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PROBING OPTICAL AND RADIO-LOUD AGN FRACTIONS : A COMPARATIVE ANALYSIS BETWEEN BCGs AND NON-BCGs SAMPLES at z < 0.1

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Abstract

Brightest cluster galaxies (BCGs) are the most massive and luminous galaxies located near the center of relaxed, virialized, and undisturbed galaxy clusters in the local Universe ([1, 2]). According to several observational studies ([3, 4]), these objects experience a special formation process differing from general galaxy evolution.

Current theoretical models (e.g., [5, 6]) predict that dry mergers are the dominant mechanisms responsible for their mass assembly at $z < 1$. These objects are often observed to host a supermassive black hole (SMBH) in their center ([7]). The process of matter accretion into these SMBHs may release a large amount of energy, resulting in Active Galactic Nuclei (AGN). There are two primary modes in which SMBH accretion can occur: the so-called 'quasar mode' and the 'radio mode'. The quasar mode involves a high accretion rate of the SMBH via an optically- thick and geometrically-thin disk, with most of the energy being released in the form of radiation. In a radio mode scenario, the SMBH accretion of gas occurs at a low rate in an optically-thin and geometrically-thick disk configuration, releasing energy in the form of relativistic particles, i.e. radio jets. The latter is typically observed in BCGs.

The evolutionary processes of BCGs are still not fully understood, and there are no specific studies comparing the frequency of different types of AGN in BCGs with respect to other types of galaxies (e.g., [8]). The main scientific question guiding my thesis project is to investigate whether the different evolution of BCGs, coupled with their "special" environment, promotes the accretion of SMBHs in their centers compared to other types of galaxies in the local universe, at $z < 0.1$. To address this question, I analyzed a sample of BCGs within the redshift range of z = 0.02-0.1. This sample was derived from the combination of the Sloan Digital Sky Survey Data Release 7 (SDSS DR7 [9]) and the C4 BCGs catalogue produced by [10, 11]. I utilized

the flux measurements of optical emission lines i.e. $H\alpha$, [OIII], $H\beta$, [NII], and [SII] doublets by the MPA-JHU team. These fluxes were estimated using methods outlined in [12]. This allowed me to conduct a selection of optical AGN through the [NII]- and [SII]- BPT diagnostic diagrams [13]. Additionally, I conducted a cross-matching of the aforementioned catalogs with a dataset obtained from [14], where the spectroscopic sample of the SDSS DR2 was cross- correlated with catalogs of galaxies observed from the National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS; [15]) and the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey [16]. Using this new catalog of BCGs probed with these radio surveys, I was able to select the BCGs that exhibit radio loudness. Following this classification, I finally estimated the fraction of BCGs classified as Optical and Radio Loud AGN. Subsequently, I derived these fractions for a sample of non-BCG selected galaxies using the same procedure employed to obtain the BCG catalog.

These analyses reveal that BCGs exhibit a higher fraction of Optical AGN $\sim 50\%$ compared to the non-BCG sample, which shows a percentage of $\sim 21\%$, consistent with the results found by [17]. Simultaneously, the analysis of Radio Loud emissions indicates that BCGs are more inclined to host Radio Loud Activity, with a fraction of $\sim 12\%$. This fraction is found to be 20 times higher than the fraction observed in the non-BCG sample of selected galaxies, which is $\sim 0.6\%$.

In conclusion, these results demonstrate that BCGs are more likely to host optical AGN activity and radio-loud emission compared to other types of galaxies. This suggests that their privileged position facilitates frequent accretion of SMBHs in both accretion modes. Previous studies, such as [10, 18, 19] have already shown a prevalence of radio AGN among the BCG population in the local Universe. However, few studies (e.g., [8]) have attempted to compare the distribution of BCGs in BPT diagrams to that of normal galaxies. The fact that the fraction of AGN is greater for special galaxies is both expected and interesting to understand the nature of these objects. Future studies will aim to test the results obtained with this sample and to understand if this higher fraction is specifically driven by differences in properties between BCGs and non-BCGs, such as mass, star formation rate, metallicity, and kinematics.

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Chapter 1

Introduction

1.1 The Active Galactic Nuclei

Active galaxies constitute a distinctive class characterized by an intensely energetic source at their center, known as an Active Galactic Nucleus (AGN). Since the first observation of an active galaxy in the early 1900s, numerous studies have been conducted on this intriguing category of galaxies. To this day, efforts persist in unraveling the nature and role of active galaxies within the broader context of galactic formation and evolution.

Research in this field has demonstrated that the intense radiation must emanate from a compact region, with a spatial dimension not exceeding 100 parsecs. This estimation was derived from the temporal variability observed in some of these sources [20]. Additionally, it has been noted that AGNs exhibit luminosity variations of over 50% within timescales ranging from days to years. Such fluctuations can only be explained if a substantial portion of the emission region is randomly connected. These observations strongly imply that the central component of AGNs is likely a Supermassive Black Hole (SMBH), namely a rapidly accreting black hole.

AGN emissions span the entire electromagnetic spectrum, with variations in the different components depending on the classification of the observed nuclei. Despite these differences in emissions, a General Model known as the "Unified model" can still be defined, which applies to each classification of AGNs. [21]

In addition to the previously mentioned supermassive black hole (SMBH) at the center, there is an accreting disk located in close proximity, serving as a primary source of UV radiation. The central region, excluding the disk, is the main contributor to X-rays, while gas clouds orbiting near the BH give rise to Broad Emission Lines, forming what is known as the Broad Line Region (BLR). In the outer regions, situated both above and below the accreting disk, the primary contributor to Narrow Emission Lines, thus defining the Narrow Line Region (NLR), is the presence of diffuse gas. Additionally, surrounding the disk, there's a toroidal-shaped volume composed of a mixture of gas and dust, leading to the partial absorption of central radiation.

The final torus-shaped volume is indeed one of the main reasons for explaining the extreme variety observed in active galaxies and the different modes in which SMBH growth occurs. From a historical perspective, AGNs are divided into two main categories: Type 1 and Type 2, with the addition of Blazars. According to the 'Unified Model,' the main difference between these categories is merely apparent, arising from nothing more than variations in the observer's line of sight and the presence of the obscuring torus.

- **Type I:** The emission lines exhibit a broad component, typically in the range of $\sim 10^3$-$10^4, \mathrm{km\ s^{-1}}$, along with a narrow component. In this configuration, the observer is situated at a small angle relative to the torus axis, allowing the radiation from circumnuclear regions to remain unobscured along the line of sight

- **Type II:** Emission lines exhibit only a narrow component, typically not exceeding $1200, \mathrm{km\ s^{-1}}$. In this scenario, the line of sight intersects the obscuring matter of the torus.

- **Blazars:** In this scenario, the observer's line of sight is closely aligned with the axis of the radio jets emanating from the source.

The substantial energy released during the accretion process of a SMBH by an AGN plays a significant role in shaping the evolution of the host galaxy. In this context, the literature often discusses positive and negative feedback mechanisms, which correspond to different physical phenomena such as radiation pressure, jet generation, and winds. Positive feedback occurs when active nuclei promote stellar formation, while negative feedback involves the suppression of star formation.

In the literature, various theoretical models of galactic evolution can be found, referring to physical mechanisms capable of heating gas on immense scales ($>> 1kpc$), as proposed by Di Matteo et al. (2005). These models are also capable of halting star formation and consequently depositing metals into the surrounding environment, as suggested by Gebhardt et al. (2000).

The most accepted theory predicts that winds generated by accretion onto the SMBH can be responsible for both mechanisms of quenching or enhancing star formation.

Two distinct AGN feedback mechanisms have been proposed, each associated with different rates of mass accretion onto the SMBH (Fabian, 2012; Harrison, 2017).

- **QSO's Radiative Feedback :** This feedback mode, often referred as quasar mode consists in a high accretion rate of the SMBH via an optically-thick and geometrically-thin disk, and most of the energy is released in form of radiation.
- **QSO's Radio Feedback :** In this scenario, the SMBH accretion of hotter gas happens with a low rate in a optically-thin and geometrically-thick disk configuration, releasing energy in form of relativistic particles. such as Radio Jets.

1.2 The Brightest Cluster Galaxies

The Hierarchical model stands as a cornerstone in our understanding of cosmic structure formation, delineating the principal pathways through which galaxies burgeon in both stellar luminosity and mass. At its core, this model elucidates how galaxies amass their content by drawing in and assimilating matter from their surroundings.

One of the most extreme examples in this context involves the study of Brightest Cluster Galaxies (BCGs), a unique class of galaxies, often situated at the center and typically standing out as the most luminous and massive objects within the entire cluster.(e.g. [22]).

Considering their environment, observational studies, such as [4], have indicated that the evolution of Brightest Cluster Galaxies (BCGs) differs from the normal galactic path. The prevailing model for cosmic structure formation (i.e. the Cold Dark Matter Model) suggests that the mass assembly of BCGs is primarily influenced by dry mergers [5, 6].

At low redshift, these objects exhibit a small dispersion in their aperture luminosities and, indeed, have been frequently chosen as standard candles for cosmological tests throughout the literature, also because of the shared properties with the cluster itself.

Mainly found to be Elliptical galaxies, BCGs seems to not be drawn from the same luminosity function as normal elliptic objects outside the cluster environment, and in general has been proven to differ also from generic Bright galaxies. (i.e. [23])

Due to their distinct evolutionary histories, the primary mechanism driving the mass growth of galaxies is associated with cooling flows within lower mass halos at high redshifts. However, at low redshifts, this phenomenon diminishes, primarily due to increased Active Galactic Nuclei (AGN) activity accreting mass into their typically hosted SMBH [7].

As presented before regarding AGN feedback, also BCGs are interested by both of the Quasi Stellar Object modes, resulting in both in the form of Optical AGN, and Radio Loud Emission such as Radio Jets(e.g. [10]).

These relativistic jets of radio emission is also recognized as one of the main explanation of the so called "Cooling flow problem". The unique relaxed and virialized environment defining the cluster often has cooling timescales much shorter than Hubble time, that following to the absence of a heating source would lead to the presence of a cooling flow.

However observational studies found that temperature of cluster cores fails to fall below $\sim 30\%$ at large radii resulting in an amount of cooling gas corresponding only to the $\sim 10\%$ expected from the existent cooling flow model. [24]

1.3 The Aim of this thesis

In this context, the main scientific question driving this work is to understand **whether the different evolution of BCGs, along with their "special" environment, affects the accretion of SMBHs in their centers compared to other types of galaxies in the local universe**.

In particular, this study will present a comparative analysis between two representative samples of BCGs and Non-BCGs to highlight the substantial differences that the cluster environment induces in SMBH accretion.

To address this particular inquiry, I conducted an analysis on a BCG sample compiled from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7), as outlined in [9], and the C4 BCGs catalogue created by [25]. For this specific BCG sample, I utilized the optical line fluxes ($H\alpha$, [OIII], $H\beta$, [NII], and [SII] doublets) provided by the MPA-JHU team to establish a comprehensive understanding of optical AGN presence through the [NII]- and [SII]- BPT diagnostic diagrams. Furthermore, through cross-matching these aforementioned catalogs with datasets derived from NVSS and FIRST radio surveys, as outlined in [14], I identified BCGs displaying radio loud emission, indicative of the existence of radio jets.

These analyses, including data description in subsection 2.1 "Data description" and data analysis in subsection 2.2 "Data analysis," will be comprehensively presented in the "Methods" chapter.

Following the "Methods" chapter, the subsequent section will delve into the third chapter, concentrating on the disclosure of the acquired outcomes.

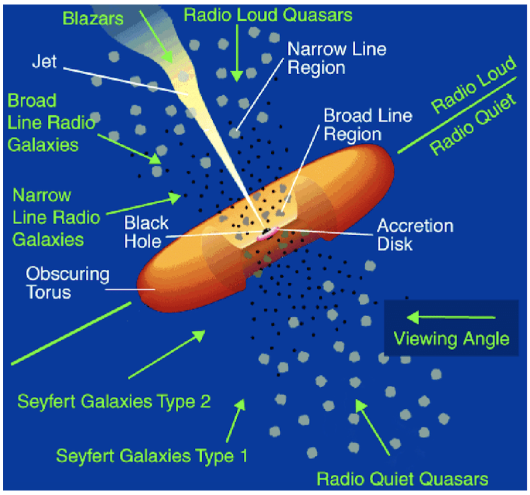

Figure 1.1: Fig 2 : Unified AGN model as proposed in [21]

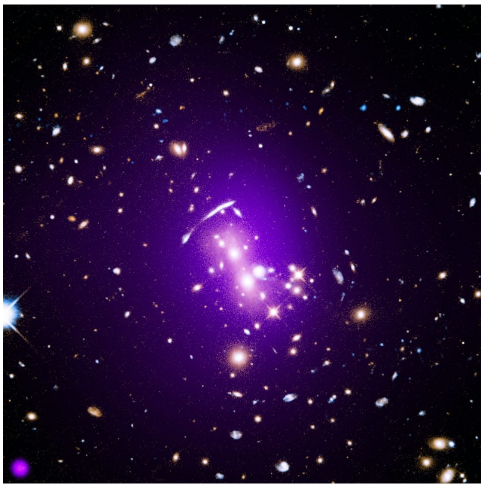

Figure 1.2: This image of galaxy cluster SPT-CLJ0310-464 X-rays from Chandra are shown along with optical data from Hubble

Chapter 2

Methods

The study of cosmic objects, such as galaxies, relies on the analysis of the electromagnetic spectrum emanating from these distant sources. Within a spectrum, various pieces of information can be extracted, with the primary focus being on the intensity of light across a range of energies or frequencies. A crucial aspect of a spectrum involves determining the intensity at specific wavelengths.

This thesis will concentrate on utilizing specific information derived from spectra (e.g., flux, flux error) associated with both permitted and forbidden emission lines. In a galactic context, particularly within a galaxy cluster, the continuum originates from the diffuse light emitted by stars. On the other hand, emission lines, which are prominently observed in such environments, are typically generated by elements like Hydrogen, Helium, Oxygen, etc.

There are various methods to investigate the electromagnetic spectrum, with the two primary branches being Spectroscopy and Photometry.

Astrophysical spectroscopy is a fundamental tool used to analyze the electromagnetic radiation emitted or absorbed by celestial objects. By examining the spectral lines and features, it is possible to mine important informations such as chemical composition, temperature, density etc.

On the other hand, photometry measures the overall brightness of celestial objects across different wavelength bands, providing information about the spectral distribution of their luminous emission.

In this Thesis Work i'll be focusing on a Spectroscopic study involving the fluxes of the Forbidden Emission lines of the spectrum as presented in the following sections.

2.1 Data Description

This thesis presents results obtained through the cross-matching of three distinct celestial catalogues:

- **SDSS DR7 :** Our Main Catalogue of galaxies
- **C4-BCG :** The BCG Catalog
- **Radio Emitters :** The survey chosen for RadioLoud identification

2.1.1 SDSS DR7

The SDSS project, or Sloan Digital Sky Survey, is a comprehensive astronomical survey that maps the universe by capturing images, spectra, and photometric data of celestial objects over a large area of the sky. [9]

Funding for the project has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society.

This ambitious project marked its beginnings in 2000 with the goals of obtaining CCD imaging in five broad bands, covering an area of $10,000\,\mathrm{deg}^2$ of high latitude sky and spectroscopy data of a million galaxies and over 100'000 quasars over the same area.

Observations have been conducted using a a dedicated wide-field 2.5 m telescope (Gunn et al. 2006) located at Apache Point Observatory (APO) near Sacramento Peak in Southern New Mexico.

The telescope employs two distinct instruments. The first is a wide-field imager equipped with 24 tiles, each containing a 2048x2048 CCD. Imaging is performed along great circles at the sidereal rate, leading to exposure times of 54.1 seconds.

The astrometry is good to 45 milliarcseconds (mas) rms per coordinate at the bright end, while the photometric calibration is made in two modalities, respectively by tying to standard reference stars and by using the overlap between adjacent imaging runs in a process called ubercalibration.

Spectra are extracted and calibrated in terms of wavelength and flux. For galaxies near the main sample flux limit, the typical signal-to-noise ratio (S/N) is 10 per pixel. The broadband spectrophotometric calibration exhibits an accuracy of 4% root mean square (rms) for point sources

(Adelman-McCarthy et al. 2008), and the wavelength calibration is precise to 2 km s^{-1}.

The SDSS data have been made public in a series of yearly data releases, This thesis works based its results from a galactic sample derived from "Data Release 7" by the Max Planck Institute for Astrophysics and Johns Hopkins University (MPA-JHU) teams, containing the derived properties of a total of 927'552 galaxy spectra.

Physical Properties of interest :

- **Line Flux :**Flux from Gaussian fit to continuum subtracted data, corrected for foreground (galactic) reddening using techniques developed by [12]
- **Error Line Flux :** Developed by analyzing the duplicate observations of galaxies, to compare the empirical spread in value determinations with the random errors.

Aggiungo un plot scat delle zone coperte da SDSS ?

2.1.2 C4 BCG Catalogue

The BCG identification within our main galaxy sample previously described, has been based on results found by A. Von der Linden et Al. [10, 11] in the further analysis made on the C4 Galaxy Cluster Catalogue originally developed by Miller et Al in 2005, whose details can be found in [25]

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2.2 Data Analysis

How we analyzed the data, where do we defined the fractions calculated ?

2.2.1 Optical analysis

Describe each population of the BPT diagram and its peculiarities, before starting the description of how we collected and processed the data to finally create BPT diagrams . Finally there's the need to explain how we interpreted the diagrams to finally calculate the fractions (in this case you need to explain which algorithm has been chosen and why)

2.2.2 Radio Analysis

I certainly need to focus on how i have chosen the range of identification, to recognize which element of sdss was effectively recognized as a Radioloud.

Following to this it is necessary to explain how we selected the elements in which define the fractions, by selecting elements of SDSS nearby the location in which best et al finds mostly its radio-emitting elements!

Chapter 3

Results

A complete description of the results produced !!

3.1 The Prevalence of AGN activity in BCGs

Describe how the evidence of the data analysis we conducted leads to the description of BCGs in a confrontation to non-BCGs, and in how different is still from a pure optical view the response of the AGN feedback.

Present absolutely the Table with all of the percentage (and the counting) values of the populations of both BPT NII and BPT SII diagnostics and introduce a confrontation with also the results found in Vitale et AL and others.

3.2 The Radio activity of BCGs

Explain the evidences found in the analysis and possible ways to improve results obtained.

There's certainly also the need to add a discussion on how it is possible that we ignore some of the BCGs in the counting, issue that should be resolved by choosing a more complete source of data regarding Radio Emitters galaxies.

Conclusions

The final chapter of the thesis is a summary of the work done. Therefore, in its first part it resembles much the introduction, adding to it the actual result of the work, its future evolution and prospects, in the view of the writer.

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