-level inefficient accretion (e.g., through mediation of the gas supply) is discussed.

Probing the Outskirts of Clusters with Chandra, Suzaku and XMM

Eric Miller
MIT

The outskirts of galaxy clusters remain relatively unexplored territory and yet are vital to our understanding of cluster growth, structure, and mass. We have embarked on a program to probe the outer ICM in a large sample of galaxy clusters, exploiting the strengths of three complementary X-ray observatories, Suzaku, XMM-Newton, and Chandra. By combining observations from the cluster core to beyond R_{200}, we are able to identify and reduce systematic uncertainties that would impede our spatial and spectral analysis using a single telescope. We present our initial sample of six clusters and describe plans to triple the size of our sample, an improvement that will allow us to produce a fiducial data set for detailed comparison with high-resolution numerical simulations.

AGN and their Environments

Brian Morsony
University of Wisconsin-Madison

I will present a series of simulations of how AGN jets interact with their environments. AGN affect their environment by forming X-ray bubbles and radio lobes in clusters, heating and mixing cluster gas, and filling space with relativistic particles. The local environment also affects the AGN by bending and eventually disrupting the jets, limiting how far jets can propagate and, for moving AGN, create bent-double radio sources.

Exploring the Cosmic Melting Pot in the Virialization Region of Galaxy

Daisuke Nagai
Yale University

Exploration of the virialization region of galaxy clusters, $R_{500} < r < 3 \times R_{500}$, is one of the frontiers in X-ray studies of the cosmic structures. It is a "cosmic melting pot", where infalling galaxies and groups are gradually stripping their metal-rich gas through their interactions with the surrounding ICM, generating clumpy and turbulent ICM and enriching it with heavy elements. In this talk, I will show that its study is a new territory for the physics of clusters and intergalactic medium and holds keys for precision cosmological work with X-ray and SZE surveys.

AGN Feedback in the Cool Core Cluster A2597

Christopher O'Dea
RIT

We present the deepest Chandra exposure yet of the central 100 kpc of Abell 2597. Our deeper data reveals the highly disturbed X-ray surface brightness distribution in more detail, including a 15 kpc long "cold" (soft excess) filament. We also present evidence that one of the previously known "ghost" cavities may be part of a much larger cavity, cospatial with low frequency radio emission, extending ~ 25 kpc from the central to outer regions of the BCG. Temperature maps derived from X-ray spectral fitting show an excess of > 3 keV gas aligned with the innermost rim of this cavity, consistent with a scenario in which the intracluster medium (ICM) is reheated as it rushes to refill the wake of the buoyantly rising bubble, as is expected in effervescent AGN feedback models.

AGN Feedback in Galaxy Groups: a Combined X-Ray/Low-Frequency Radio View

Ewan O'Sullivan
University of Birmingham, UK

We present results from a combined X-ray/low-radio-frequency study of 18 galaxy groups with a wide range of morphologies and radio powers. Most galaxies in the Universe are found in galaxy groups, whose low masses mean that AGN feedback may have a greater effect than in the more widely studied galaxy clusters. Chandra's ability to identify disturbed structures, such as shocks and cavities, complements our 235-610∼MHz GMRT observations, which are able to detect evidence of older, lower-power AGN outbursts, in some cases over multiple activity cycles. We use these data to study the relationship between the radio and mechanical power of AGN jets across 7 decades of radio luminosity, and discuss the uncertainties in this relation and its impact on models of AGN heating over cosmological time.

Probes of Cluster Turbulence

S. Peng Oh
University of California, Santa Barbara

Volume-filling turbulence in clusters has important consequences for nonthermal pressure support, thermal conduction, metal and entropy transport. However, depending on the nature of the stirring process, bulk motions in the ICM could be patchy (e.g., confined to the wakes of galaxies and subhalos). We discuss quantitative constraints that Astro-H might be able to place. If turbulence is only partially volume filling, then a bimodal spectral structure could potentially be seen in Astro-H spectra. We run Markov Chain Monte Carlo simulations of gaussian mixture modeling to predict the accuracy with which multiple parameters like the turbulent linewidth, volume filling factor, and coherence scale of velocity field can be extracted from the data.

Detailed Investigation of X-Ray Cavities in a Poor Cluster cD galaxy NGC 6338

Mahadev Pandge
Swami Ramanand Teerth Marathwad University (India)

We present results based on the analysis of Chandra observations on the poor cluster cD galaxy NGC 6338, with an objective of examining properties of X-ray cavities. We have detected a pair of cavities, which are displaced ∼4.01kpc from X-ray center of the cluster. Both these cavities show a decrement in the surface brightness profile. Spectroscopic analysis enabled us to examine the variations in derived parameters like luminosity, electron density, entropy, metal abundance, temperature, and enthalpy, etc. We also derive various cavity properties like age, power, size and pressure within cavities. The energy associated with both cavities is 6.9×10^{58}, 5.6×10^{58} ergs, resp. Our results imply that these cavities are originated due to the AGN feedback associated with cluster cooling flow.

Substructure in Galaxy Clusters Identification through Six Morphology Parameters

Viral Parekh
University of Cape Town

Recent spectral and spatial X-ray observations of galaxy clusters suggests subclustering and merging in many clusters.Hence galaxy clusters can be grouped into two categories; relaxed and non-relaxed clusters.We have investigated the use of six morphological parameters (Gini, Asymmetry, M_{20}, Concentration, Ellipticity, Smoothness and Gini 2nd order) to differentiate between relaxed and non-relaxed scenarios.We initially simulated different relaxed and non-relaxed morphologies with multiple beta profiles and then also simulated these clusters for Chandra observation using the MARX simulator software.Finally,we applied our method to a different redshift sample of clusters from the Chandra archive. In this talk I will present the promising results from the six morphological parameter calculations.

The Role of Shock Heating in AGN Feedback

Scott Randall
Harvard-Smithsonian Center for Astrophysics

Feedback between the ICM and the central AGN is the most likely solution to the so-called "cooling flow problem" in galaxy clusters. Although the internal energies of ICM cavities inflated by AGN jets are generally large enough to offset cooling in the gas, it is not clear how and where this energy is released to heat the ICM. AGN outburst shocks, which are driven by the rapid inflation of the X-ray cavities, heat the ICM isotropically and close to the central AGN, as required for AGN feedback to operate. I will discuss the role of outburst shocks in AGN feedback, focusing on multiwavelength observations of the galaxy group NGC 5813 as an example, including initial results from a deep (650 ks) Chandra observation, the longest Chandra imaging observation of a galaxy group core to date.

All Mixed Up - Relations between Cluster Thermal and Non-Thermal Plasmas

Lawrence Rudnick
University of Minnesota

I report on explorations of the spatial and physical relationships between cluster thermal and relativistic plasmas. In Coma, we find a large shock-like structure bordering the radio halo which led to its recovery in X-rays. However, the overall structure of the radio halo is not well matched to the diffuse X-rays, suggesting multiple energization sources. New EVLA observations of A2256 using RM synthesis allows us to start probing its line of sight structure – tailed radio galaxies show local Faraday effects, confusing estimates of the cluster-wide fields. Numerical simulations show how these AGNs interact with the cluster weather. Finally, we constrain the relativistic plasma energization in X-ray clusters using a radio stacking experiment.

Revealing the ICM transport Properties with a Deep Chandra Observation of A2146

Helen Russell
University of Waterloo

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. I will present the first results from a new 400ks Chandra observation and a GMRT 325MHz radio observation of the merging cluster Abell 2146, which contains both a bow shock and the first known example of an upstream cluster merger shock. The X-ray dataset shows complex and potentially turbulent substructure along the edges of the subcluster core and provides new tests of the establishment of electron-ion equilibrium behind each shock front. The GMRT observation reveals the surprising result of no extended radio emission, no giant radio halo or relic in this major merger.

MHD Simulations of Ram Pressure Stripping in Late-Type Galaxies

Mateusz Ruszkowski
University of Michigan

We present first magnetohydrodynamical (MHD) simulations of ram pressure stripping in late type galaxies in the intracluster medium (ICM). Our simulations include magnetic fields, radiative cooling, and self gravity of the gas. We show that the interaction of the galaxies with the sub-equipartition ICM magnetic fields on scales comparable to the galactic disk scales, leads to the formation of magnetic "shield" protecting the galaxies, which can severely limit the amount of ram pressure stripping. This magnetic draping effect also affects the topology of the tails, and the amount of turbulent mixing on the ICM-tail interface. We make predictions regarding the observational signatures of ram pressure stripping tails.

Chandra's Clear View of the Structure of Clusters

Craig Sarazin
University of Virginia

I will review the discoveries made with Chandra high-resolution X-ray observations of the structure of clusters of galaxies. I will emphasize two topics. First, I will describe the observations of the central regions of cool core cluster, where radio sources are seen to be interacting with and possibly heating the X-ray gas. Second, I will discuss observational X-ray features resulting from mergers and other dynamical events in clusters.

3C186: A Luminous Quasar in the Center of a Strong Cooling Core Cluster at z>1

Aneta Siemiginowska
SAO/CXC

We present the results from a deep Chandra observation of the X-ray luminous galaxy cluster surrounding the powerful ($L \sim 10^{47}$ erg/s) quasar 3C186 at $z = 1.06$. We derived the cluster properties, e.g. mass and X-ray luminosity, gas mass fraction, temperature and metal abundances. We measure cooling times at several radii, with the cooling time of $7.5 \pm 2.6 \times 10^8$yrs at 25 kpc distance from the center. The amount of cool gas is enough to fuel the black hole and to power the luminous quasar. The radiative power of the quasar exceeds the kinematic power of the radio source, suggesting that radiative heating may be important. We discuss several aspects of quasar-cluster interactions and the impact of the luminous quasar on the cluster.

Cosmological Simulations of AGN Feedback in Groups and Clusters

Debora Sijacki
CfA, Harvard University

I will review numerical techniques employed to simulate black hole formation, accretion and feedback processes in cosmological simulations of structure formation. In particular, I will discuss how black holes co-evolve with forming groups and clusters of galaxies from high redshifts to the present epoch, and how AGN feedback modifies gaseous and stellar properties in the central regions of these systems. I will also elaborate on various shortcomings of the widely used cosmological codes illustrating how they affect simulated properties of galaxy clusters and to which extent this reflects on our understanding of feedback processes in cluster cores.

On the High-Energy Non-Thermal Emission Generated in the Intracluster Medium

Lukasz Stawarz
ISAS/JAXA

Here we analyze the inverse-Compton (IC) emission of ultrarelativistic electrons present within the intracluster medium (ICM), taking into account however not only the Cosmic Microwave Background (CMB) radiation as the seed photon population for the IC scatterings, but also other lower-energy photon fields such as Extragalactic Background Light (EBL) in the infrared-to-optical range, near-infrared and optical emission of the cD host galaxy, or the soft X-ray emission of the cluster gas. We show that all these additional populations of the target photons play an important role in shaping the high-energy emission of clusters, which can be probed in hard X-rays and gamma-rays by present and future instruments such as Swift/BAT, Suzaku or Fermi/LAT.

Discovery of Gas Bulk Motion in the Galaxy Cluster Abell 2256 with Suzaku

Takayuki Tamura
ISAS, JAXA

The Suzaku observations of Abell 2256 are presented. This is a prototypical and well-studied merging system, exhibiting substructures both in the gas and galaxies. In order to measure Doppler shifts of iron K-shell lines from gas components by the Suzaku XIS, the energy scale of the instrument was evaluated carefully. A significant shift of the radial velocity of the sub component gas was detected. The difference is found to be 1500 ± 300 (statistical) ± 300 (systematic) km/s. The X-ray determined absolute redshifts of the main and sub components are consistent with those of member galaxies in optical. The observation indicates robustly that the X-ray emitting gas is moving together with galaxies as a substructure within the cluster (Tamura et al. 2011 PASJ in press).

A Census of Mid-Infrared Selected AGN in Massive Galaxy Clusters at $0 < z < 1.3$

Adam Tomczak
Texas A&M University

We conduct a deep mid-IR census of nine massive galaxy clusters at $0 < z < 1.3$ with a total of ~ 1500 spectroscopic member galaxies using mid-IR color selection with *Spitzer*/IRAC. We determine the cluster IR-AGN fraction to be uniformly low($< 1\%$) at $z < 1$, consistent with similar X-ray studies. Our results show that there is not a large population of AGN that are missed in these previous works. Furthermore, since the fraction of 24μm sources in these clusters shows a factor of 4 increase from $z \sim 0 - 1$ our results imply that cluster 24μm emission is dominated by star formation. Although our sample is limited, we show that the cluster IR-AGN fraction is not strongly correlated with star formation at $z < 1$, but suggest that IR-AGN may have a more prominent role at $z > 1$.

Substructures in Galaxy Clusters

Alexey Vikhlinin
SAO

Galaxy clusters form via hierarchical growth from the surrounding large scale structures. The infalling groups and subclusters enrich, mix, and heat the intracluster gas. I will discuss the importance of correct physical description of the merging and substructure destruction processes for building more accurate cluster models.

Baryons in the Outskirts of the Nearest, Brightest Galaxy Clusters

Norbert Werner
KIPAC/Stanford University

Studies of the diffuse X-ray emitting gas in galaxy clusters have provided powerful constraints on cosmological parameters and insights into plasma astrophysics. However, measurements of the faint cluster outskirts have become possible only over the last few years. I will review the Suzaku measurements of the thermodynamic properties of the ICM at large radii and present the latest results for the Perseus and Virgo clusters of galaxies. In particular I will discuss the evidence for a clumpy distribution of the gas in the outskirts, which is important for understanding the physics of the ongoing growth of clusters from the surrounding cosmic web.

Substructure in Galaxy Clusters Identified by Double-lobed Radio

Joshua Wing
Boston University

Using radio sources from the FIRST survey, and optical counterparts in the SDSS, we have identified a large number of galaxy clusters. These radio sources are driven by AGN, and our cluster sample includes objects with bent, and straight, double-lobed sources. We also included a single-component comparison sample. We examine these galaxy clusters for evidence of optical substructure, testing the possibility that bent sources are formed in large-scale mergers. We use a suite of substructure analysis tools to determine the location and extent of substructure visible in the optical distribution of cluster galaxies. We also examine the X-ray structure of sources with available Chandra observations for additional evidence of substructure and as a comparison to our optical tests.

Velocity Field in the ICM: Observational Signatures and Constraints

Irina Zhuravleva
MPA

We discuss various ways of measuring ICM velocities using current and future X-ray observatories. In particular, we focus on (i) the resonant scattering effect in X-ray lines, which provides interesting constraints on the amplitudes, spatial scales and anisotropy of motions in centers of clusters, and (ii) on fluctuations of the X-ray surface brightness. The next generation of high spectral resolution X-ray observatories will be able to measure shift and broadening of lines with high accuracy. Using simulations of galaxy clusters we investigate the relation of these observables with the structure function and the power spectrum of gas motions.

The Physics of Gas Sloshing in Clusters of Galaxies

John ZuHone
NASA/Goddard Space Flight Center

Many X-ray observations of relaxed galaxy clusters reveal the presence of sharp, spiral-shaped 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 the cool-core gas "sloshing" in the gravitational potential. Their sharpness and stability has important implications for the microphysics of the ICM. The sloshing motions may have other effects, such as contributing to the heating of the cluster core and the acceleration of relativistic particles. I will present simulations of gas sloshing in clusters, explain their formation and evolution, and discuss the implications for the physics of the ICM.

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