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The Role of Active Galactic Nuclei Feedback in Shaping the Dynamics of Galaxy Cluster Centers

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Abstract:

The role of Active Galactic Nuclei (AGN) feedback in shaping the dynamics of galaxy cluster centers has emerged as a pivotal research area in contemporary astrophysics. Recent observations, particularly those revealing cavities in the intracluster medium (ICM), have underscored the significance of feedback mechanisms driven by supermassive black holes (SMBHs) located at the centers of galaxies. This feedback is now recognized as a key factor in accurately modeling the evolution of both galactic and extragalactic systems. The current era of X-ray astronomy, marked by missions such as Chandra and XMM-Newton, has revolutionized our understanding of "cool-core" (CC) galaxy clusters and groups. Rather than the traditional view, which emphasized the cooling of hot gas and its subsequent inflow toward the cluster center, a more nuanced picture has emerged. This new paradigm illustrates a complex dynamical interplay within the ICM, where AGN activity induces heating that counteracts cooling processes, maintaining a delicate balance. In this study, we specifically investigate AGN feedback processes occurring in the centers of galaxy clusters. We analyze how AGN feedback leads to the formation of periodic jets and examine their impact on the surrounding ICM. By correlating the duty cycle of episodic jet activity with the cooling time (CT) of the central ICM, we aim to determine whether the central AGN is engaged in a feedback loop with the ICM, thereby influencing its thermal and dynamical state. Additionally, we explore the critical differences between galaxy clusters and groups within the framework of ICM cooling and AGN feedback. Our hypothesis suggests that a larger fraction of gas contributes to star formation in galaxy groups compared to clusters, where a significant portion of the gas is thought to be funneled into the central AGN. By examining these distinctions, we seek to clarify the mechanisms governing star formation and AGN activity in different environments. Ultimately, this research aims to elucidate the intricate role of AGN feedback in shaping the dynamics of galaxy cluster centers, enhancing our understanding of its broader implications for galaxy formation and evolution across various cosmic structures. Through this investigation, we hope to provide valuable insights into the complex interplay between AGN feedback, ICM cooling, and star formation processes, thereby contributing to a more comprehensive understanding of galaxy evolution in the universe.

Keywords: Active Galactic Nuclei (AGN), Feedback Mechanisms, Intracluster Medium (ICM),Galaxy Clusters, Cooling Flows, Star Formation

1. Introduction

In view of observational evidence and theoretical models, the primary source of feedback has been identified as the outflowing material and energy injection, likely occurring intermittently, from the active galactic nucleus (AGN) of dominant cD galaxies, which host the most massive black holes in the local

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Universe. AGNs manifest as central radio sources, which are commonly observed in cool-core clusters. Most cool-core clusters exhibit highly disturbed X-ray morphologies. Cavities observed in X-ray data, along with sharp discontinuities interpreted as shocks, indicate a connection between the intracluster medium (ICM) and the AGN. The frequency and diversity of cavities detected in both radio and X-ray observations of the hot ICM provide direct evidence of widespread AGN-driven events. AGN feedback encompasses a wide range of phenomena, influencing everything from galaxy evolution and star formation to explaining the observed correlation between the supermassive black hole (SMBH) at the galaxy's center and the bulge's velocity dispersion. This correlation suggests a feedback mechanism between the central SMBH and the surrounding bulge, regulating cool-core clusters and accounting for the suppressed but ongoing star formation and gas cooling. However, the exact details of how the feedback cycle operates remain uncertain. Feedback is also essential for preventing the overproduction of massive galaxies, which is otherwise predicted by dark matter-only galaxy simulations. Thus, understanding the true nature of AGN feedback is crucial for developing a comprehensive model of galaxy formation.

2.Types of AGN Mechanisms

2.1. Radiative Mode

The quasar mode, also called the wind mode or radiative mode, operates when the AGN luminosity is high, near the Eddington limit (which is the maximum luminosity a quasi-stellar object (QSO) can achieve when the outward radiative pressure is balanced by the inward gravitational force). This mode is mostly observed in young QSOs at high redshift ($z \sim 2$-3). Due to radiation pressure exerted on the surrounding ionized gas, the accretion core reaches its limit for gas accretion and begins to expel gas in the form of winds.

2.2. Kinetic Mode

The kinetic mode, also known as the maintenance mode or radio mode, operates when a galaxy has a hot halo or is located at the center of a galaxy group or cluster. In this mode, the accreting black hole produces powerful jets. If AGN feedback ejects and depletes a galaxy of gas, the galaxy can be replenished either by accreting gas from its surroundings (if isolated) or by drawing in intracluster gas (plasma) in a cluster or group environment. The primary role of kinetic mode is to maintain the cavity by either keeping it empty or preventing gas cooling through heating. This mode provides some of the clearest observable examples of AGN feedback, particularly through the detection of bubbles in the centers of galaxy clusters.

The brightest galaxies at the cores of clusters are often surrounded by gas with a short cooling time, which suggests that a cooling wind should be occurring [1]. Some important gas properties of a small sample of objects are shown in Fig. 2.2.1, ranging from the low-mass cluster A262 to the high-luminosity cluster A1835. Each cluster exhibits a significant spatial temperature drop within a 120 kpc radius, and all show a radiative cooling time falling below 110 Gyr within 12 kpc. An approximate mass cooling rate, assuming the absence of a radio source, can be determined by calculating the gas mass within this radius per unit cooling time.

Several stages of this feedback process are observable in X-ray and radio surveys. In some cases, accretion around the SMBH generates ultrafast relativistic jets, which inflate bubbles of relativistic plasma on either side of the galactic core, similar to a balloon. These bubbles are buoyant in the intracluster medium (ICM), detaching and rising as new bubbles form. The deepest bubbles are typically circular and, in the best-studied case (Perseus cluster), are surrounded by a dense, high-pressure region. As they rise through the hot gas, they gradually transform into pseudo-bubbles and eventually become undetectable in high-frequency radio observations.

There are far fewer observed outer bubbles, but they can appear at large radii and tend to be larger than expected (Fig. 2.2.2). This discrepancy could be due to their rise speed being dependent on their size—for example, larger bubbles may rise more slowly while smaller bubbles move faster, allowing them to catch up, or vice versa [2].

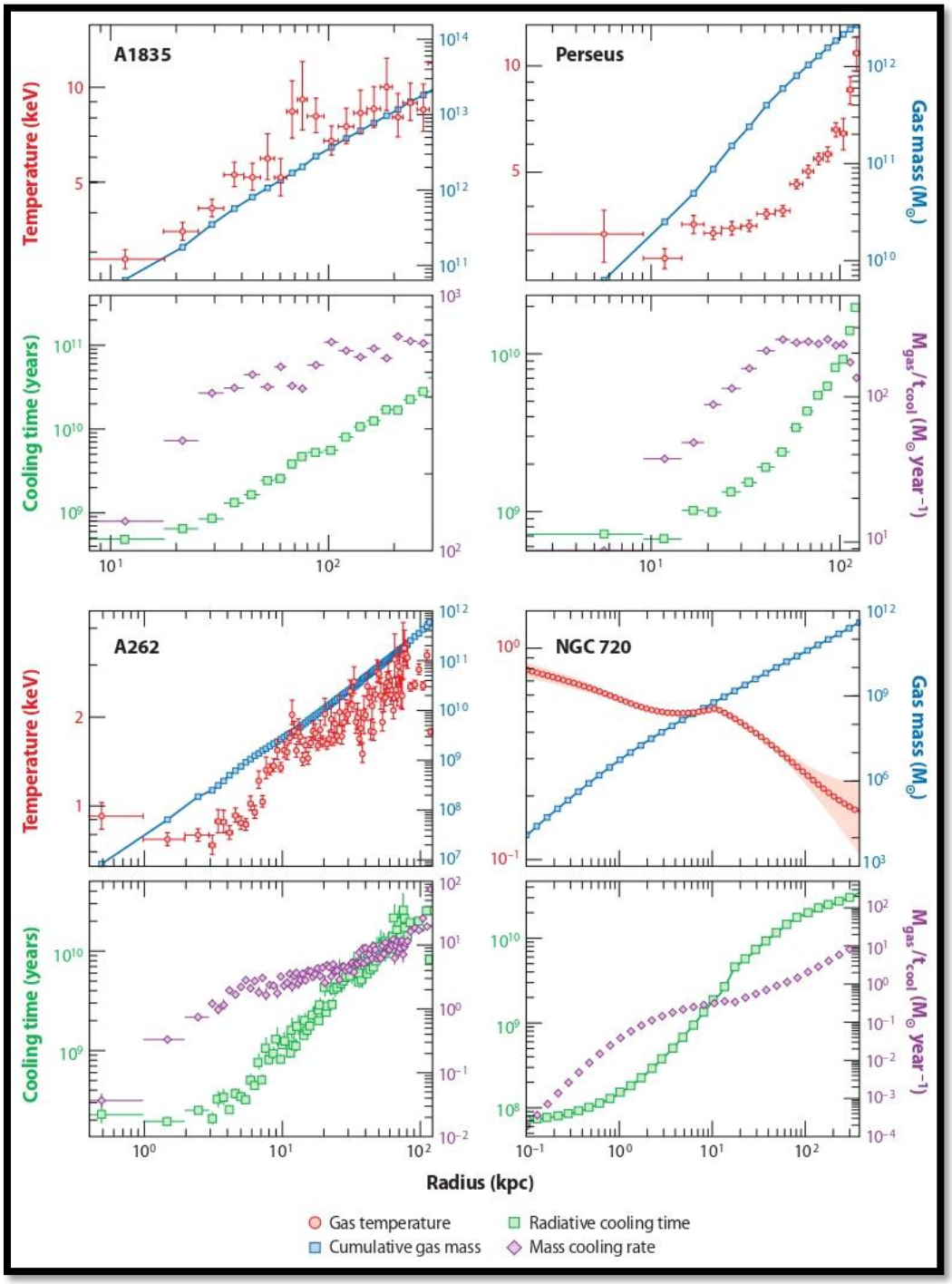

Fig 2.2.1: Properties of gas for Abell 426, Abell 1835 (A1835), Abell 262 (A262), and Milky Way mass elliptical galaxy NGC 720.

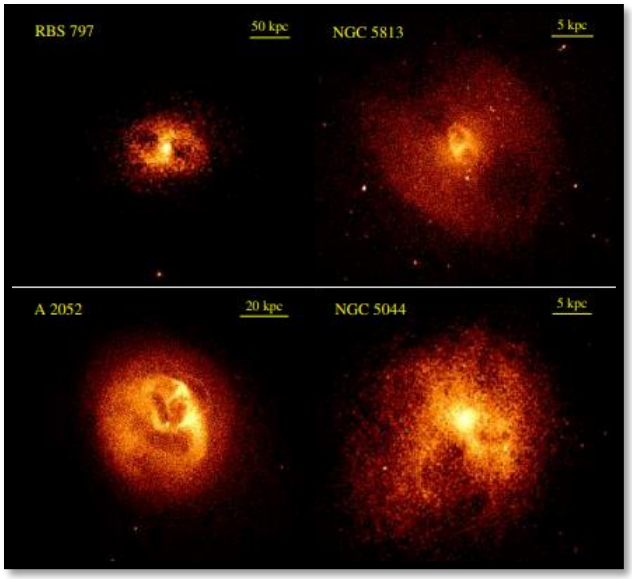

Fig 2.2.2: Chandra X-ray photos showing the dramatic interaction of the central AGN on the neighbouring gas.

3. M-Singma ($\mathbf{M_{BH} - \sigma}$) Relation

[3] brought up that a quasar at near Eddington limit can forestall accretion into supermassive BH at the most extreme conceivable rate gave that,

$$M_{BH} \sim \frac{f\sigma^5\sigma_T}{4\pi G^2 m_p c} \quad (1)$$

where σ_T is Thomson cross-section for scattering of electron

f is the mass of the gas inside the galaxy (fractional)

The Eddington luminosity is given by,

$$L_{Ed} = \frac{4\pi G M_{BH} m_p c}{\sigma_T} \quad (2)$$

Assume, that the electromagnetic radiation-pressure from the Eddington-limited quasar $\frac{L_{Ed}}{c}$ has eject the gas, of mass $M_{gas} = fM_{gal}$, to the outskirts of the galaxy.

Balancing the radiational outward force with the inward one due to gravity gives

$$\frac{4\pi G M_{BH} m_p}{\sigma_T} = \frac{L_{Ed}}{c} \quad (3)$$

$$\frac{L_{Ed}}{c} = \frac{GM_{gal}M_{gas}}{r^2} = \frac{fGM_{gal}^2}{r^2} = \frac{fG}{r^2}\left(\frac{2\sigma^2 r}{G}\right)^2 \quad (4)$$

$$i.e. \quad \frac{4\pi G M_{BH} m_p}{\sigma_T} = \frac{f4\sigma^4}{G} \quad (5)$$

The independence of radius in the formula implies that it applies within that galaxy. The understanding that this straightforward equation gives with the noticed $M_{BH} - \sigma$ connection can be deciphered as observational proof for AGN feedback.

4. AGN Feeback and Galaxy Evolution

One of the primary issues in orthodox cosmological model is the reason not many baryons have turned into stars. Mathematical simulations of cosmological construction development that incorporate the baryonic dynamics and the cooling (radiative) measures foresee that 20% of the baryons must have consolidated into galaxies, only 10% have been seen as stars. Specifically, productions that incorporate just gravitational warming foresee an extreme baryonic cooling that outcomes in a populace of galaxies which are excessively huge and excessively splendid regarding the ones noticed. Rather than dwelling in cD galaxies as anticipated by observations, most baryons are detected in ICM of clusters and groups. This issue may discover an answer in the nongravitational warming provided by supernovae and active galactic cores (AGN). Heating through AGN seems, by all accounts, to be the most probable instrument to actually diminish the reservoir of gas from ICM in big galaxies and to explain the noticed entropy profiles. AGNs are controlled by gradual addition of material onto a black hole via accretion, which is situated at the core of each elliptical galaxy bulge. Matter accreting onto a BH deliveries an energy of the request for $E_{BH} = \epsilon Mc^2$, where $\epsilon \approx 0.1$ is efficiency of turning into energy. Now, for SMBHs of masses $\sim 10^9 M_{\odot}$, the measure of energy delivered during their formation is in the order of magnitude of $E_{BH} \sim 2 \times 10^{62}\, erg\, s^{-1}$[4]. One important fact to notice is that even a little portion (1%) of the energy provided into the bulge region could heat and spurt away its whole gas reservoirs in small fractions and hinder cooling, in this way explaining the absence of formation of star near the galactic core. An extraordinary revelation acquired as of late in astronomy is the relationship between velocity dispersion (σ) of the galaxy's bulge and black hole mass at the core (Supermassive MBH) used to approximate the mass of the actual bulge. This MBH - σ expression proposes that properties of the galaxy (large – scale) and the properties of the black holes (small – scale) are connected. Specifically, each huge galaxy appears to have a black hole at the nucleus, with mass $\sim 0.2 - 0.4\%$ of the bulge mass. Such a relationship may also be seen from the way that the central BH can manage the measure of gas accessible for formation of stars in the galaxy. Thus, bulge formation and the formation of black holes are firmly connected. Consequently, supermassive black holes can impact the galactic evolution. The actual cycle managing these mechanisms has been designated "feedback," and the comprehension of its detailed mechanism is one of the fundamental open issues in extragalactic astronomy.

5. Positive and Negative Feedback

Huge and fast outflows are practically pervasive in cluster center radio sources (CCRS). These outflows are recognized at various scales, from parsec-scale ultrafast $(0.1\, times\, the\, speed\, of\, light)$ outflows distinguished in X-rays to kiloparsec-scale outflows identified in ionized gas with speeds up to $\sim 1{,}000\, km\, s^{-1}$ and in various gas phases. Some few models hypotheses that these gigantic and quick outflows can stifle star arrangement in the host galaxy, by eliminating and warming the interstellar medium (ICM). But, any case, from the observational perspective, it has not yet been obviously surveyed if and how the presence of spatially uncertain outflows compares with the rate of formation of stars in the host galaxies. Furthermore, theorists have indeed proposed that there is no factual connection between the two. On the contrary, with the introduction of near infrared IFU (vital field unit) spectrographs data of redshift $z \approx 2 - 3$ quasars have uncovered a anti-correlation between the region of the fast outflowing gas and the star formation in the host galaxy. Furthermore, an important observation from these objects tells that, the outflow seems to influence the gas repositories just along its way, while star formation remains high throughout, with star-formation rates (SFRs) as high as $120\, M_{\odot}\, yr^{-1}$. However, few of direct observations of feedbacks has been tracked down and the accessible information propose that a lot of gas is drawn along in AGN-driven outflows (Fig 5.1.). Nonetheless, just a small part of the outflowing gas may drift from the source, while a large division may flow back onto the galaxy at later occasions. Besides, in any event,

for the couple of sources showing proof of feedback, the general effect doesn't appear to bring about a full shut-down of star formation [5].

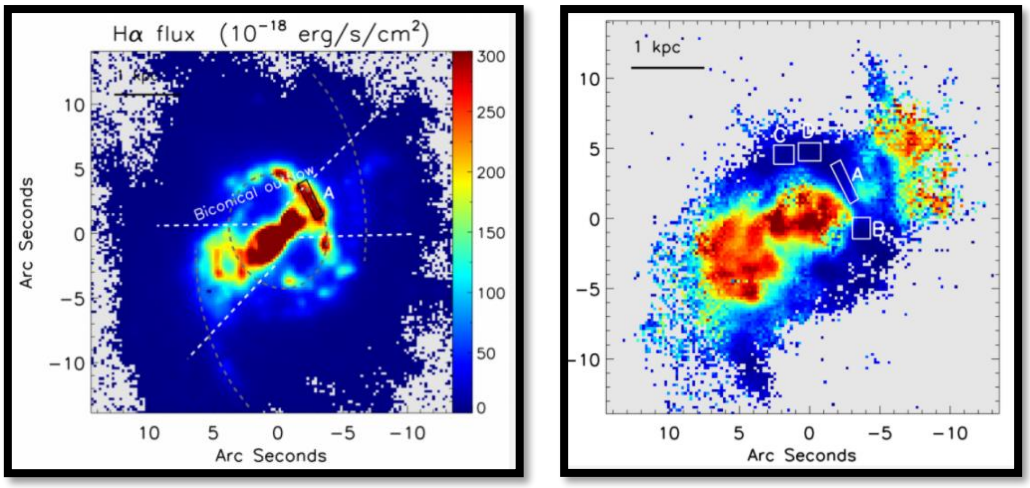

Fig 5.1: (a) NGC 5728 emission map in H_{α}, the color depicts the amount of flux in a given pixel. The position of spiral arms and ring of star formation are shown with grey-dashed lines, while a outflow (biconical) is shown in white-dashed lines. (b) Emission fraction in each pixel from AGN contributions.

An additional interesting part of fast outflows is that they can likewise facilitate in formation of stars, both in the galactic plane through radiative compression or on the other hand straightforwardly in the outflowing gas. These 'positive feedback' models have been proposed by a few theorists to explain noticed connections between AGN luminosity and nuclear star rate of formation, plus in bulge formation near the center. Recent observations show that, formation of stars in outflows might be normal in galaxies, conceivably adding to the morphological advancement of galaxies just as to the advancement in size also, i.e., velocity dispersion in spheroidal parts. The effect of the AGNs feedbacks on their host galaxies is still to be observed properly. Notwithstanding, with aggregating proof supporting a delayed instead of ejective part in hindering star formation, the discernment among experts likewise seems to agree.

6. AGN Downsizing

The most luminous and enormous AGN were generally various at redshifts of $\sim 2-3$, less-luminous crested at progressively lower redshifts with the most un-luminous topping near redshift ~ 1. Scaling back of AGN was first found in X-ray observations and was again affirmed in optical and different bands, in which the core stands apart unmistakably over the encompassing galaxy objects. This finding is something contrary to what is essentially anticipated in a progressive *cold dark matter universe* which proposes the clusters of galaxies (most massive objects) are formed at last. It demonstrates that something is quenching the quasars behavior and the most broadly acknowledged answer is that it is because of AGN feedback [6]. Some models suggest huge galaxies converge to create an SMBH encompassed by thick gas and the gas take care of both active core (through accretion) and formation of stars (cooling) The force of AGN drifts the gas away leaving a dead redshifted galaxy. Investigations of the shades of galaxies show that galaxies proceed onward a shading size outline from the blue haze of galaxies forming stars to the red haze of dead ones.

7. Heating/Cooling Balance (Maintenance Mode Feedback)

Let us now study about how close the apparent heating/cooling balance is established and maintained. The absence of high star formation rates projects that cooling doesn't exceed warming by 20% or thereabouts. The presence of focal plenitude inclinations and articulated temperature drops shows that warming doesn't for the most part exceed cooling by much by the same token. This addresses a generally close equilibrium which needs to proceed more than twenty to many bubbling cycles.

A straightforward one-dimensional feedback cycle appears to be from the outset sight conceivable. When an excessive amount of gas begins cooling, the accumulation rate should build making the warming rate go up and the other way around. The length scales included reach above a factor of at least $\sim 10\text{^}9$ and timescales included over the entire cooling stream locale are long, up to and past a Gyr, and down to a Myr at the accretion range. This implies that feedback would be deferred or possibly that there could be hysteresis.

But angular momentum could prevent mass from accreting close to SMBH. Here, Bondi acceleration could be a helpful tool since it depends on a point mass implanted in a static medium. The gas accumulating onto the focal black opening goes at any rate through around $5\ significant\ degrees\ in\ range$ from where the gravitational field of the focal mass starts to rule gas movements, for example the Bondi range, to the middle. The actual stream starts farther. It is improbable that precise energy can be disregarded. One methodology is to expect that the accretion to be viscous as far as possible so angular momentum is effectively moved outward at all radii. The entire close region of radii of $100\ kpc$, from after the Bondi range to the deepest region where the stream gets supersonic, could look like an Advection Dominated Growth Flow (ADAF) as proposed paper [7]. This does at any rate take into consideration simple section of the gas without it getting stifled by angular momentum.

8. ICM Cooling and AGN Feedback (AND BCG Properties) Of Galaxy Groups

Now, I intend to research on cool-core and non-cool-core effects of galaxy groups and clusters through publicly available X-ray survey data and contrast them with the AGN radio yield to comprehend the relation of ICM cooling and feedback (by supermassive black holes). We likewise plan to research the Biggest cluster galaxies (BCGs) to perceive if they are influenced by cooling and warming cycles, and contrast the properties of groups with clusters. By using data from *Chandra* of sample of $25\ galaxy\ groups$, I obliged the central-cooling times (CCTs) of the ICM and characterized the groups as non-cool core (NCC), weak cool core (WCC) and strong cool center (SCC) according to their CCTs. The complete radio luminosity of the BCG was observed by utilizing information from radio catalogue which thus was contrasted with the CT (cooling time) of the ICM to comprehend the connection between gas cooling and feedback. The revelation that CT of the ICM in the core of numerous clusters, the alleged cool-center clusters, is more limited than the Hubble time which is defined as the reciprocal of the Hubble constant, $1/H_0$, prompted the revisions of the cooling model. In this model, as gas cools hydrostatically, it is compacted by the hot, overlying gas, creating a cooling stream. After early signs from ASCA, the information from the reflection grating spectrometer (RGS) instrument on *XMM-Newton* have shown that the actual mass deposition rates miss the mark concerning the forecasts by a significant degree. This information showed that insufficient cool gas was available in the cool-center clusters. Further, UV and Optical surveys uncovered a similar degree of incompatibility between the anticipated and noticed star formation rates.

The ancient cooling model doesn't consider any radiative component notwithstanding radiative cooling of the intracluster gas. Lately, a few models consolidating warming systems have been explored, for example, warming by active galactic cores (AGN), supernovae and thermal conduction. Especially, self-controlled AGN feedback has acquired courtesy lately. Excellent relationships between X-ray bubble areas in the ICM, for example cavities and radio projections, have given trustworthiness to this theory. Attempting to comprehend the connection between gas cooling in the ICM and AGN feedback effects on galaxy groups is key in our comprehension of the exact contrasts among clusters and groups. Galaxy groups, being frameworks not as huge as clusters, have for some time been viewed as downsized variants of clusters. The meaning of a group and cluster is extremely vague and a general guideline definition is to assign frameworks containing under 50 galaxies as a gathering or more 50 as a cluster, and recently there has been some idea that gatherings can't be basically treated as downsized forms of clusters. For example, in clusters the ICM for the majority part overwhelms the baryonic content, while for groups the united mass of the part galaxies may exceed the baryonic mass in the intracluster medium. Moreover, the primary cooling instrument in groups (line emission) varies from that in clusters (thermal bremsstrahlung). On a basic level, feedback from an AGN would have a more prominent effect on the groups due to the fact of the smaller gravitational potential.

The brightest cluster galaxies (BCGs) have a unique part in the previously mentioned mechanism. These are exceptionally luminous galaxies, (cD type), and are by and large found very near the X-ray peak (less than $50h^{-1}kpc$ in 90% of the cases). Galactic properties, similar to the bulge luminosity and velocity dispersion, have very much characterized scaling relations, permitting one to in a roundabout way to measure the mass of the SMBH, which could be contrasted with the AGN action. Brightest cluster galaxies likewise help in contemplating the work of cooling gas in formation of stars where the gas cooling produce new stars.

9. Data Analysis

9.1. Radio Data Analysis - Our Work with Publicly Available Data:

All the radio information needed for this work was either aggregated from existing radio indexes or writing **(Table 9.1.1)**. I got information at a few frequencies between 10 MHz and 15 GHz. The significant lists utilized for this speculation were the *SUMSS (843 MHz), NVSS (1.4 GHz) and VLSS (74 MHz)* lists.

Since this investigation includes radio sources related with BCGs at the focal point of dark matter halo, it is basic to set a basis for whether a gathering has a central radio source. Exceptional work done by [8,9] suggest that a radio source should be situated inside $50\ h^{-1}\ kpc$ of the peak of X-ray so that it can be sorted as a CRS (Central radio source). For CRSs with extended emission, I examined the radio emission from the lobes too, since we will likely get a relationship between the complete radio emission from the central AGN and CCT. Radio emission from AGN is described by the synchrotron radiation expressed as a force law connection given by

$$S_\nu \propto \nu^{-\alpha}, \qquad (6)$$

Here, S_ν is the flux density at the frequency ν and $\alpha$is the spectral index.

A major part of the synchrotron emission is from the low frequencies

$(< 1.4\,GHz)$, making it profoundly essential to get information on these recurrence scales. In addition, a complete radio spectral energy emission is beneficial since that allows spectral breaks. Self-absorption is

described by a negative spectral index, especially at lower frequencies. The incorporated radio luminosity between a couple of frequencies $\nu_i \; and \; \nu_{i+1}$ is given by,

$$L_{i+1} = 4\pi D_L^2 \frac{S_0 \nu_o^{\alpha_{i+1,i}}}{1-\alpha_{i+1,i}} \left(\nu_{i+1}^{1-\alpha_{i+1,i}} - \nu_i^{1-\alpha_{i+1,i}} \right) \quad (7)$$

Here, S_0 is flux density at frequency $\nu_{i+1,i}$ or ν_i ,

$\alpha_{i+1,i}$ is the spectral index among the two frequencies

D_L is the luminosity distance.

Table 9.1.1: Radio data for central radio source

Cluster	ν (GHz)	Flux density (mJy)	$L_{1.4\mathrm{GHz}}(10^{32}$ erg/s/Hz)	$L_{\mathrm{tot}}10^{42}$ (erg/s)	SI of 1
A0160	1.4[†] 0.408[a]	1042.8±35.7 1660±60	$0.44847^{+0.0154}_{-0.0153}$	$0.4676^{+0.0147}_{-0.0276}$	
HCG62	1.4[†]	4.9±0.5	$0.000195^{+0.00002}_{-0.00002}$	$0.000205^{+0.00002}_{-0.000021}$	YES
IC1262	1.4[†]	87.6±6.3	$0.021156^{+0.001521}_{-0.005625}$	$0.0215^{+0.0015}_{-0.0016}$	YES
IC1633	1.4[b]	1.59±0.039	$0.00015891^{+0.000005}_{-0.000005}$	$0.00017142^{+0.000005}_{-0.000005}$	YES
MKW4	1.4[c] 4.86[c]	2.40±0.5 0.35±0.1	$0.00213^{+0.000045}_{-0.000045}$	$0.000815^{+0.003810}_{-0.000767}$	
MKW8	1.4[†] 4.86[c]	2.54±0.1 2.09±0.15	$0.000402^{+0.000025}_{-0.000025}$	$0.000504^{+0.000088}_{-0.000031}$	
NGC 326	1.4[†] 0.174[♣] 0.074[‡]	1802±59 5100±510 12320±1440	$0.85239^{+0.0279}_{-0.0279}$	$0.880^{+0.095}_{-0.101}$	
NGC 507	1.4[†] 0.074[‡]	120.5±6.0 3250.0±490.0	$0.007150^{+0.000354}_{-0.000354}$	$0.008970^{+0.001430}_{-0.002890}$	
NGC 533	1.4[†]	28.6±1.0	$0.00183^{+0.00006}_{-0.00006}$	$0.00194^{+0.000069}_{-0.000066}$	YES
NGC 777	1.4[†]	7.0±0.5	$0.000413^{+0.000029}_{-0.000029}$	$0.000437^{+0.000031}_{-0.000031}$	YES
NGC 1132	1.4[†]	5.4±0.6	$0.000667^{+0.00007}_{0.00007}$	$0.000717^{+0.00008}_{0.00008}$	YES
NGC 1550	1.4[†] 2.38[d] 0.074[‡]	16.6±1.6 8.0±3.0 670.0±177.0	$0.000547^{+0.000053}_{-0.000053}$	$0.00089^{+0.00015}_{-0.00004}$	
NGC 4936	1.4[†] 0.843[♣]	39.8±1.6 35.2±1.9	$0.00117^{+0.00005}_{-0.00005}$	$0.00048^{+0.00001}_{-0.00002}$	
NGC 5129	1.4[†]	7.2±0.5	$0.00082^{+0.00006}_{-0.00006}$	$0.00088^{+0.00006}_{-0.00006}$	YES
NGC 5419	1.4[†] 0.843[♣] 0.074[‡]	349.2±12.2 529.3±16 1580±240	$0.01536^{+0.00064}_{-0.00064}$	$0.01162^{+0.00097}_{-0.00114}$	
NGC 6269	1.4[†] 0.074[‡]	50±1.9 560±100	$0.012532^{+0.00048}_{-0.00048}$	$0.01166^{+0.00079}_{-0.00104}$	
NGC 6338	1.4[†]	57±1.8	$0.0095806^{+0.00030}_{-0.00030}$	$0.01034^{+0.00033}_{-0.00033}$	YES
RXCJ2214	1.4[†]	1604.7±50.7	$0.24691^{+0.00780}_{-0.00780}$	$0.2530^{+0.0051}_{-0.0051}$	YES
S0463	0.843[♣]	314±9.6	-	$0.0687^{+0.0003}_{-0.0003}$	YES
SS2B	1.4[†]	31.9±1.4	$0.00160^{+0.00009}_{-0.00009}$	$0.00169^{+0.00010}_{-0.00010}$	YES

To ascertain the aggregate radio luminosity between 15 MHz and 20 GHz, the spectral index at the most minimal noticed recurrence was extrapolated to 15 MHz, and the unearthly index at the most noteworthy noticed recurrence was extrapolated to 20 GHz. The incorporated radio luminosity was then determined as $L_{tot} = \Sigma L_{i+1}$. In the instance of inaccessibility of multi-recurrence information, we expected an index of 1 all through the energy range. This must be achieved for 11 CRSs in the example [10].

9.2. Brightest Galaxy Cluster (BCG) Data Analysis - Our Work with Publicly Available Data:

For the analysis of BCG, we followed a similar procedure as explained by Mittal (2009). The BCG Near infrared (NIR) K-band magnitude are taken from the 2MASS Extended Source Inventory, for example the *XSC*. Redshifts were gotten from the *NASA/IPAC Extragalactic Database (NED)*. The sizes were remedied for Galactic extinction utilizing maps of dust [11]. The extents were at that point changed over to luminosity under the Vega framework, accepting an outright K-band Vega powered size equivalent to $3.32\,mag$. Studies like Marconi [12] and [13] have set up all around characterized scaling relations between galaxies' NIR bulge luminosity also, the SMBH mass, predictable with results acquired from velocity dispersion [14]. We utilize the scaling connection from Marconi and Hunt (2003) to get the SMBH mass,

$$\log_{10}\left(\frac{M_{BH}}{M_{\odot}}\right) = a + b\left[\log_{10}\left(\frac{L_{BCG}}{L_{\odot}}\right) - 10.9\right] \quad (8)$$

Here, $a = 8.21 \pm 0.05$ and $b = 1.13 \pm 0.15$

The inferred SMBH mass was contrasted with the incorporated radio luminosity. The BCG glows were contrasted with the worldwide cluster properties, similar to the complete X-ray luminosity LX and mass M500.

10. Results

10.1. Cool Core and Non-Cool Core Fraction - Our Work with Publicly Available Data

Hudson et al. (2010) investigated 17 variables utilizing Kaye's Mixture Mode (KMM) algorithm as portrayed [15], where the CCT showed a solid trimodal circulation. Accordingly, the creators isolated the clusters into three classes: strong cool core (SCC) clusters with CCTs under $1\,Gyr$, weak cool core (WCC) clusters with CCTs between $1\,Gyr\ and\ 7.7\,Gyr$, and non cool core (NCC) clusters with CCT above $7.7\,Gyr$. Utilizing a similar characterization framework, we present our example named SCC, WCC, what's more, NCC bunches in Table 10.1.1. A histogram is plotted between core cooling time and fraction (Fig 10.1.2). The calculated the NCC fraction is 23%, WCC fraction is 27% and SCC fraction is 50% (Fig 10.1.1).

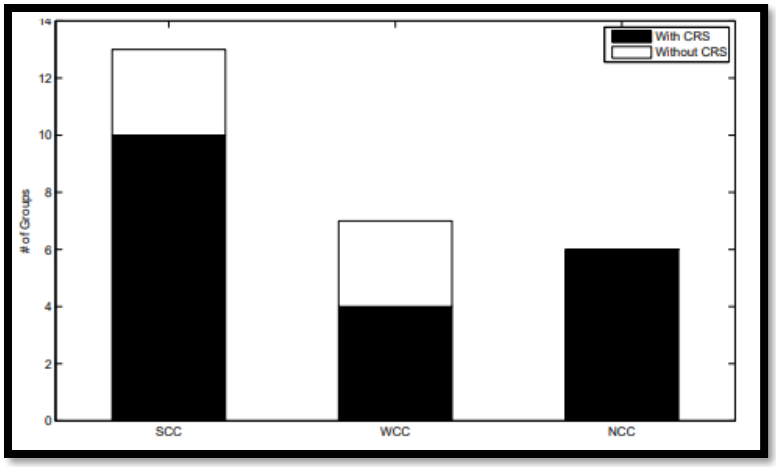

Fig. 10.1.1: NCC, WCC, and SCC groups in fraction. Shaded regions depicts groups with CRS

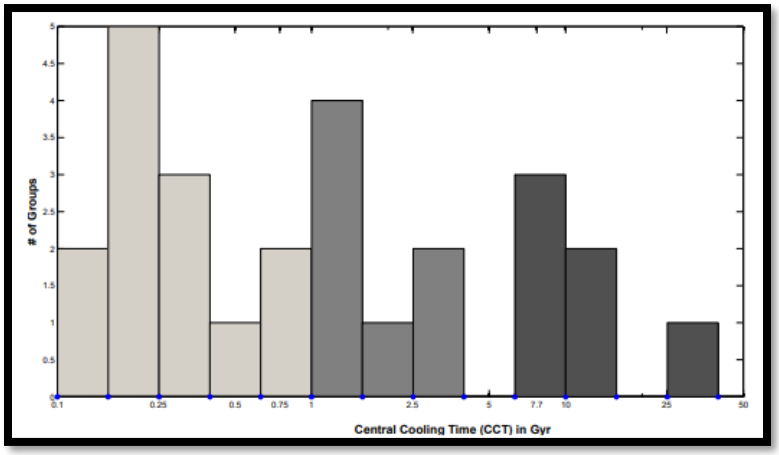

Fig. 10.1.2: Histogram of CCT (central cooling time). Increasing cooling time is shown by the increasing tones of grey. Dark grey shows NCC groups, light grey shows SCC groups and medium grey shows WCC groups

10.2. Central Cooling Time Vs. Total Radio Luminosity - Our Work with Publicly Available Data:

Mittal et al. (2009) paper proposes that there is an anti-correlation pattern between the CCTs and the complete radio luminosity for cool core clusters, what breaks down for cooling times more limited than $1\,Gyr$. Here, we show the best fit acquired for the CC clusters from Mittal (2009) to feature the contrast among clusters and groups. The force law fit for the CC clusters from Mittal et al. (2009) is given by:

$$L_{tot} = (0.041 \pm 0.015) \times (t_{cool})^{-3.16\pm0.38} \quad (9)$$

It is fascinating to take note of that all strong cool-core groups and the vast majority of the weak cool-core groups show a fairly lower radio yield than which fits best for clusters. This was first insinuated in Mittal

(2009), where the groups in that example (all SCC) were clear exceptions and we affirm this interestingly with a large example of gatherings (Fig. 10.2.1).

Group name	EP (RA/DEC)	n_0 (10^{-2} cm^{-3})	T_0 keV	CCT (in Gyr)	K_0 (keVcm^2)	CC type	CRS?
A0160	01 : 12 : 59.67 +15 : 29 : 29.11	$0.380^{+0.068}_{-0.068}$	$2.38^{+0.218}_{-0.218}$	$8.04^{+1.26}_{-1.83}$	$97.7^{+10.1}_{-13.7}$	NCC	YES
A1177	11 : 09 : 44.38 +21 : 45 : 32.81	$0.600^{+0.130}_{-0.130}$	$1.63^{+0.08}_{-0.08}$	$3.77^{+0.67}_{-1.04}$	$49.4^{+6.05}_{-8.73}$	WCC	NO
ESO55	04 : 54 : 52.31 −18 : 06 : 54.29	$0.760^{+0.14}_{-0.14}$	$1.88^{0.13}_{-0.13}$	$2.70^{+0.40}_{-0.57}$	$48.6^{+5.18}_{-7.07}$	WCC	NO
HCG62	12 : 53 : 06.00 −09 : 12 : 11.57	$3.80^{+1.23}_{-1.23}$	$0.813^{+0.008}_{-0.008}$	$0.214^{+0.0523}_{-0.1023}$	$7.19^{+1.23}_{-2.14}$	SCC	YES
HCG97	23 : 47 : 23.03 −02 : 18 : 00.49	$1.44^{+0.19}_{-0.19}$	$0.992^{+0.015}_{-0.015}$	$0.977^{+0.114}_{-0.149}$	$16.8^{+1.33}_{-1.66}$	SCC	NO
IC1262	17 : 33 : 03.07 +43 : 45 : 34.88	$4.12^{+0.13}_{-0.13}$	$1.63^{+0.03}_{-0.03}$	$0.504^{+0.015}_{-0.016}$	$13.7^{+0.280}_{-0.295}$	SCC	YES
IC1633	01 : 09 : 56.07 −45 : 55 : 52.28	$0.38^{+0.0883}_{-0.0883}$	$2.82^{+0.13}_{-0.13}$	$8.20^{+1.54}_{-2.48}$	$115^{+15.1}_{-22.3}$	NCC	YES
MKW4	12 : 04 : 27.14 +01 : 53 : 45.18	$3.91^{+0.34}_{-0.34}$	$1.57^{+0.02}_{-0.02}$	$0.258^{+0.0207}_{-0.0246}$	$13.6^{+0.737}_{-0.852}$	SCC	YES
MKW8	14 : 40 : 42.99 +03 : 27 : 56.98	$0.34^{+0.0453}_{-0.0453}$	$3.69^{+0.18}_{-0.18}$	$10.1^{+1.19}_{-1.56}$	$163^{+13.0}_{-16.3}$	NCC	YES
NGC326	00 : 58 : 22.82 +26 : 51 : 51.26	$0.34^{+0.079}_{-0.079}$	$1.87^{+0.09}_{-0.09}$	$7.77^{+1.46}_{-2.35}$	$82.7^{+10.8}_{-15.9}$	NCC	YES
NGC507	01 : 23 : 39.93 +33 : 15 : 21.98	$1.09^{+0.13}_{-0.13}$	$1.22^{+0.02}_{-0.02}$	$1.22^{+0.13}_{-0.16}$	$24.8^{+1.79}_{-2.19}$	WCC	YES
NGC533	01 : 25 : 31.45 +01 : 45 : 32.69	$4.67^{+0.68}_{-0.68}$	$0.889^{+0.011}_{-0.011}$	$0.191^{+0.0244}_{-0.0327}$	$6.85^{+0.59}_{-0.758}$	SCC	YES
NGC777	02 : 00 : 14.94 +31 : 25 : 46.28	$4.99^{+1.17}_{-1.17}$	$1.21^{+0.05}_{-0.05}$	$0.167^{+0.0318}_{-0.0513}$	$8.92^{+1.17}_{-1.74}$	SCC	YES
NGC1132	02 : 52 : 51.81 −01 : 16 : 28.85	$1.21^{+0.11}_{-0.11}$	$1.17^{+0.04}_{-0.04}$	$1.08^{+0.11}_{-0.09}$	$22.2^{+1.25}_{-1.46}$	WCC	YES
NGC1550	04 : 19 : 38.37 +02 : 24 : 38.92	$5.53^{+0.35}_{-0.35}$	$1.21^{+0.007}_{-0.007}$	$0.231^{+0.014}_{-0.016}$	$8.34^{+0.334}_{-0.371}$	SCC	YES
NGC4325	12 : 23 : 06.52 +10 : 37 : 15.52	$3.39^{+0.25}_{-0.25}$	$0.899^{+0.009}_{-0.009}$	$0.244^{+0.017}_{-0.019}$	$8.58^{+0.398}_{-0.449}$	SCC	NO
NGC4936	13 : 04 : 17.08 −30 : 31 : 35.37	$0.620^{+0.14}_{-0.14}$	$0.949^{+0.039}_{-0.039}$	$1.54^{+0.26}_{-0.45}$	$28.1^{+3.57}_{-5.23}$	WCC	YES
NGC5129	13 : 24 : 10.08 +13 : 58 : 37.06	$3.30^{+0.74}_{-0.74}$	$0.894^{+0.026}_{-0.026}$	$0.298^{+0.054}_{-0.086}$	$8.69^{+1.10}_{-1.60}$	SCC	YES
NGC5419	14 : 03 : 38.77 −33 : 58 : 41.81	$0.210^{+0.086}_{-0.086}$	$2.09^{+0.097}_{-0.097}$	$13.1^{+9.16}_{-3.81}$	$127^{+26.1}_{-53.6}$	NCC	YES
NGC6269	16 : 57 : 58.01 +27 : 51 : 15.07	$2.10^{+0.37}_{-0.37}$	$1.53^{+0.07}_{-0.07}$	$0.914^{+0.137}_{-0.197}$	$20.1^{+2.06}_{-2.77}$	SCC	YES
NGC6338	17 : 15 : 22.99 +57 : 24 : 39.06	$5.43^{+0.36}_{-0.36}$	$1.27^{+0.02}_{-0.02}$	$0.252^{+0.0157}_{-0.0179}$	$8.86^{+0.371}_{-0.414}$	SCC	YES
NGC6482	17 : 51 : 48.81 +23 : 04 : 18.19	$7.35^{+1.43}_{-1.43}$	$0.940^{+0.021}_{-0.021}$	$0.134^{+0.0218}_{-0.0323}$	$5.36^{+0.599}_{-0.831}$	SCC	NO
RXCJ1022	10 : 22 : 09.98 +38 : 31 : 22.32	$0.93^{0.17}_{-0.17}$	$1.99^{+0.07}_{-0.07}$	$2.45^{+0.38}_{-0.55}$	$45.0^{+4.76}_{-6.48}$	WCC	NO
RXCJ2214	22 : 14 : 45.95 +13 : 50 : 23.76	$1.09^{+0.23}_{-0.23}$	$1.12^{+0.05}_{-0.05}$	$1.47^{+0.39}_{-0.25}$	$22.8^{+2.73}_{-3.89}$	WCC	YES
S0463	04 : 29 : 07.54 −53 : 49 : 39.44	$0.12^{+0.0270}_{-0.0270}$	$3.50^{+0.48}_{-0.48}$	$32.6^{+5.99}_{-9.47}$	$309^{+39.2}_{-57.4}$	NCC	YES
SS2B153	10 : 50 : 26.12 −12 : 50 : 41.32	$7.5^{+1.29}_{-1.29}$	$0.997^{+0.012}_{-0.012}$	$0.103^{+0.0151}_{-0.0214}$	$5.61^{+0.563}_{-0.752}$	SCC	YES

Table 10.1.1: Tabulated data of various groups (with or without CRS)

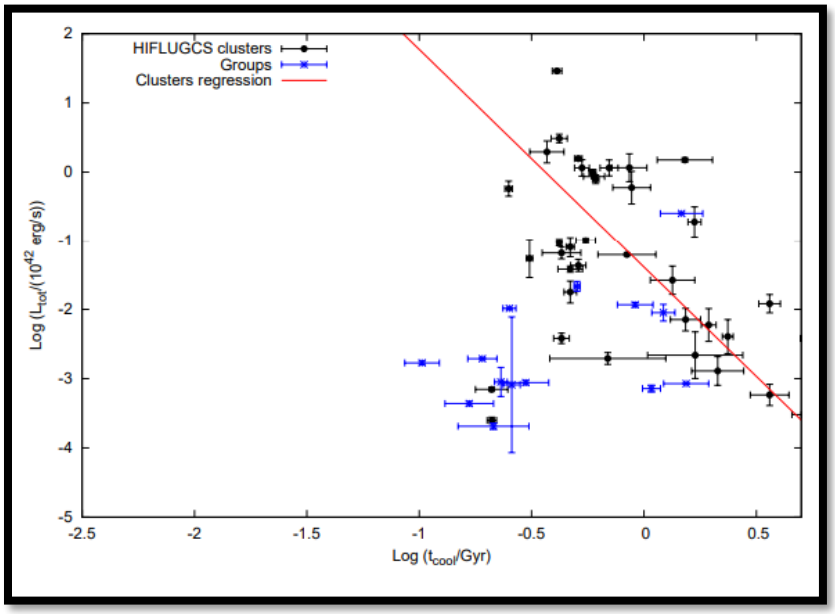

Fig. 10.2.1: CCT vs. Total radio luminosity with red best fit line for clusters from Mittal et al. (2009).

10.3. SMBH Mass Vs. Total Radio Luminosity

The Supermassive BH mass shows no relation/connection with the complete radio luminosity (Fig. 10.3.1). Using the example as WCC, SCC, and NCC additionally doesn't yield any perceivable connections. However, this is conversely with the HIFLUGCS test, which shows an ineffective connection for the SCC clusters (relationship coefficient of 0.46). I also calculate a correlation coefficient of 0.30 for all groups and a little low of 0.18 for only SCC groups. In Table 10.3.1 represent the mean Supermassive BH masses and radio luminosities for the diverse cool core sorts alongside their standard errors to examine whether distinctive CC gatherings have methodically various masses or potentially luminosity. We observe that the groups with non-cool core have a methodically higher Supermassive BH mass and a lot more radio luminosity than the WCC and SCC groups.

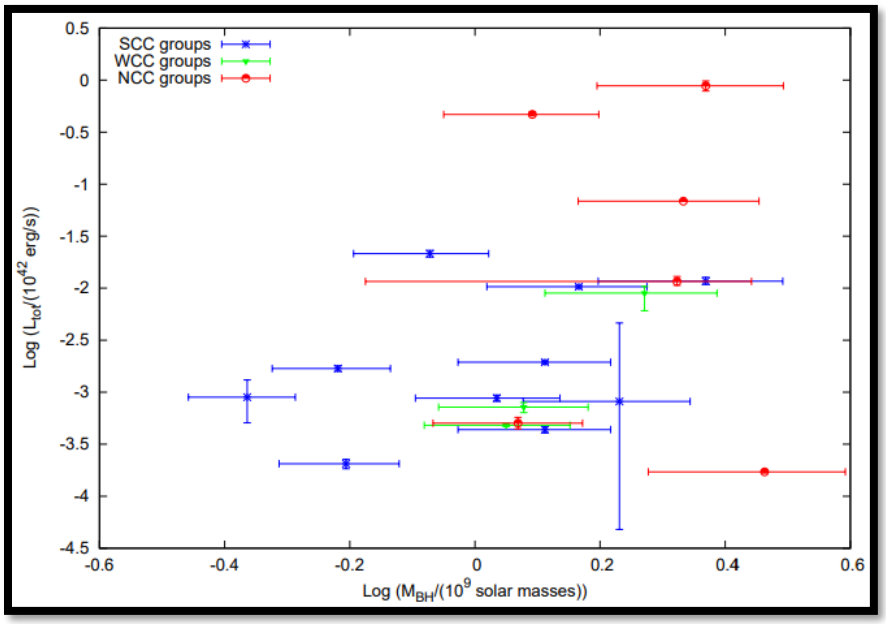

Fig. 10.3.2: Mass of Supermassive BH vs. Total radio luminosity

Group	Mean SMBH mass (10^9 solar masses)	Mean radio luminosity (10^{42} erg/s)
SCC	1.17±0.18	0.0050±0.0023
WCC	1.39±0.24	0.0034±0.0028
NCC	1.98±0.27	0.24±0.15

Table 10.3.1: Radio luminosities and SMBH masses (mean) for various cool core groups

11. Discussion of Results

11.1. Cool Core Fraction and Properties

A correlation between the group sample and the HIFLUGCS concerning cool core fractions are shown in Table 11.1.1. We notice that the noticed part of CC groups is like that of clusters. It merits reviewing that the Malmquist predisposition brings about higher noticed CC cluster fractions and this ought to

subjectively extend to the group samples. Simulations have shown that SCC frameworks are chosen specially as a result of their higher luminosity at a given temperature and rectifying this inclination decreases the part of SCC frameworks by about 25%. [16] show that the cool core (CC) inclination because of more extreme surface luminance profiles increments for less luminous frameworks like groups.

Point of Distinction	Group sample	HIFLUGCS
% of CC systems (SCC+WCC)	77	72
% of SCC systems	50	44
% of WCC systems	27	28
% of NCC systems	23	28

Table 11.1.1: Comparison between surveyed HIFLUGCS and groups samples.

11.2. AGN Activity

The main result of the investigation of the HIFLUGCS samples by Mittal (2009) was that as the CCT diminishes, the probability of cluster facilitating a CRS increments. Every strong cool-core clusters contain a CRS and this part drops to 40% for the non-cool-core clusters. The small number of clusters and groups with CRS, ordered based on the CCT, is appeared in Table 11.2.1. We see that, in contrast to clusters, the CRS division in bunches doesn't scale with diminishing CCT.

Figure 10.2.1 shows that practically all CC groups have an exceptionally low radio luminosity contrasted with CC clusters. Quantitatively, we track down that the middle of the radio luminosity of the groups with cool core is $0.169 \times 10^{40}\ erg/s$ contrasted with $6.21 \times 10^{40}\ erg/s$ for the clusters with cool core. This is in excess of a significant degree contrast among clusters and groups.

Point of Distinction	Group sample	HIFLUGCS sample
% of CC systems with CRS	70	75
% of NCC systems with CRS	100	45
% of WCC systems with CRS	57	67
% of SCC systems with CRS	77	100

Table 11.2.1: CRS fractions

Accepting that gas cooling is answerable for the radio yield of AGN, this low result infers that insufficient gas is being accumulated onto the Supermassive BH. This might just be because of groups having low amount of gas than clusters to accumulate onto the Supermassive BH. Note that the mass of gas for clusters is likewise a significant degree higher than that for groups (Fig. 11.2.1), making it conceivable that the justification a lower radio yield for groups is just an absence of enough cooling gas, however, we likewise note that the relationship between the mass of gas and the radio luminosity is feeble (0.43 for a consolidated example of clusters and groups), bringing up the issue whether this straightforward explanation is adequate to explain the low radio yield.

The connection coefficient between Supermassive BH mass and radio yield is low, driving one to speculate that there is no relationship between these two amounts. This connection has always been petulant, with examines prompting clashing outcomes. Curiously, the NCC Supermassive BH masses are efficiently more

than the other Supermassive BHs, raising the likelihood that these articles may presumably be languishing from more grounded radio upheavals from larger SMBHs which may have obliterated their cool center. Despite the fact that an enticing chance, it could likewise just be a determination impact and may not affect with the cool core idea of these objects.

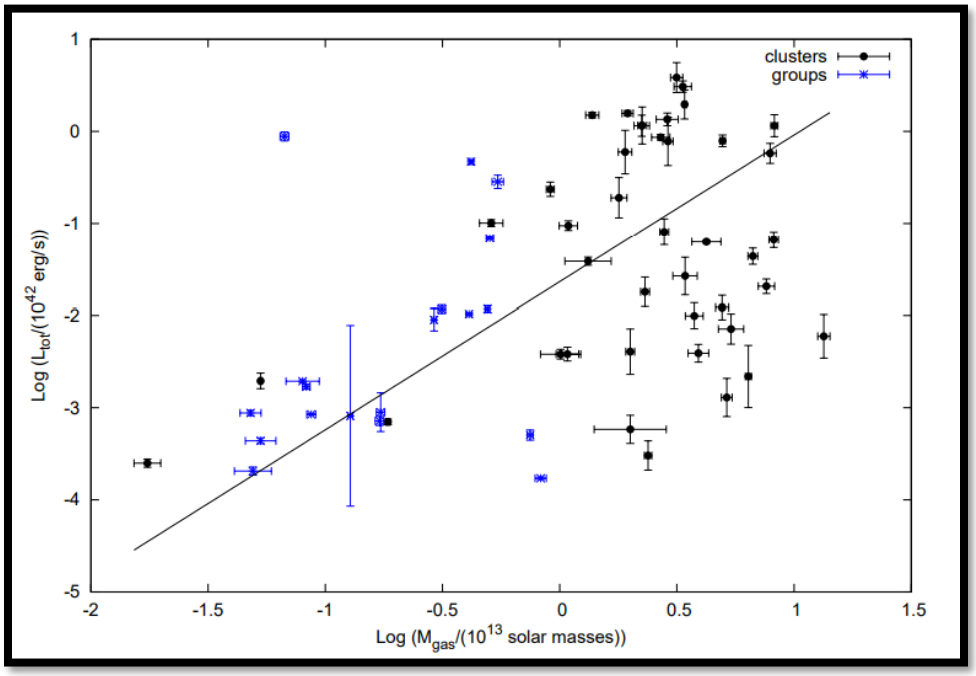

Fig. 11.2.1: Gas mass vs. total radio luminosity. The gas masses plotted here are within r_{500} and are burrowed from Zhang et al. (2011) and Eckmiller et al. (2011) for groups and clusters.

11.3. Star Formation Role

When attempting to comprehend the connection between cooling of gas and AGN feedback in groups, one can't disregard the job of formation of stars. It was proposed by authors like [17] that less gigantic clusters/groups are more productive star forming conditions. [17] shows that for clusters and groups, formation of stars kicks in when the focal entropy is under $30\ keV\ cm^2$, with the conditions that the X-ray and galaxy bulges are inside $20\ kpc$. In the example we have taken, all our cool core BCGs are inside $20\ kpc$ of the Xray EP, and every SCC groups and a couple of WCC groups have a focal entropy well beneath as far as possible, in this way satisfying these standards for star arrangement. [18] used UV information from *GALEX* to propose that there is a favourable relationship between rate of star formation and gas cooling time (CT) for cool-core cluster BCGs, to such an extent that the SFR increments with diminishing cooling time. Also, much of the time the old-style mass statement rates for our cool-core groups isn't excessively high (a best guess yields a middle of $<\ 10\ M_{\odot}/yr$ determined at a range where CT is $7.7\ Gyr$) which implies that one can't preclude the likelihood that star development is being powered by a large portion of the cooling gas. More grounded relationships between the CTs and rate of star formation were seen for groups than for clusters can prove this theory [18].

12. Conclusion

In this comprehensive investigation of the Intracluster Medium (ICM) cooling and Active Galactic Nuclei (AGN) feedback within a sample of 25 Chandra galaxy groups, we have uncovered significant insights that contribute to our understanding of the complex interplay between these phenomena. The results of our study reveal critical distinctions between galaxy groups and clusters, challenging the traditional view that groups are merely scaled-down versions of clusters. This conclusion is supported by several key findings that highlight the unique characteristics of galaxy groups, particularly in relation to their cooling flows and AGN activity. One of the most striking outcomes of our analysis is the observation that the galaxy groups exhibit similar Subcluster Cooling Core (SCC), Weak Cooling Core (WCC), and Non-Cooling Core (NCC) classifications as those found in the High-Redshift Frontier for Large-Scale Structure (HIFLUGCS) cluster samples. This similarity suggests that the mechanisms governing cooling flows in galaxy groups may share fundamental properties with those in larger clusters. However, the nuances of these mechanisms become apparent when we delve deeper into the cooling times and temperature profiles of the groups. Notably, we found that 23% of the groups with a central cooling time (CCT) of less than or equal to 1 Gyr do not exhibit a drop in core temperature. This finding raises intriguing questions about the thermal history of these systems. It is plausible that these groups have experienced a partial or delayed warming of their cool cores, potentially due to prior AGN activity or other heating mechanisms. Furthermore, this phenomenon may be indicative of fossil groups, which are characterized by their old stellar populations and the absence of significant recent mergers.

In contrast to the HIFLUGCS sample, our study did not observe an increase in the Cool Core Radio Source (CRS) fraction with decreasing CCT. This divergence serves as a critical indicator of the differences between clusters and groups within the AGN heating and ICM cooling paradigm. The lack of correlation between core-cooling time and the integrated radio luminosity of the CRS further emphasizes this distinction. Specifically, we found that the CRSs associated with strong cool-core groups possess significantly lower radio luminosities compared to those in clusters. This observation suggests that the mechanisms driving AGN feedback in galaxy groups may differ fundamentally from those in clusters, where the more massive gravitational potential wells can sustain more vigorous AGN activity. Moreover, our investigation posits that star formation may play a crucial role in regulating the cooling gas within these groups. In scenarios where strong star formation is prevalent, the inflow of gas to the supermassive black hole (SMBH) may be insufficient to produce the high radiative output typically associated with AGN feedback. This could explain why certain SCC groups do not exhibit a corresponding CRS, as the energy output from the AGN is not as pronounced due to the competing processes of star formation and gas cooling. The interplay between star formation and AGN feedback in galaxy groups thus presents a complex dynamic that warrants further exploration. In conclusion, our findings underscore the notion that galaxy groups are not simply scaled-down versions of galaxy clusters but rather possess distinct characteristics that influence their thermal and dynamical evolution. The differences observed in ICM cooling and AGN feedback mechanisms highlight the need for a nuanced understanding of these systems. As we continue to investigate the intricate relationships between cooling flows, AGN activity, and star formation in galaxy groups, it becomes increasingly clear that these systems represent a unique environment in which to study the evolution of galaxies and their central black holes. Future research should aim to expand upon these findings by incorporating larger samples and exploring the effects of environmental factors on the cooling and feedback processes in galaxy groups. By doing so, we can further elucidate the role of AGN feedback in shaping the properties of the ICM and the galaxies that reside within these fascinating cosmic structures. Ultimately, this study contributes to a growing body of evidence that challenges conventional paradigms in astrophysics and encourages a reevaluation of the relationships between galaxy groups and clusters. As we refine our understanding of these systems, we pave the way for new insights into the formation and evolution of galaxies in the universe, highlighting the importance of continued observational and theoretical efforts in this dynamic field of research. The implications of our findings extend beyond the immediate context of galaxy groups, offering a broader perspective on the processes that govern the evolution of cosmic structures and the intricate balance between cooling and heating mechanisms in the universe.

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15.Conflict of Interest

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