UNIVERSITEIT VAN AMSTERDAM

Joint Radio and X-Ray Analysis of Powerful Feedback Systems

G.D. Kokotanekov

Summary

Galaxy clusters are the most massive bound objects in the universe (Fig. A). They are located at the nodes of the large-scale filamentary structure known as the cosmic web and form by subsequent merging of smaller structures. In addition to the dominant dark matter (~75%, on average) and the large numbers of visible galaxies (~5%), clusters also contain enormous reservoirs of diffuse hot gas (~20%). Roughly 90% of the baryons in clusters reside in the hot plasma of the intracluster medium (ICM), while the rest form stars in galaxies. The hot gas forms a hydrostatic atmosphere, which fills up the space between the galaxies and is kept in place by the gravity of a dark matter halo. Gas temperatures typically range from 10^6 to 10^8 K, which makes it observable in X-rays. The intracluster plasma of the ICM is primarily comprised of ionized hydrogen and helium, mixed with traces of heavier elements.

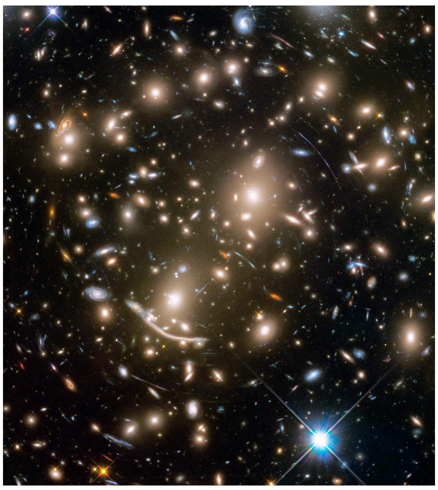

Figure A: Optical image of the galaxy cluster Abell 370 from the Hubble Space Telescope, where the galaxies comprising the cluster can be distinguished. Image from NASA, ESA.

Active galactic nuclei (AGN) that appear in the centers of galaxy clusters are the most energetic objects in the Universe (Fig. B). The central engine of an AGN is a compact supermassive black hole (SMBH), whose strong gravitational field traps not only matter but also light. The black hole is fed through accretion disk, a relatively flat structure which is a consequence of the conservation of angular momentum of the infalling material (primarily gas and dust from the interstellar matter).

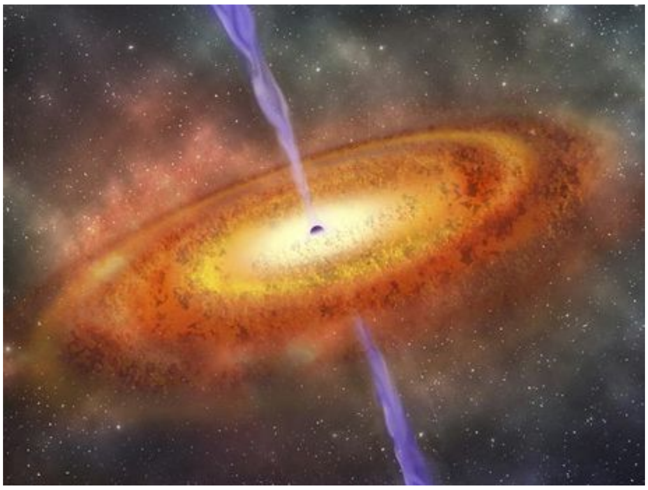

Figure B: Artist's impression of an AGN with the central supermassive black hole, the accretion disc, and the two oppositely-directed jets. Figure from Carnegie/AP.

The X-ray and radio studies of clusters in the last few decades have drawn our attention to the role played by radio-loud AGN in the thermal balance of the hot gas in galaxy clusters. AGN feedback refers to the process of interaction between the energy injected by relativistic jets originating near SMBHs at the centers of the clusters and the surrounding ICM. The central SMBH is feeding energy back into its surroundings at a rate enough to balance the loss of energy through cooling. The energy deposited into the AGN's environment is believed to moderate the availability of fuel for the accretion process that regulates both the growth of the black hole and the formation of stars in the surrounding galaxy. Thus, AGN feedback is the most plausible candidate to explain the lack of excessively bright cluster central galaxies predicted by many simulations.

Many observed (cool-core, relaxed) clusters have shown evidence of the interaction between the SMBH and its environment. In these systems, the radio jets of the AGN have pushed out cavities in the cluster's atmosphere, creating surface-brightness depressions observed in X-rays. In most of the studied systems those cavities have round shape and appear in pairs situated on the two sides of the SMBH (Fig. C).

In most systems, the depressions in X-ray surface brightness are found to be filled with the extended diffuse radio lobes produced by the jets. This spatial anti-correlation between the X-rays and radio provides strong circumstantial evidence that the AGN activity is responsible for the observed X-ray cavities. Given this common origin, X-rays directly probe the mechanical effects of the feedback process, while radio observations reveal the radiative output of the lobes. Combined X-ray and radio observations can provide constraints on the AGN energy output and the radio radiative efficiency, as well as the physical properties of the radio lobes and the ICM.

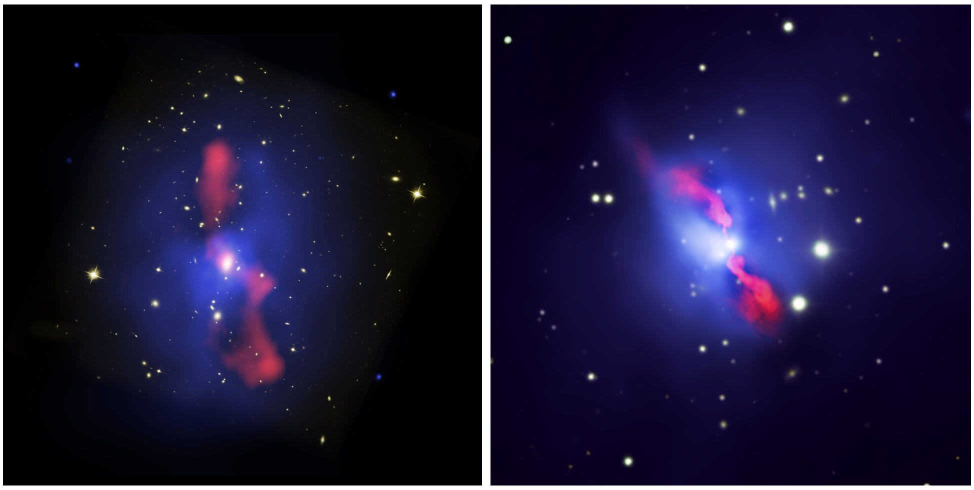

Figure C: The images demonstrate how the two opposite radio lobes fill in the symmetric X-ray cavities. Both images show the combination of X-ray (blue), optical (white), and high-frequency radio wavelengths (red). *Left:* Image of the inner 200″ (700 kpc) of the cluster MS 0735.6+7421. Credit: McNamara et al. 2009. *Right:* Image of the central region of the Hydra A cluster. Credit: chandra.harvard.edu.

In this thesis we combine X-ray and radio observations in order to study the profound effect the tiny, but powerful SMBH has on the observed morphology of the ICM. We primarily focus on low-frequency radio observations since they allow us to detect older, diffuse emission at larger radii and trace the AGN activity over longer timescales. This thesis contains four chapters, including an introduction on the interaction between the intracluster medium and the central supermassive black hole.

In the first part of Chapter 2 we present a new analysis of the widely used relation between cavity power and radio luminosity in clusters of galaxies with evidence for strong AGN feedback. We study the correlation at low radio frequencies using two new surveys – the first alternative data release of the TIFR GMRT Sky Survey (TGSS ADR1) at 148 MHz and LOFAR's first all-sky survey, the Multifrequency Snapshot Sky Survey (MSSS) at 140 MHz. We find a scaling relation $P_{\rm cav} \propto L_{148}^{\beta}$, with a logarithmic slope of $\beta = 0.51 \pm 0.14$, which is in good agreement with previous results based on data at 327 MHz. The large scatter present in this correlation confirms the conclusion reached at higher frequencies that the total radio luminosity at a single frequency is a poor predictor of the total jet power. We also show that including additional measurements at 148 MHz is insufficient to improve the spectral aging correction and reduce the scatter in the correlation. This new low-frequency analysis highlights the fact that existing cavity power to radio luminosity relations are based on a relatively narrow range of AGN outburst ages. We discuss how the correlation could be extended using low frequency data from the LOFAR Two-metre Sky Survey (LoTSS) in combination with future, complementary deeper X-ray observations.

In the second part of Chapter 2 we focus on a subset of four well-resolved sources with MSSS. We examine the detected extended structures at low frequencies and compare with the morphology known from higher frequency images and *Chandra* X-ray maps. In the case of Perseus we discuss details in the structures of the radio mini-halo, while in the 2A 0335+096 cluster we observe new diffuse emission associated with multiple X-ray cavities and likely originating from past activity. For A2199 and MS 0735.6+7421, we confirm that the observed low-frequency radio lobes are confined to the extents known from higher frequencies.

In Chapter 3 we analyze AGN activity signatures in the rich nearby galaxy cluster Abell 1795 aiming to confirm and characterize the long-term feedback history in the system. We combine radio observations at 610 and 235 MHz from the Giant Metrewave Radio Telescope (GMRT) with 3.4 Msec X-ray data from the *Chandra* Observatory. Extracting radial temperature profiles, as well as X-ray and radio surface brightness profiles in three directions showing major morphological disturbances, we highlight the signatures of activity in the system. For the first time we observe radio emission corresponding to the NW X-ray depression, which provides evidence in favor of the classification of the depression as a cavity. We identify two other X-ray cavities situated NW and SW of the AGN. While the central radio emission corresponding to the inner cavities shows flatter spectral index, the radio extensions associated with the furthest X-ray cavities consist of aged plasma. All observed signatures both in radio and X-ray are consistent with several consecutive episodes of AGN activity, which gave rise to the observed morphology NW and SW from the core. In the southern region, we confirm the cooling wake hypothesis for the origin of the long tail. The deep X-ray data also allows us to distinguish significant distortions in the tail's inner parts, which we attribute to the activity of the AGN.

Chapter 4 presents a new radio spectral-aging analysis of the powerful FR II radio galaxy Cygnus A. Using new broadband observations from all array configurations of the Karl G. Jansky Very Large Array (VLA), we study the morphology of the source and investigate the plasma age distribution in the lobes by constraining the integrated spectrum between 2 and 8 GHz. We present new spectral index and spectral age maps at sub-arcsec resolution as well as high-dynamic range continuum images at 3 and 6 GHz with resolution of $0.75''$ and $0.35''$, respectively. Based on these detailed age maps, we examine the different substructures in the lobes and investigate the potential implications for the dynamics of the gas in the two radio lobes of Cygnus A. The spectral modeling used to derive the age maps also allows us to identify regions in the lobes which show signatures of significant electron population mixing. The derived synchrotron ages range up to 3.2 Myr, implying that the observed radio emission in the lobes is recent compared to the age of the cocoon shock inferred from X-ray observations. Our spectral maps for the first time highlight the path of the radio jet throughout the eastern lobe. By comparing the observed X-ray and radio structures, we show that the radio morphology of the jet is seen to anti-correlate with the X-ray jet structure in both the E and W lobes. We argue that the outer relic X-ray jet in both lobes is situated between the observed outgoing radio jet and the backflow from the hotspot regions. Our analysis suggests that the young radio plasma preferentially avoids the regions where the relic X-ray jet structures are seen.