

**REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING**

**STRUCTURAL FORMATION AND CHEMICAL
ENRICHMENT PATTERNS IN ISOLATED
GALAXIES: A CASE STUDY OF MRK1216 AND
INSIGHTS INTO RED NUGGET EVOLUTION**

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A thesis submitted by Muhammed Kıyami ERDİM in partial fulfillment of the requirements for the degree of **DOCTOR OF PHILOSOPHY** is approved by the committee on 14.02.2024 in Department of Physics, Physics Program.

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Muhammed Kiyami ERDİM

Signature

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LIST OF SYMBOLS

SB	Barred Spirel Galaxy
cm	Centimeter
S_0	Central Intensity of Surface Brightness
c_{200}	Concentration parameter for R_{200}
t_c	Cooling Time
r_c	Core Radius
$\rho_{crit}(z)$	Critical Mass Density
dof	Degrees of Freedom
R_e	Effective Radius (Half Light Radius)
E	Elliptical Galaxy
ϵ	Emissivity
t_{ff}	Free-Falling Time
He	Helium
H_0	Hubble Constant
H	Hydrogen
n_H	Hydrogen Column Density
K	Kelvin
km	Kilometer
S0	Lenticular Galaxy
Li	Lithium
L	Luminosity
M_{200}	Mass value for R_{200}
Ω_M	Matter density

μ	Mean
Γ	Power-Law Index
R_{200}	Radius value for 200 times the critical mass density
z	Redshift
$R_{(Ia)}$	SN Ia Ratio
s	Second
S/N	Signal to Noise
β	Slope parameter of Beta Model
$M_{\odot}$	Solar Mass
S	Spiral Galaxy
σ	Standard Deviation
M_{*}	Stellar Mass
T	Temperature
kT	Temperature in energy unit
Ω_{Λ}	Vacuum

LIST OF ABBREVIATIONS

ABS	Absorption
AGB	Asymptotic Giant Branch
AGN	Active Galactic Nuclei
APEC	Astrophysical Plasma Emission Code
AtomDB	Atomic Database
CALDB	Calibration Database
CCA	Chaotic Cold Accretion
CCD	Charge Coupled Devices
CC	Cool-Core
CEG	Compact Elliptical Galaxy
CHEERS	Chemical Enrichment RGS Sample
CIAO	Chandra Interactive Analysis of Observations
CMB	Cosmic Microwave Background
CXB	Cosmic X-Ray Background
DEC	Declination
EPIC	European Photon Imaging Camera
ESAS	Extended Source Analysis Software
ESA	European Space Agency
ETG	Early Type Galaxy
FL	Fluorescent Lines
FOV	Field of View
FWHM	Full Width at Half Maximum
GADEM	Gaussian Distribution of Emission Measure

GH	Galactic Halo
GTI	Good Time Interval
HEASARCH	High Energy Astrophysics Science Archive Research Center
HEW	Half Energy Width
IGIMF	Integrated Galaxy-wide Initial Mass Function
IMF	Initial Mass Function
ISM	Inter-Stellar Medium
ICM	Intra-Cluster Medium
IGrM	Intra-Group Medium
IsoCEG	Isolated Compact Elliptical Galaxy
keV	Kiloelectron Volt
Λ CDM	Lambda Cold Dark Matter
LHB	Local Hot Bubble
LHB	Local Hot Bubble
LMXB	Low Mass X-ray Binary
LPGS	Lodders Palme Gail Proto-Solar
LSS	Large Scale Structure
MOS	Metal Oxide Semi-conductor
MRG	Massive Relic Galaxy
MZR	Mass to Metallicity Relation
Mrk	Markarian
NASA	National Aeronautics and Space Administration
NCC	Non Cool-Core
NGC	New General Catalogue
NXB	None X-Ray Background
OM	Optical Monitor
pc	Parsec
PHABS	Photoelectric Absorption
PSF	Point Spread Function

QPB	Quiescent Particle Background
QPB	Quiescent Particle Background
RASS	ROSAT All-Sky Survey
RA	Right Ascension
RGS	Reflection Grating Spectrometer Optical Monitor
ROSAT	Röntgensatellit
SAS	Science Analysis System
SE	Source Emission
SMBH	Super Massive Black Hole
SNla	Supernova Type Ia
SN	Supernova
SNcc	Supernova Core-Collapse
SNe	Supernovae
SP	Soft Proton
TBABS	Tuebingen-Boulder Absorption Model.
UPS	Unresolved Point Sources
UV	Ultraviolet
VGADEM	Variable GADEM
X-IFU	X-ray Integral Field Unit
XMM	X-ray Multi-mirror Mission
XRISM	X-ray Imaging and Spectroscopy Mission

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ABSTRACT

Structural Formation and Chemical Enrichment Patterns in Isolated Galaxies: A Case Study of Mrk1216 and Insights into Red Nugget Evolution

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Doctor of Philosophy Thesis

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The complex evolution of matter in the Universe has been an ongoing area of research in cosmology and astrophysics. Among the various proposed models, the Λ CDM (Lambda Cold Dark Matter) model has stood out by providing a solid mathematical basis for the expansion of the Universe, the cosmic microwave background (CMB), dark matter, and the formation of large-scale structures. In this thesis, the hierarchical formation model predicted by Λ CDM cosmology and the chemical enrichment processes intertwined with this formation are discussed. According to the hierarchical formation model, the massive elliptical galaxies we observe in the nearby universe formed in two stages. In this two-stage evolution, the dense centers of massive elliptical galaxies are formed primarily through gas-rich mergers. These gas-rich mergers also trigger a rapid and effective star formation process. The structures formed at the end of this process, which continues until around $z \sim 2$, are called "red-nugget". Star formation processes are largely completed in the first stage. Then the slower second phase begins. At this stage, the galaxy enters the process of merging with the nearby gas-poor structures. With the second stage, galaxies continue their development in terms of both size and stellar mass. However, the inherently random nature of these mergers may cause some galaxies, such as Mrk1216, to skip the second stage by not experiencing these mergers. This causes them to preserve their properties after completing the first stage ($z \sim 2$), and reach to the present day as almost unchanged relic structures. This thesis focuses on Mrk1216, an Isolated Compact Elliptical Galaxy (IsoCEG) and Massive Relic Galaxy (MRG) that offers a unique opportunity for detailed analysis due to its unusual evolutionary process. Furthermore, the unusual evolution of

Mrk1216, its lack of strong intrinsic activity, and its isolation make it a valuable case study for understanding the effects of mergers and Active Galactic Nucleus (AGN) processes on elemental production and distribution. This study also aims to provide insights into the enrichment patterns in the early universe and the effects of dynamic processes on elemental evolution through the chemical properties of Mrk1216. At this point, the prominent model regarding the chemical evolution of matter is the "early enrichment" scenario. This scenario suggests that element synthesis largely occurs before the aggregation of matter. In conclusion, this study interprets the information obtained by carefully examining the chemical structure of Mrk1216 through the current chemical enrichment scenario.

Keywords: Elliptical galaxies, red-nuggets, chemical enrichment, structural formation, X-ray observations.



İzole Gökadalarda Yapısal Oluşum ve Kimyasal Zenginleşme Örüntüleri: Mrk1216'nın İncelenmesi ve Kırmızı Yığın Evrimine Dair Bulgular

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Evren'deki maddenin karmaşık evrimi, kozmoloji ve astrofizikte süregelen bir araştırma alanı olmuştur. Önerilen çeşitli modeller arasında, Λ CDM (Lambda Soğuk Karanlık Madde) modeli, Evren'in genişlemesi, kozmik mikrodalga arka planı (CMB), karanlık madde ve büyük ölçekli yapıların oluşumu konularında sağlam bir matematiksel temel sağlayarak öne çıkmıştır. Bu tez çalışmasında, Λ CDM kozmolojisinin öngördüğü hiyerarşik oluşum modeli ve bu oluşum ile iç içe geçmiş olan kimyasal zenginleşme süreçleri ele alınmıştır. Hiyerarşik oluşum modeline göre yakın evrende gözlemlediğimiz büyük kütleli eliptik galaksiler iki aşamada olmuştur. Bu iki aşamalı evrimde öncelikle gaz zengin birleşmeler yolu ile büyük kütleli eliptik galaksilerin yoğun merkezleri oluşur. Bu gaz zengin birleşmeler hızlı ve etkili bir yıldız oluşum sürecini de tetikler. $z \sim 2$ civarına kadar devam eden bu sürecin sonunda oluşan yapılara "kırmızı-yığın" (red-nugget) adı verilmiştir. Yıldız oluşum süreçleri ilk aşamada büyük ölçüde tamamlanmıştır. Ardından daha yavaş olan ikinci aşama başlar. Bu aşamada galaksi, civarında bulunan gazca fakir yapılar ile birleşme sürecine girer. İkinci aşama ile galaksiler hem boyutça hem de yıldız kütlesi açısından gelişimlerini sürdürürler. Ancak, bu birleşmelerin doğası gereği rastgele oluşu, Mrk1216 gibi bazı galaksilerin bu birleşmeleri yaşamayarak ikinci aşamayı atlamasına yol açabilir. Bu da onların ilk aşamayı tamamlamalarının ardından ($z \sim 2$) mevcut özelliklerini korumalarına ve neredeyse hiç değişmemiş kalıntı yapılar olarak günümüze ulaşmalarına neden olur. Bu tez çalışması, sıradışı evrimsel süreci nedeniyle detaylı bir analiz için eşsiz bir fırsat sunan İzole Kompakt Eliptik Galaksi (IsoCEG) ve Büyük Kalıntı Galaksi (MRG) olan Mrk1216'ya odaklanmaktadır. Ayrıca, Mrk1216'nın

sıradışı evrimi, güçlü içsel etkinlik eksikliği ve izole oluşu, onu birleşmelerin ve AGÇ (Aktif Galaktik Çekirdek) süreçlerinin element üretimi ve dağılımı üzerindeki etkilerini anlama için değerli bir vaka çalışması yapmaktadır. Bu çalışma ayrıca Mrk1216'nın kimyasal özellikleri üzerinden erken evrendeki zenginleşme modellerine ve dinamik süreçlerin element evrimi üzerindeki etkilerine dair içgörüler sunmayı hedefler. Bu noktada maddenin kimyasal evrimi ile ilgili öne çıkan model ise "erken zenginleşme" senaryosudur. Bu senaryo, element sentezinin büyük oranda maddenin kümeleşmesinden önce gerçekleştiğini öne sürer. Sonuç olarak bu çalışma, Mrk1216'nın kimyasal yapısının dikkatli biçimde incelenmesi ile elde edilen bilgileri, mevcut kimyasal zenginleşme senaryosu üzerinden de yorumlamaktadır.

Anahtar Kelimeler: Eliptik gökadarlar, kırmızı yığın gökadarlar, kimyasal zenginleşme, yapısal oluşum, X-ışını gözlemleri.



1

INTRODUCTION

1.1 Literature Review

The evolution of matter in the Universe has always been a subject of intense curiosity and investigation within the fields of cosmology and astrophysics. For this purpose, various theories and models have been discussed and proposed throughout the history of these fields. Among these models, Λ CDM (Lambda Cold Dark Matter) model is the most prominent one. This cosmological model provides us with insights and a mathematical foundation regarding the expansion of the Universe, the observed cosmic microwave background (CMB) radiation, indirect observations of dark matter, and the formation of large-scale structures like galaxies, galaxy clusters, filamentary structure of cosmic web [1].

Certainly, the effectiveness of the current model depends on its ability to explain both past and future observations of the associated phenomena. The ongoing process involves evaluating points where theoretical predictions align with observational results, expanding or correcting our existing perspective. This continuous process involves examining instances where theoretical predictions align with observational outcomes, refining our perspective. One potential contribution could involve introducing new points of intersection or comparison in areas where theory and observation have yet to converge.

In this regard two main topics need to be addressed. The first is how the structures in the Universe are formed according to the Λ CDM cosmology. The second is how the chemical enrichment of matter takes place within this process. Regarding the first topic, we will discuss the structural formation scenario predicted by the current cosmology and observational supports, specifically for massive elliptical galaxies related to our topic. Regarding the second topic, we will explore the synthesis mechanisms of elements within those ellipticals, involving stellar processes and supernovae.

1.1.1 Structural Evolution

According to the Λ CDM model, structures in the Universe have formed in a hierarchical manner. In other words, small structures first emerged, and those structures combined to form larger ones. This scenario is commonly referred to as "bottom-up" scenario in the literature. Massive elliptical galaxies represent a specific example within this broader scenario. In this context, the hierarchical development of high-mass elliptical galaxies at $z = 0$ occurred in two stages. In the first stage, gas-rich (wet) mergers take place. These wet mergers create the core of the galaxy, consequently forms its supermassive black hole (SMBH). They also trigger an efficient star formation phase due to the dense gas content. This rapid stage occurred in a dissipative manner and was mostly completed at $z \sim 2$. The compact galaxies formed during the course are called "red nuggets" [2–7].

After the completion of the first stage, a slower and long-term process begins. In this stage, red-nuggets start merging with surrounding lower-mass systems. However, since much of the dense gas in those systems has already converted into stellar mass in the initial stage, the gas ratio is now much lower, and such mergers are characterized as "dry-mergers". These mergers do not trigger star formation and are relatively collisionless. They generally do not significantly impact the center of the galaxy but they contribute to its size and stellar mass. This slow "accretion" phase continues until $z = 0$. This two-stage evolution is supported by many observations, semi-analytic models and simulations [2–6, 8, and references therein].

However, due to the stochastic nature of mergers, certain galaxies may not progress to the 'dry-merger' phase in the second stage because of the low matter density in their surroundings, resulting in an interrupted evolution [5, 9]. In other words, they skip the second stage. These galaxies, formed in isolation, can persist almost untouched until the present day, retaining red-nugget properties around $z \sim 2$. Such relic galaxies at low redshift have been reported in the literature, NGC 1277, PGC 032873, and Mrk 1216 [5]. These galaxies exhibit distinctive structural features, including the concentration of stellar population, velocity dispersion profile, and black hole mass scaling relation, setting them apart from present-day high-mass ellipticals and resembling early red-nugget galaxies. Furthermore, other studies have indicated that these "Compact Elliptical Galaxies" (CEGs) are similar to red-nugget structures in our vicinity [4]. Consequently, these compact galaxies are relics that have nearly ceased evolving and have remained largely unchanged throughout cosmic history. In this regard, extensive studies have been conducted, examining compact galaxies in detail and modeling various aspects of their characteristics such as mass, velocity distribution, luminosity, size, stellar population, and dark matter ratio. These studies have reported the distinctions between red-nugget-like relics, compact structures, and present-day high-mass elliptical galaxies in detail [6, 10, 11].

With the current observation technology, it is extremely challenging to observe and examine the interstellar medium (ISM) of a red-nugget around $z \sim 2$. Due to their unique conditions, these isolated structures (or CEGs) provide us an extraordinary advantage. By utilizing this advantage, we can study galaxies located very close to us and easily observable at multiple wavelengths, obtaining significant findings and clues about the processes in the early universe. For instance, the X-ray observations of galaxies like Mrk1216 have been studied in this context. Its dark matter content, baryonic matter ratio, etc., is modelled by applying hydrostatic equilibrium conditions to the X-ray emissions of its ISM [6].

Similarly, the ISMs of such galaxies can be explored in terms of chemical abundances, and the obtained information can contribute to our understanding of both structural formation and chemical enrichment processes. Moreover, an evolution without the mentioned dry-mergers, as in the second stage, provides an additional opportunity. By this way, it is possible to investigate the effects of dynamical activities (mergers) on galactic evolution.

1.1.2 Chemical Evolution

The synthesis mechanisms of elements within galaxies are closely tied to their structural formation processes. Through the evolution process of the matter in the Universe, stars and supernova explosions are the main source of elemental nucleosynthesis. Almost all elements, except for the primordial ones like hydrogen (H), helium (He), and a small amount of lithium (Li), are synthesised through these stellar events. These elements are spread into space through various mechanisms. The elements we observe in large scale structures like galaxies and galaxy clusters have built up over billions of years through the ongoing nucleosynthesis of elements. Our current knowledge about the elemental synthesis mechanisms are still being developed. Research continues on star formation processes, the formation of large-scale structures, and how they affect the synthesis of elements along the cosmic timeline.

The predominant model of chemical evolution is the 'early enrichment' hypothesis. This hypothesis posits that element synthesis predominantly occurred before the accretion of matter into larger structures, rather than as an enrichment process occurring after accretion. This scenario is supported by contemporary observations and simulations, contributing to the ongoing advancement of our comprehension of cosmic element synthesis. Robust evidence is the observations of enriched gas at galaxy clusters outskirts, and a floor metal abundance value. Measuring a uniform contribution of supernovae (SNe) types to the total enrichment is also a strong indication. This method is based on the fact that each SNe type has a different element yield, thus their relative contribution can be calculated from the cumulative abundance pattern. Consequently, the observed homogeneity of SNe

contribution suggest that even the most distinct areas in a cluster (i.e., central areas and the outskirts) should have gone through a similar enrichment process [12–15]. Some of the reported results reach event beyond virial radius [16]. Furthermore, peak epoch of star formation seen around $z \sim 2$, and exponential drop afterwards is also supporting this scenario [17, and references therein].

Unfortunately, observing X-ray emitting plasma around $z \sim 2$ remains challenging. Therefore interpretations for the early periods of enrichment will be partially indirect. Nevertheless, studying structures similar to red-nuggets in this regard can help improve our knowledge about the early period and make them more consistent.

1.1.3 Isolated Compact Elliptical Galaxy (IsoCEG) Mrk1216

Despite numerous studies on this subject in the literature, there is no study examining the hot X-ray emitting ISM and comparing compact and relic galaxies in terms of chemical enrichment scenarios. In this thesis, we aimed to make such a comparison for the first time. For this purpose, we examined the ISM of the isolated compact galaxy Mrk1216 and make interpretations in terms of both structural formation and chemical enrichment scenarios.

Mrk1216 has been analyzed extensively across various studies in the literature, spanning different wavelengths. Notably, it exhibits structural distinctions that place it in a unique category among nearby massive Early Type Galaxies (ETGs). Primarily, Mrk1216’s halo density stands out as a positive outlier in the Λ CDM c_{200}/M_{200} relation, indicating an unusually early formation time [6]. This observation classifies Mrk1216 as a Compact Elliptical Galaxy (CEG) [11]. Moreover, Mrk1216 is considered an isolated galaxy, with only two neighboring galaxies identified within a 1 Mpc radius, both significantly fainter (2 mag in K-band) than Mrk1216 itself [3, 6, 10].

Mrk1216 has an estimated distance of 94.2 ± 2 Mpc and a redshift value of 0.021328 (NASA/IPAC Extragalactic Database (NED)¹) [10]. The effective radius (R_e) of Mrk1216 is 2.8 ± 0.1 kpc, with a stellar velocity dispersion (σ_e) of 308 ± 8 km/s [11]. The X-ray luminosity within 100 kpc radius is $L_x(< 100 \text{ kpc}) = 1.7 \pm 0.1 \times 10^{42}$ erg/s (in the 0.5 – 7.0 keV energy range). Mrk1216’s total mass within R_{500} is estimated to be $M_{500} = 4.5 \pm 0.5 \times 10^{12} M_\odot$, comprising the combined mass of its Black Hole (BH), stars, gas, and Dark Matter (DM), with a gas fraction of $f_{gas,500} = 0.058 \pm 0.008$ [6]. Stellar, gas, and DM properties of the Mrk1216 shares remarkable similarities with the nearby fossil group NGC6482 [6, 11]. Therefore, the extended X-ray emission around Mrk1216 suggests the possibility of it being part of a fossil group, formed around the relic galaxy Mrk1216 [6].

¹<https://ned.ipac.caltech.edu/>

Additionally, Mrk1216's mean mass-weighted stellar age is 12.8 ± 1.5 Gyr, with a metallicity of 0.259 ± 0.052 dex [3]. Its stellar mass within $4R_e$ is $2.0 \pm 0.8 \times 10^{11} M_\odot$ [10]. The morphology, dynamics, and density profile of Mrk1216 closely resemble those of massive galaxies at $z > 2$, distinguishing it from massive ETGs at $z \sim 0$ and indicating its relic nature [3, 5]. Consequently, Mrk1216 can be defined as a Massive Relic Galaxy (MRG) and an Isolated Compact Elliptical Galaxy (IsoCEG) as the dominant component of the possible fossil group surrounding it.

The main reason for this unexpected evolution path of Mrk1216 is thought to be a result of an interruption on the two phase galaxy formation scenario [6], as mentioned in previous section. Within this context, Mrk1216 is a galaxy that thought to be skipped the second phase of this process and became massive "relic galaxy" that serves as a largely untouched descendant of the red nugget population at high redshift [6, 10, 11, 18]. In other words, a nearby analogue of the high-redshift red nuggets. The fact that some galaxies have reached to the present day without undergoing mergers is a natural outcome of the probabilistic nature of these interactions [5, 9]. The random environments in which galaxies find themselves by chance can profoundly influence their evolution, as in between the range of being a relic or normal ETG [3]. Furthermore, the prominently peaked high-velocity dispersion profile of Mrk1216 serves as additional confirmation of its similarity to red nuggets, as they are characterized by their significantly greater compactness and disk-like isophotes, suggesting fast rotation, which sets them apart from the current population of early-type galaxies [4].

Mrk1216 is also observed to be free from strong internal activities like AGN outbursts. [6] searched for signs of an AGN feedback and did not detect any features in the central area. Combining with the additional results (e.g., temperature, entropy, t_c/t_{ff} profiles), they suggested a gentle and "precipitation-regulated" AGN feedback process for Mrk1216. This makes Mrk1216 also a good candidate for inspecting the effects of passive AGN evolution.

1.2 Objective of the Thesis

As being analogues of the high-redshift red nuggets, chemical properties of the Mrk1216 might give important clues about the universe at early epochs ($z \sim 2$) [18], in terms of enrichment scenarios. Furthermore, since Mrk1216 has predominantly remained unaffected by mergers and AGN outbursts, we can engage in discussions about the ways in which these processes influence the production and distribution of elements. These characteristics put Mrk1216 in a unique position, offering us the opportunity to explore the ISMs of galaxies in early epochs [6], which are beyond the reach of current X-ray observation

technology. This allows for a more substantial interpretation and prediction of the factors influencing chemical evolution processes and their respective degrees.

In light of these information, we focus on the differences between the measured properties of Mrk1216 and ETGs that have completed a two-phase evolution process and make interpretations by comparing their characteristics. While dynamic features are more likely to vary over time, chemical properties leave a more persistent trace of the evolutionary process [19–21]. Therefore, it is particularly crucial to utilize elemental abundances and other parameters derived from these abundances (e.g., ratios of the elements, relative contribution of SNe types to the ISM enrichment and their radial variations) to gain insights into the evolution process.

Throughout this thesis, the Λ CDM cosmology was adopted with a Hubble constant of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, a matter density of $\Omega_M = 0.27$, and a cosmological constant of $\Omega_\Lambda = 0.73$. All quoted uncertainties are at the 1σ confidence level unless stated otherwise.

2.1 Structural Formation

Our understanding of the formation and development of matter in the universe is grounded in the Lambda Cold Dark Matter (Λ CDM) cosmology. Λ CDM serves as a mathematical model and parameterization of the Big Bang cosmology. Although it is not yet a complete model that can explain everything, its strength lies in the remarkable alignment with a numerous cosmological observations spanning diverse temporal and spatial scales. Built upon certain assumptions, including the validity of general relativity as the prevailing theory of gravity and the presence of five fundamental elements - dark energy, dark matter, baryonic matter (normal matter), photons, and neutrinos - the model also posits the very low curvature of space. According to LCDM, density variations manifested early in the universe and exist ubiquitously. Consequently, the model provides a coherent explanation for the characteristics of the Cosmic Microwave Background (CMB) radiation, the observed accelerated expansion of the universe, and the hierarchical formation of Large Scale Structures (LSS) in a bottom-up scenario [1].

According to the hierarchical formation model of the Λ CDM cosmology, early forms of galaxies are started to cool down radiatively after virialisation [22]. As the temperature decreased, they became smaller and denser in time. Thus, the effects of gravitation increased up to a point that the star formation was triggered. While their structural evolution continued in the form of hierarchical formation through mergers, chemical evolution processes also began with the transition to this new phase.

2.2 Evolution of Galaxies

In addition to this general structural formation model, the evolutionary paths of galaxies may vary significantly due to environmental effects, resulting in various galaxy types [23]. There are numerous ways for categorizing these types, such as by their color, internal reddening, amount of interstellar gas, star-formation rate, etc. But the most well-known is the morphological classification made by Hubble, due to historical reasons [22]. This shape

based classification contains 4 categories: Spiral galaxies, Elliptical galaxies, Lenticular galaxies and Irregular galaxies [24].

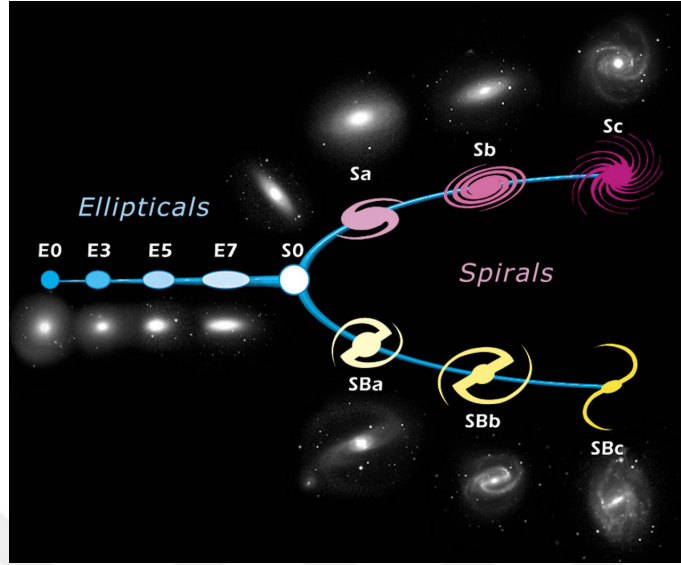


Figure 2.1 Morphological classification of galaxies (image: NASA/ESA).

Spiral galaxies consist of two main parts: a disk with spiral arm-like structures and a central bulge. They also split into two sub-categories by rather having a bar-like structure along the center or not: "normal spirals" and "barred spirals" as shown in the Figure 2.1, S's and SB's, respectively. Within this classification system, spiral galaxies ordered by being early-type or late-type. However, it is important to note that this naming convention is just a historical definition, does not reflect the actual evolution process. Unlike spiral galaxies, ellipticals (E's) does not have any distinct structural feature. They have elliptical isophotes. (Isophotes are the contour lines with same brightness intensities.) Therefore, isophotes of an elliptical structure are ellipses. Elipticity of this galaxy type is defined as $\epsilon \equiv 1 - b/a$. Here a and b denote the semimajor and semiminor axes, respectively. S0 (Lenticular) galaxies are the intermediate form between spirals and ellipticals. They represent the transition between these two types. They have a bulge and a disk-like structure without spiral arms. Additionally, S0 and elliptical galaxies are categorised as early-type, where the spirals are late-type galaxies, which is also just a traditional naming convention. Finally, irregular galaxies are the outliers of this morphological classification system. They have either a weak or no regular structure.

It is important to note that the morphology of a galaxy is tightly linked to its evolution path and properties of their content varies greatly. For example, spiral galaxies are active systems in terms of star-formation, while the elliptical galaxies has nearly or completely ended their star-formation phase long time ago and hosting mostly old stars, therefore appear red in optical observations [22].

2.2.1 Early-Type Galaxies

According to cosmological simulations, the structural evolution of massive early-type galaxies (ETGs) are believed to comprise two phases [2]. In phase 1, the gas undergoes a dissipative inflow process, triggering a rapid star-formation process, forming a super-massive black hole [5, 6]. This phase commences in the early stages of the Universe and persists until approximately $z \sim 2$. Compact ($R_e \lesssim 2$ kpc) and massive ($M_\star \gtrsim 10^{11} M_\odot$) galaxies are formed at the end of this phase [5]. The dark matter halo accompanying the newly forming galaxy is also affected, causing it to undergo some contraction [25]. These massive, compact objects are called "red-nuggets" can be observable at $z > 2$, and are widely believed to be the predecessor of today's massive ellipticals [2, 6, 25].

After the end of phase 1, a slow accretion phase takes place. In phase 2, relatively small stellar satellite systems infall into the forming galaxy. These satellite systems form at relatively early epochs ($z > 3$) beyond the virial radius of the galaxy. This slow and long-term phase initiates around $z \sim 3$ and continues until $z \sim 0$ [2]. Additionally, these systems mainly consist of stars, not gas. Therefore, the infalling process is 'non-dissipative', 'collisionless', and has little to no effect on star-formation [6]. Phase 2 leads to a substantial increase in mass and size for massive systems [3, 11].

ETGs (i.e. Ellipticals and S0s), are generally characterized by old stellar populations, red colors, limited cold gas and dust, and the absence of spiral arms. However, these characteristics are not mutually exclusive. Applying diverse selection criteria for ETGs results in distinct sets of galaxies, as observed in various studies [26, and references therein]. Their emissions can be approximated by Eq. 2.1 [27]. In this expression $b(n) \simeq 2n - 0.327$ [28]. R_e represents the radius encompassing half of the entire projected galaxy luminosity, while I_e denotes the surface brightness at R_e . Notably, the study revealed a positive correlation between the Sérsic index (n), which is associated with the concentration of the galaxy (expressing the ratio of light within the central regions to that in the outskirts), and the overall luminosity of the galaxy [26].

$$I(R) = I_e \exp \left\{ -b(n) \left[\left(\frac{R}{R_e} \right)^{1/n} - 1 \right] \right\} \quad (2.1)$$

In addition to their stellar mass, the presence of hot gas is crucial in the formation and evolution of ETGs. This hot gas [29, $\sim 0.3 - 1.2$ keV], known as the Inter-Stellar Medium (ISM), predominantly emits in the X-ray band and often extends beyond the optical size into the outskirts. It reveals large-scale structural characteristics such as cavities, cold fronts, filaments, and tails, serving as indicators of key evolutionary mechanisms. These mechanisms encompass Active Galactic Nuclei (AGN) feedback, merging history, accre-

tion/stripping, as well as processes related to star formation and quenching [30]. Additionally, this hot plasma is enriched with metals through stellar mass loss and supernova (SN) ejecta, providing crucial insights into the stellar and chemical evolution history [29].

2.2.2 Isolated Galaxies

Considering the two-stage formation and development process, we can inspect how dependent the evolutionary journey of galaxies is on environmental factors. For instance, a galaxy situated in a relatively denser and more crowded region has a higher likelihood of experiencing a galaxy merger or any other structural form. Consequently, it can swiftly continue its evolution through both intense dynamic processes and the structural and chemical evolutionary processes triggered by these dynamics. Of course, the opposite scenario is also possible. A galaxy might happen to be in a region with much lower cosmic density, allowing its evolution to remain relatively unaffected by significant dynamic influences [3, 31]. This non-uniform galaxy distribution is also confirmed by various observations [32, e.g.]. In this context, the majority of galaxies in the local Universe (54%) are observed to be concentrated within virialized groups and clusters, while an additional 20% are situated in collapsing regions around these structures. The remaining galaxies (26%) are categorized as "field" galaxies [33].

A sub-group within this category, "isolated galaxies", generally can be defined as objects with no significant companions in a given volume [34]. Another distinctive criterion is that they have not been significantly influenced by their closest neighbors during a past crossing time ($\sim 3 \times 10^9$ years) [35]. Historically, various technical definitions have been proposed for the categorization of isolated galaxies. An alternative definition is as follows: An isolated galaxy can be defined as when its evolution in terms of structure and stellar content has been dominated by internal forces for most of its life. Or, in other terms, when the external forces are not able to cause any noticeable changes in at least for $\sim 2 \times 10^9$ years [36, and references therein]. Nonetheless, the fraction of isolated galaxies in the Universe is still uncertain [33].

Furthermore, the isolated structures of such galaxies present a rare opportunity for observers. In environments where external interactions are minimal, the mechanisms of internal influences can be investigated more efficiently, and the impact of their development in the absence of certain external influences can be examined in a more effective manner [33–35].

2.3 Chemical Enrichment in Galaxies

Examining the elemental enrichment status of galaxies provides valuable insights into their evolutionary processes. Analyzing the spectrum of hot plasma, known as the Interstellar Medium (ISM), radiating in the X-ray band and filling interstellar space allows us to measure the abundance of numerous elements. These elements, synthesized and dispersed within various stars and supernova explosions (SNe), enrich the ISM [29].

Incorporating data on the quantities of these elements, their relative ratios, and their variations, dependent on the galaxy type, evolutionary stage, and environmental factors, enables comprehensive inferences [29]. This process involves establishing a connection between elemental ratios and distributions within the ISM and chemical evolutionary processes, providing a foundation for valuable insights.

A crucial factor facilitating such inferences is the variation in synthesized elements among different types of stars and supernovae. Through the mosaic of elements produced and dispersed by a multitude of diverse types over billions of years, we can estimate the total contributions of each type. Therefore, it is essential to explore the mechanisms and key features of these various processes for a complete understanding.

In our context, we categorize these different nucleosynthesis mechanisms into three groups: Type Ia supernova (SNIa), Core-collapse supernova (SNcc), and Asymptotic Giant Branch (AGB) stars [37, 38]. The following section provides brief information about these supernova types and AGB stars within the context of chemical enrichment.

2.3.1 Elemental Nucleosynthesis

Because all these heavy elements, or metals, have different atomic masses, hence different binding energies, they do not all originate from the same stellar sources. Since heavy elements possess distinct atomic masses and consequently varying binding energies, they do not have a common stellar origin [38]. The unique nucleosynthetic products of each supernova type contribute significantly to the chemical diversity observed in galaxies. These explosive events enrich the ISM with distinct sets of elements, influencing the composition of subsequent generations of stars and planetary systems.

Supernovae are powerful and cataclysmic stellar explosions that occur at the end of a star's life cycle. These events release an immense amount of energy, briefly outshining entire galaxies. Supernovae play a crucial role in the universe's evolution by dispersing heavy elements forged in the star's core into space, contributing to the formation of new stars and planetary systems.

¹<https://astronomy.swin.edu.au/cosmos/S/Supernova+Classification>

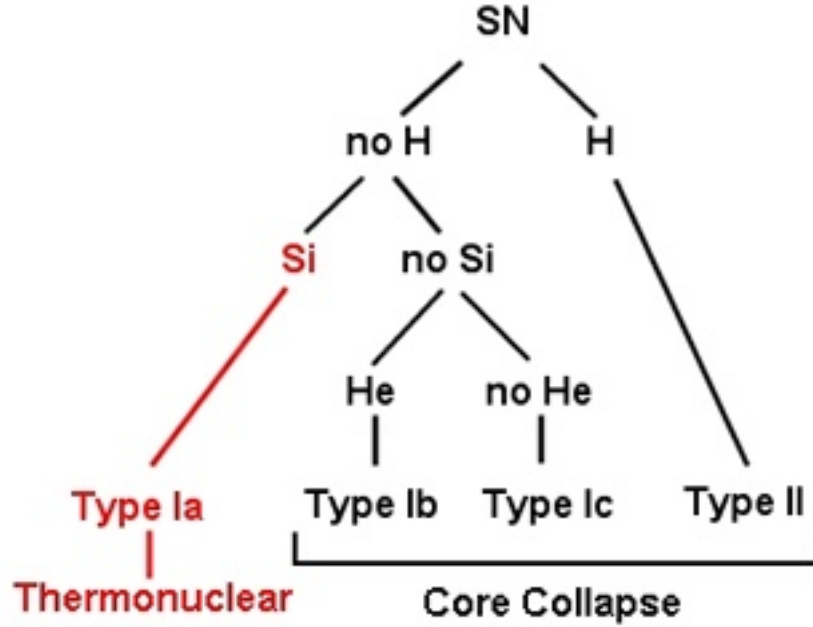


Figure 2.2 Supernova classification (image¹)

Supernovae explosions are broadly categorized into two types: thermonuclear explosions and core-collapse explosions. Understanding the distinctions in progenitors and explosion mechanisms is pivotal for classifying various supernova types. Type Ia supernovae, classified under thermonuclear explosions, are likely caused by the thermonuclear explosions of white dwarf stars. Ongoing debates persist regarding whether these explosions originate from single white dwarfs (single-degenerate) or merging white dwarf binaries (double-degenerate). Type Ia supernovae lack hydrogen and display a distinctive silicon absorption line at their peak luminosity.

In contrast, core-collapse supernovae include Type Ib, Ic, and II, occurring when massive stars exhaust their nuclear fuel and undergo gravitational collapse. Type Ib and Ic supernovae are characterized by the absence of hydrogen lines, indicating the prior loss of the outer envelope, while Type II supernovae show hydrogen lines.

2.3.2 Type Ia Supernovae (SNIa)

Low-mass stars ($\lesssim 10M_{\odot}$), when reaching the end of their lives, leave behind a dense core known as a white dwarf (WD). The internal pressure of WDs, unlike main-sequence stars, is independent of temperature. If a WD gains sufficient mass, it can undergo explosive nucleosynthesis, disrupting and ejecting even the heaviest elements. Consequently, Type Ia supernovae (SNIa) release significant amounts of elements such as Ar, Ca, Cr, Mn, Fe, and Ni, along with smaller amounts of O, Ne, and Mg. The precise nature of SNIa progenitors

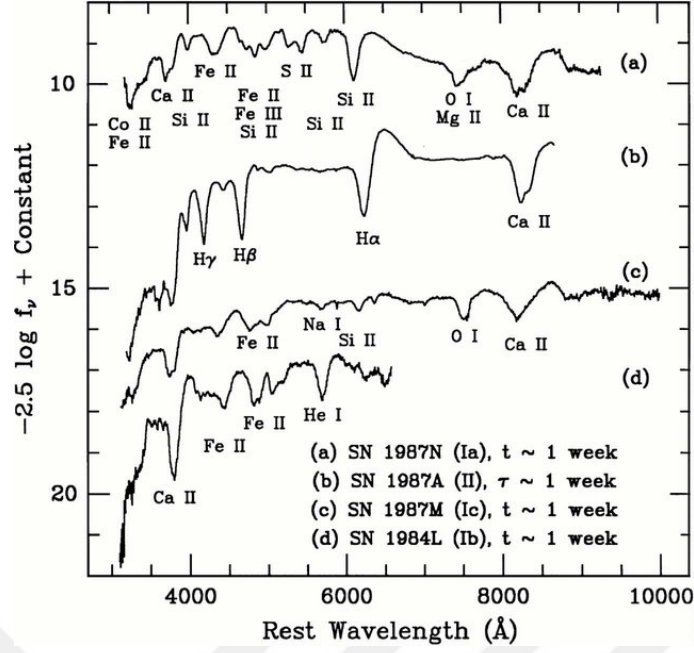


Figure 2.3 Spectra of different supernova types [39].

and their explosion mechanisms remains a mystery. Two main scenarios involve a gradual accumulation of material from a main-sequence companion (single-degenerate) or a merger with another WD (double-degenerate). The explosion mechanisms include deflagration or delayed detonation, resulting in different element yields. Deflagration models produce more Ni, while delayed-detonation models yield less Ni but more intermediate elements. A deflagration wave propagates through the star at a subsonic speed, and in delayed-detonation models, this wave transforms into a detonation at a specific density [29, 37, 38, 40].

2.3.3 Core-Collapse Supernovae (SNcc)

The death of massive stars is characterized by nuclear fusion, leading to an inert iron core. As the core approaches its effective Chandrasekhar mass, collapse emerges, and the star undergoes a powerful explosion core-collapse supernova. This phenomenon, firstly recognized by [41] in 1934. This spectacular event expels a fraction of the potential energy liberated during collapse, leaving behind a neutron star or black hole. The overall understanding of supernovae has grown over the years, yet many questions about these cosmic phenomena remain unanswered.

Massive stars, ($\gtrsim 10M_{\odot}$), undergo significant changes when about 10% of their hydrogen has burned into helium (He). As these stars evolve, they synthesize and burn heavier elements in concentric layers in their cores, forming a sequence of burning elements. The nucleosynthesis process stops at iron (Fe) and nickel (Ni) due to its endothermic nature.

Consequently, end-of-life nucleosynthesis in core-collapse supernovae (SNcc) primarily ejects elements like oxygen (O), neon (Ne), magnesium (Mg), silicon (Si), and sulfur (S), with limited amounts of heavier elements [29, 37, 38, 42–44].

The relative importance of these yields depends on factors such as the initial mass of the parent star, the initial metallicity (Z_{init}), and details of the explosion mechanism. When considering a population of massive stars rather than an individual star, integrated yields over the initial mass function (IMF) become crucial. The IMF describes the expected frequency of stars at birth based on their mass [45]. Different IMFs, like "Salpeter" [46] or "top-heavy" [47], result in varying integrated yields, impacting X/Fe abundance ratios [38].

2.3.4 Asymptotic Giant Branch (AGB) Stars

Another source of ISM enrichment is AGB stars. AGB stars represent a late evolutionary stage of low- to intermediate-mass stars, typically ranging from 0.8 to 8 $M_{\odot}$. As these stars exhaust their core hydrogen, they undergo thermal pulses, causing them to expand and become red giants. One distinctive feature of AGB stars is their ability to undergo s-process nucleosynthesis, where slow neutron captures lead to the production of heavier elements [43, 48].

Most elements lighter than oxygen, especially carbon (C) and nitrogen (N), along with fluorine (F) and sodium (Na), are primarily synthesized by low-mass stars during their AGB phase. These elements are released into the interstellar medium (ISM) through powerful winds, with the yields influenced by the initial mass and metallicities of the stars, similar to supernova type II contributions. The exact composition of elements dispersed by AGB stars can vary based on the initial mass of the star, its metallicity, and the specific conditions during its evolutionary stages [38, 43, 44, 48–50].

In summary, AGB stars, through their nucleosynthesis processes and mass-loss mechanisms, contribute substantially to the chemical enrichment of galaxies. Although AGB stars significantly contribute to the enrichment of the interstellar medium (ISM), their contribution to the measured and calculated elements within the scope of this thesis is practically negligible. Therefore, AGB yield models have not been taken into account in the calculations of supernova ratios.

2.4 X-ray Emission of Galaxies

The ISM is a highly ionized plasma due to the gravitational potential of dark matter, with elements like Hydrogen and Helium completely stripped of electrons. This hot medium

emits X-rays through quantum interactions, offering insights into the ISM. X-ray spectroscopy allows measurements of several physical quantities, such as temperature and density at various locations [51].

The X-ray emission from ionized atoms, described by the coronal approximation, simplifies in optically-thin, collisional equilibrium plasmas. Three crucial conditions define the thermodynamic state, assuming free photons, atoms with electrons mainly in ground states, and local relaxation to a Maxwellian distribution around a common electron temperature, T . These approximations are valid for low radiation densities in galaxies, allowing a simplified understanding of X-ray processes in the ISM [51].

This hot ($\sim 10^7 - 10^8$ K) plasma in galaxies (and clusters), characterized by densities ranging from 10^{-5} to 10^{-1} (cm^{-3}), facilitates straightforward X-ray spectra modeling. Three fundamental emission processes contribute to the radiation: free-free or bremsstrahlung radiation (caused by the deflection of charged particles off of one another), free-bound or recombination radiation, and bound-bound or deexcitation radiation. The first two lead to continuum radiation, while the latter results in line radiation. Notably, there is an exception to bound-bound transitions, which is the forbidden radiative transition from the 2s to the 1s state. This transition occurs through a very slow two-photon process, generating continuum radiation with a branching ratio distribution function. All radiative processes depend on electron-ion collisions, with rates proportional to temperature, electron density, and ion density. It is important to highlight that the predominant radiation process at ISM temperatures is continuum bremsstrahlung, and its temperature dependence is approximately proportional to $\propto T^{1/2}$ [52, 53].

2.4.1 Ionisation Equilibrium

The distribution of atoms among different charge states is governed by a delicate equilibrium between ionizations and recombinations. This equilibrium is defined by a system of coupled differential equations that describe the interplay of ionization and recombination processes among adjacent charge states. The equations take the form as shown in Eq. 2.2.

$$\frac{dn_i}{dt} = -I_i n_e n_i - R_i n_i + I_{i-1} n_e n_{i-1} + R_{i+1} n_e n_{i+1} \quad (2.2)$$

Here, n_e is the electron number density, n_i is the density of atoms in the i th charge state, I_i is the ionization rate from the i th charge state, and R_i is the recombination rate from the i th state. Spatial diffusion of the ionization balance is neglected. The ion density is conventionally expressed relative to the hydrogen number density (n_H), introducing the relative abundance (a_i) and the fraction of atoms in a specific charge state (f_i). Conse-

quently, $n_i = n_H f_i a_i$, where $n_H a_i$ cancels out of the equations. Assuming a steady-state for collisional equilibrium (where the left-hand side is set to zero), the equations simplify to the Eq. 2.3.

$$0 = I_i f_i + R_{i+1} f_{i+1} \quad (2.3)$$

Collisional equilibrium is achieved over time if a plasma remains undisturbed for a sufficiently long period (comparable to the inverse of the recombination rate). Numerous calculations have explored this ionization balance as a function of electron temperature [54–57].

Once the ionization balance is established, the X-ray spectrum can be computed by considering various radiation processes, with bremsstrahlung and K and L shell transitions being the most significant for discrete line emission [51].

2.4.2 Continuum Emissions

Three components of continuum emission is free–free (bremsstrahlung), free–bound (recombination), and bound–bound (deexcitation), as mentioned previously. Combination of these components created the continuum emission of the observed spectra.

For the radiation of bremsstrahlung emission, the power per energy per volume can be roughly approximated by Eq. 2.4 [51].

$$\frac{d^2 P}{dV dE} \approx 10^{-11} n_e n_H T^{-1/2} e^{-\frac{E}{kT}} \text{ cm}^{-3} \text{ s}^{-1} \quad (2.4)$$

Here n_e is the electron density, n_H is the hydrogen density, E is the photon energy, k is Boltzmann's constant, and T is the electron temperature in Kelvin. Therefore, the total radiated power can be given as Eq. 2.5 [51].

$$\frac{dP}{dV} \approx 10^{-27} n_e n_H T^{-1/2} \text{ ergs cm}^{-3} \text{ s}^{-1} \quad (2.5)$$

Additionally, the emissivity in units of frequency (ν) can be expressed as the following equation 2.6, where the emissivity is defined as the emitted energy per unit time, per frequency and volume (Eq. 2.7) [52].

$$\epsilon_{\nu}^{ff} = \frac{2^5 \pi e^6}{3 m_e c^3} \left(\frac{2\pi}{3 m_e k} \right)^{1/2} Z^2 n_e n_i g_{ff}(Z, T_g, \nu) T_g^{-1/2} \times \exp(-h\nu/kT_g) \quad (2.6)$$

$$\epsilon_{\nu} \equiv \frac{dL}{dV d\nu} \quad (2.7)$$

Here n_e , n_i , and Z is the number density of electrons, ions, and charges, respectively. $g_{ff}(Z, T_g, \nu)$ component is the gaunt factor which makes corrections for the quantum mechanical effects and distant collisions [58]. Intensity of radiation emitted by each unit volume of gas can be given as Eq. 2.8 [59].

$$B_{\nu} = 6.2 \times 10^{-39} g \exp\left(\frac{-h\nu}{k_B T}\right) \frac{1}{\sqrt{T}} n_e \quad (2.8)$$

In the expression, B_{ν} denotes the intensity, g is the Gaunt factor, a function dependent on ν with a value approximately equal to unity, and n_e represents the electron density. When accounting for the emission region having a volume V , the total radiated energy, L_{ν} , and the total luminosity, L is obtained by integrating over the emitted spectrum, is formulated in Eq. 2.9 and 2.10, respectively.

$$L_{\nu} = 4\pi \times 6.2 \times 10^{-39} g \exp\left(\frac{-h\nu}{k_B T}\right) \frac{1}{\sqrt{T}} \int n_e^2 dV \quad (2.9)$$

$$L = 1.64 \times 10^{-27} g \sqrt{T} \int n_e^2 dV \quad (2.10)$$

Here L_{ν} is in the units of $\text{erg s}^{-1} \text{Hz}^{-1}$ and $\int n_e^2 dV$ is the emission measure.

The second component of the continuum emission is the free-bound (recombination) radiation, where ion captures an electron and emits a photon. The free-bound transition equation is given by the Eq. 2.11.

$$\begin{aligned} \epsilon_{\nu}^{fb}(X^i) d\nu &= n(X^{i+1}) n_e \sum_l \frac{\omega_l(X^i)}{\omega_{gs}(X^{i+1})} a_{\nu}^l(X^i) \\ &\times \frac{h^4 \nu^3}{c^2} \left[\frac{2}{\pi (m_e k T_g)^3} \right]^{1/2} \exp \left[- \left(\frac{h\nu - \chi_l(X^i)}{k T_g} \right) \right] \end{aligned} \quad (2.11)$$

In this context, l represents the summation over all energy levels within the ion X^i , gs denotes the ground state of the recombining ion X^{i+1} , ω corresponds to the statistical weights of the levels, a_ν^l signifies the photoionization cross-section, and $\chi_l(X^i)$ represents the ionization potential for each energy level in the ion [52].

The last component of the continuum is the bound–bound (two-photon decay) emission. The emissivity of this radiation is given in Eq. 2.12.

$$\epsilon_\nu^{2q} \propto n_p n_e \gamma_\nu(2q) \quad (2.12)$$

Here, $\gamma_\nu(2q)$ is the emission coefficient (2.13).

$$\gamma_\nu(2q) = \frac{h A(\gamma) \gamma X \alpha_B(T)}{A_2} \quad (2.13)$$

In the equation 2.13 [52], where $\gamma = \nu/\nu_{12}$, $A_2 = 8.227 \text{ s}^{-1}$ denotes the total probability per second of emitting a photon with energy $\gamma h \nu_{12}$ as one part of the pair. Here, X represents the probability per combination for the occurrence of a two-photon decay, and $\alpha_B(T)$ is the overall recombination coefficient [60]. The coefficient $\alpha_B(T)$, measured in $\text{cm}^3 \text{ s}^{-1}$, is expressed as follows.

$$\alpha_B(T) = 1.627 \times 10^{-13} t^{-1/2} [1 - 1.657 \log(t) + 0.584 t^{1/3}] \quad (2.14)$$

where $t = 10^{-4} T$.

Thus, the total emissivity of the continuum emission can be obtained by summing the three components: free-free (bremsstrahlung), free–bound (recombination), and bound–bound (deexcitation) emissions (Eq. 2.10).

$$\epsilon_\nu^{(tot)} = \epsilon_\nu^{ff} + \epsilon_\nu^{fb} + \epsilon_\nu^{bb} \quad (2.15)$$

2.4.3 Line Emissions

In addition to the continuum emission, line emissions that arises from various atomic processes are also crucial tools for X-ray spectroscopy. These atomic processes include collisional excitation, radiative recombination, dielectronic recombination, and resonant excitation [51].

The intensity of an emission line is determined by the excitation and recombination rates, which are directly proportional to the integral of velocity multiplied by the cross-section for a specific process over a Maxwellian distribution. The volume emissivity for a particular emission line is computed using equations like:

$$\epsilon = n_e n_i (C^{II} f_{i-1} + C^E f_i + \alpha^R f_{i+1}) \quad (2.16)$$

where C^{II} represents the rate of inner shell ionization processes, C^E is the sum of collisional excitation processes, α^R is the sum of recombination, and f_i fraction of atoms in a given charge state [51].

Diagnostics of elemental abundances in the ISM involve a comparison between the flux in spectral lines and that of the continuum. The majority of X-ray lines are commonly excited through collisional processes initiated by electrons. This forms the fundamental basis for conducting diagnostic assessments of elemental abundances in the ISM. The equation 2.17 offers a representation of the integrated emissivity associated with a line excited through collisional processes [38].

$$\begin{aligned} \int \epsilon_{\text{line}}(E) dE &\propto n(X^i) n_e E T^{-1/2} \Omega(T) e^{-\Delta E/kT} \\ &\propto \left[\frac{n(X^i)}{n_X} \right] \left[\frac{n_X}{n_p} \right] \left[\frac{n_p}{n_e} \right] n_e^2 E \Omega(T) T^{-1/2} e^{-\Delta E/kT} \end{aligned} \quad (2.17)$$

Here, ΔE is the excitation energy above the ground state of the excited level and $\Omega(T)$ is the strength of the collision. Due to the ISM being approximately in collisional ionization equilibrium (CIE), the ionization fractions for an element (represented as $n(X^i)/n_X$ for an element X) depend solely on the electron temperature T and are independent of ISM density. This leads to the line emissivity being proportional to both the density squared and the abundance of the relevant element $[n_X/n_p]$. At low densities (as in ISM), the ratio of line emission to continuum is density-independent but directly proportional to the abundance of the corresponding element. By determining the electron temperature (T) from line ratios or the shape of the X-ray continuum spectrum, the line-to-continuum ratio, particularly the equivalent width of the line, can be easily converted into an elemental abundance.

2.4.4 Absorption

Absorption is also an important factor while dealing with X-ray spectra due to the fact that the ultraviolet light and X-rays can be efficiently absorbed by neutral and partially ionized material, as extensively discussed in [61]. The absorption phenomenon manifests as an exponential reduction in the received light intensity, represented by $I \propto e^{-\tau}$, where the optical depth τ is defined as $\tau = \sigma N_H$. Here, N_H denotes the integral of neutral hydrogen along the line of sight in cm^{-2} . The absorption cross section $\sigma(X(Z), E)$, a function of photon energy $E = h\nu$, accounts for the abundances of all other metals contributing to absorption in the intervening medium, with $X(Z)$ characterizing the relative abundance of element Z concerning the hydrogen column density N_H [62].

The ISM hosts large quantities of such absorbing material in the form of a complex multiphase collection of ions, atoms, molecules, and dust grains spread throughout our Galaxy's thin stellar disk. This multiphase ISM exhibits a wide range of densities ($10^{-4} < n_{H,ISM} < 10^6, \text{cm}^{-3}$), contributing prominently to X-ray absorption [63, and references there in].

The total absorption cross section of the ISM can be expressed as the sum of cross section of three components, gas, molecules and grains (Eq. 2.18). Therefore, the observed intensity can be written as in Eq. 2.19 (see [61] for further details).

$$\sigma_{ISM} = \sigma_{gas} + \sigma_{molecules} + \sigma_{grains} \quad (2.18)$$

$$I_{obs}(E) = e^{-\sigma_{ISM}(E)N_H} I_{source}(E) \quad (2.19)$$

3

OBSERVATION AND DATA REDUCTION

3.1 XMM-Newton X-Ray Observatory

The XMM-Newton (X-ray Multi Mirror) X-ray observatory, launched by the European Space Agency (ESA) in December 1999, stands as a cornerstone in the realm of X-ray astronomy [64]. Named after Sir Isaac Newton, the telescope is equipped with three state-of-the-art X-ray telescopes and an array of scientific instruments, enabling it to capture X-ray images and spectra of celestial objects. The observatory's primary mission is to explore the X-ray universe, studying a diverse range of astronomical phenomena, including active galactic nuclei, galaxies, galaxy clusters, supernova remnants, and stellar coronae.



Figure 3.1 Image of the XMM-Newton X-ray observatory (image: ESA/XMM-Newton).

XMM-Newton is equipped with three advanced X-ray telescopes: the European Photon Imaging Camera (EPIC), the Reflection Grating Spectrometer (RGS), and the Optical Monitor (OM). Each instrument plays a unique role in capturing and analyzing X-ray emissions from celestial objects.

- **European Photon Imaging Camera (EPIC):** EPIC consists of three X-ray cameras: EPIC-pn (PN), EPIC-MOS1, and EPIC-MOS2. These cameras utilize charge-coupled devices (CCDs) to detect X-ray photons and provide detailed imaging capabilities. EPIC-pn, with high sensitivity in the high-energy X-ray range, offers exceptional imaging capabilities.
- **Reflection Grating Spectrometer (RGS):** RGS specializes in high-resolution X-ray spectroscopy, utilizing diffraction gratings to disperse X-rays. This technology allows scientists to study the detailed spectral lines of X-ray emissions, enhancing the observatory's ability to analyze chemical composition and temperature.
- **Optical Monitor (OM):** The Optical Monitor complements X-ray instruments by offering simultaneous optical and ultraviolet observations of celestial targets. With features like a filter wheel and grisms, it facilitates various imaging and spectroscopic modes.

Table 3.1 Technical details of XMM-Newton Observatory

Instrument	EPIC MOS	EPIC pn	RGS	OM
Bandpass	0.15-12 keV	0.15-12 keV	0.35-2.5 keV	180-600 nm
Sensitivity	$\sim 10^{-14}$ ^(a)	$\sim 10^{-14}$ ^(a)	$\sim 8 \times 10^{-5}$ ^(b)	20.7 mag ^(c)
Field of view (FOV)	30'	30'	$\sim 5'$	17'
PSF (FWHM/HEW)	5"/14"	6"/15"	N/A	1.4"-2.0"
Pixel size	40 μm (1.1")	150 μm (4.1")	81 μm (9×10^{-3} Å)	0.476513"
Timing resolution	1.75 ms	0.03 ms	0.6 s	0.5 s
Spectral resolution ^(d)	~ 70 eV	~ 80 eV	0.04/0.025 Å ^(e)	180 ^(f)

^a In the range 0.15-12.0 keV, in units of $\text{erg s}^{-1} \text{cm}^{-2}$

^b O VII 0.57 keV line flux in $\text{photons cm}^{-2} \text{s}^{-1}$, for an integration time of 10 ks and a background of $10^{-4} \text{photons cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$

^c 5- σ detection of an A0 star in 1000 s.

^d At 1 keV energy

^e In -1. and -2. order, resp.; at 1 keV, this corresponds to 3.2/2.0 eV (HEW).

^f Resolving power ($\lambda/\Delta\lambda$) with UV and optical grism.

XMM-Newton operates in a highly elliptical orbit, ranging from approximately 7,000 to 114,000 kilometers above Earth's surface. This orbital choice ensures long observation periods without interference from Earth's atmosphere, optimizing the capture of X-ray data from a wide range of astronomical sources.

To manage observations effectively, XMM-Newton follows a systematic scheduling process, considering the specific requirements of each instrument and the scientific objectives of proposed observations. Proving resilient beyond its initial mission lifespan, XMM-Newton has been providing valuable data for exploring the X-ray universe.

XMM-Newton's X-ray telescopes boast unmatched sensitivity, featuring the largest effective area among focusing telescopes. This high sensitivity is achieved by utilizing 58 thin nested mirror shells in each X-ray telescope, resulting in a point-spread function (PSF) that has a full width at half maximum (FWHM) of approximately 6'' and a half energy width (HEW) of around 15''.

In terms of spectral resolution, XMM-Newton excels across both moderate and high ranges. The EPIC CCD cameras provide moderate spectral resolution, exhibiting a resolving power ($E/\Delta E$) within the range of 20 to 50. Conversely, the RGS spectrometers offer significantly higher spectral resolution, reaching values between 200 and 800.

Table 3.2 Comparison table of XMM-Newton Observatory with other X-ray satellites

Satellite	Mirror PSF FWHM (") ^(a) HEW (") ^(b)	E. Range [keV]	Eff. Area at 1 keV [cm ²]	Energy Res. at 1 keV [eV]
XMM	6 / 15	0.15 - 12	4650	4 (RGS)
Chandra	0.2 / 0.5	0.1 - 10	555 (ACIS-S)	1 (HETG)
ROSAT	3.5 / 7	0.1 - 2.4	400	500
ASCA	73 / 174	0.5 - 10	350	100
Suzaku	96-120 / 108-138	0.2 - 600	1760 (XIS)	50
RXTE	n.a. / n.a. ^(c)	2-250	n.a. ^(c)	n.a. ^(c)
Swift	8.8 / 18	0.2-10 (XRT)	133.5	70
NuSTAR	18 / 58	3-79	n.a. ^(c)	n.a. ^(c)

^a FWHM: Full Width at Half Maximum.

^b HEW: Half Energy Width.

^c n.a.: not available or not applicable.

Simultaneous operation of all six science instruments enhances XMM-Newton's observational capabilities. Operating independently, these instruments offer flexible scheduling for exposures. The inclusion of the OM optical/UV telescope enables simultaneous optical/UV observations, facilitating the monitoring and identification of optical/UV counterparts for X-ray sources observed by the X-ray telescopes.

Benefiting from a highly elliptical orbit, XMM-Newton ensures long continuous visibility of a target for up to approximately 40 hours. This extended visibility, coupled with a minimum height for science observations at 46,000 km, is particularly advantageous for studying source variability and optimizing overall observatory efficiency.

The European Photon Imaging Camera (EPIC) constitutes a vital component of the XMM-Newton observatory, enhancing its capabilities for X-ray observations. With two X-ray telescopes equipped with EPIC MOS CCD arrays and the third utilizing the EPIC pn CCD camera, these instruments enable highly sensitive imaging observations within a 30' field of view (FOV) and an energy range spanning from 0.2 to 12 keV. Notably, they offer moderate spectral resolution ($E/\Delta E \sim 20 - 50$) and angular resolution ($\sim 6''$ FWHM; $\sim 15''$ HEW).

The EPIC pn camera stands out for its ability to operate with exceptionally high time resolution, reaching 0.03 ms in the timing mode and 0.007 ms in the burst mode, albeit with a low duty cycle of 3%. However, the absolute timing accuracy relies on the correlation between on-board time and universal time, monitored regularly through observations of the Crab Pulsar.

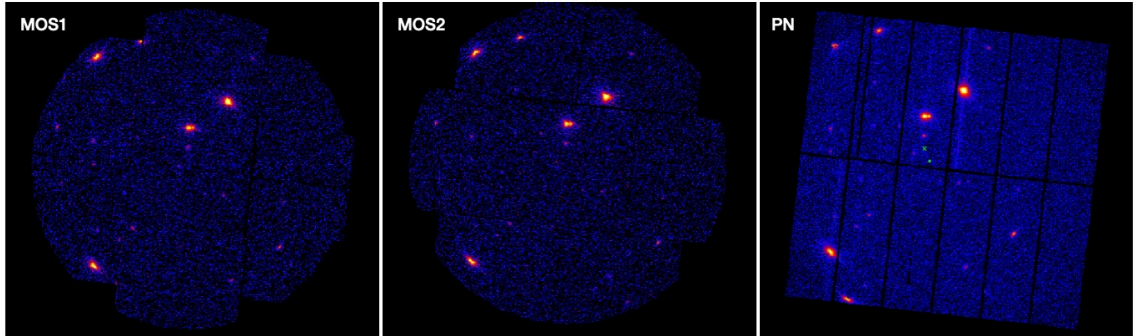


Figure 3.2 Field of view for both EPIC MOS and EPIC pn cameras (image: ESA/XMM-Newton).

The layout of EPIC detectors and the X-ray telescope's field of view for both EPIC MOS and EPIC pn cameras is illustrated in Figure 3.3 and Figure 3.2, respectively. Key details include the slight offset of the pn chip array from the optical axis, ensuring optimal energy collection for on-axis point sources. The EPIC MOS cameras are rotated by 90° relative to each other, and the dead spaces between MOS chips are attributed to detector edges. Technical details¹ of the XMM-Newton observatory are also listed in Table 3.1. Lastly, a comparison table² of XMM-Newton with some of the other X-ray satellites are listed in Table 3.2

In 2005, an event suggested micrometeorite impact, causing damage to MOS1 CCD6,

¹https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/basics.html

²https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/xmmcomp.html

Comparison of focal plane organisation of EPIC MOS and pn cameras

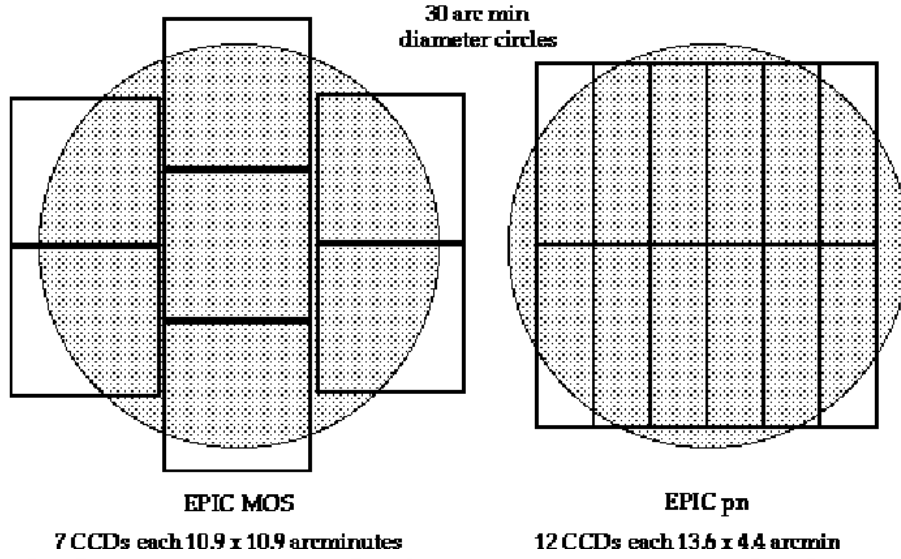


Figure 3.3 The layout of EPIC detectors (image: ESA/XMM-Newton).

Table 3.3 Observation Summary of Mrk1216

Obj. Name	Obs. ID	Obs. Date	Instrument	Exposure (ks)
Mrk1216	0822960201	2018-11-01	EPIC/RGS	~ 109.7

leading to its deactivation. A similar event in 2012 impacted MOS1-CCD3, rendering it unusable for science. Despite these incidents, scientific observations continue with adaptations, and observers are encouraged to refer to dedicated web pages^{3,4} for comprehensive assessments of these events' scientific impact.

3.2 Data Reduction

We analyzed the archival XMM-Newton [65] observation of the isolated compact elliptical galaxy Mrk1216 (RA:08^h28^m47.11^s, DEC:−06^d56^m24.5^s) with 109.7 ks total exposure. The observation was performed at 2018-11-01 with observation id 0822960201. The observation summary is given in Table 3.3.

We used both EPIC (MOS1, MOS2, pn) and RGS instruments of XMM-Newton for analyzing Mrk1216. The EPIC instrument is used for imaging analysis and extracting spectra of selected annuli, shown in Figure 3.10. RGS is used for extracting high resolution spectrum of central area. The steps of the analysis, adopted methods and used software are described in the following sections, in detail.

³<https://www.cosmos.esa.int/web/xmm-newton/mos1-ccd6>

⁴<https://www.cosmos.esa.int/web/xmm-newton/mos1-ccd3>

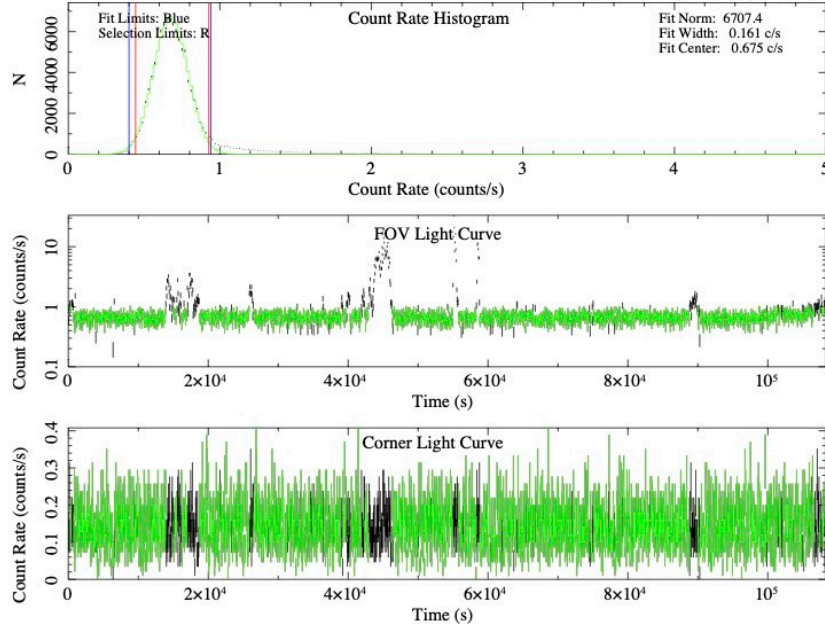


Figure 3.4 Count rate histogram and light-curve for MOS1 camera. The time intervals that contain soft proton contamination are shown in black color.

3.2.1 EPIC Analysis

The XMM-Newton observation data of Mrk1216 underwent processing through the Extended Source Analysis Software (ESAS), which is integrated into Science Analysis System (SAS) version 19. Following the analysis procedures outlined by [66], the methodology employed in this thesis can be outlined as follows: *emchain* and *epchain* tools were used for initial filtering and calibration. *emchain* is applied to MOS event files and *epchain* is applied to pn event files. In order to eliminate the faulty pixels, Event files were also filtered with the `FLAG == 0` condition. For MOS, events with one to four pixels (`PATTERN ≤ 12`) were selected, while for pn instruments, only double pixel events (`PATTERN ≤ 4`) were retained. The *mos-filter* and *pn-filter* tasks were applied to detect time intervals contaminated by soft-protons (SP). Thus, the tasks can calculate uncontaminated or clean time intervals named good time intervals (GTIs). Point source detection utilized the *wavdetect* tool from the *CIAO* software [67]. A *mask* file was then created, incorporating the detected point sources for use within ESAS tasks, facilitating the exclusion of these sources from the data. Following the cleaning process, spectral files were extracted using the *mos-spectra*, *mos_back*, *pn-spectra*, and *pn_back* tools.

The count rate histograms and light-curves for each camera are shown in Figures 3.4, 3.5 and 3.6. The filtered time intervals that exceed the average count rate, due to the soft proton (SP) contamination, (see Section 3.2.3), are also shown in the Figures. The filtered images of Mrk1216 from MOS1, MOS2 and PN cameras are shown in Figure 3.7.

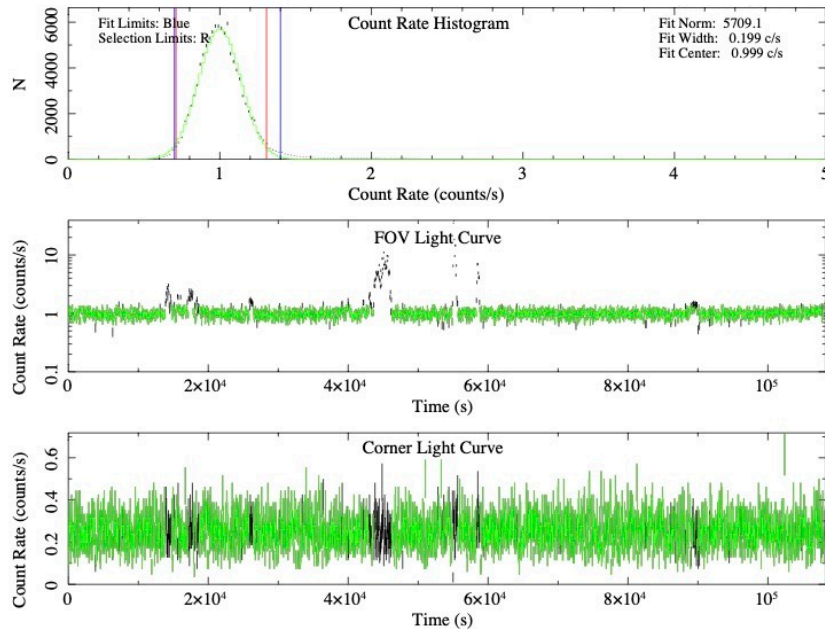


Figure 3.5 Count rate histogram and light-curve for MOS2 camera. The time intervals that contain soft proton contamination are shown in black color.

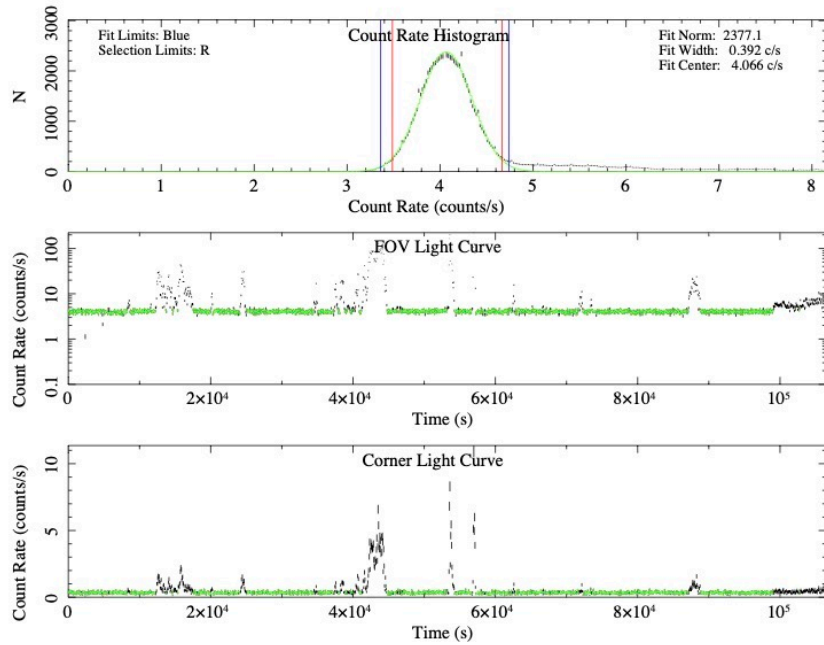


Figure 3.6 Count rate histogram and light-curve for PN camera. The time intervals that contain soft proton contamination are shown in black color.

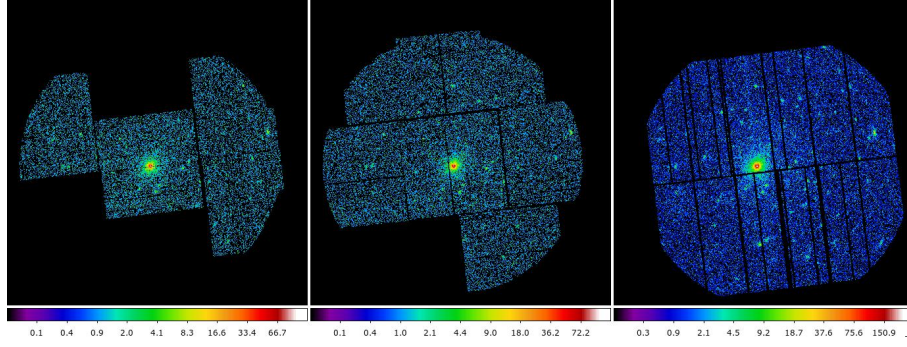


Figure 3.7 Images of Mrk1216 for each camera (mos1, mos2 and PN, respectively).

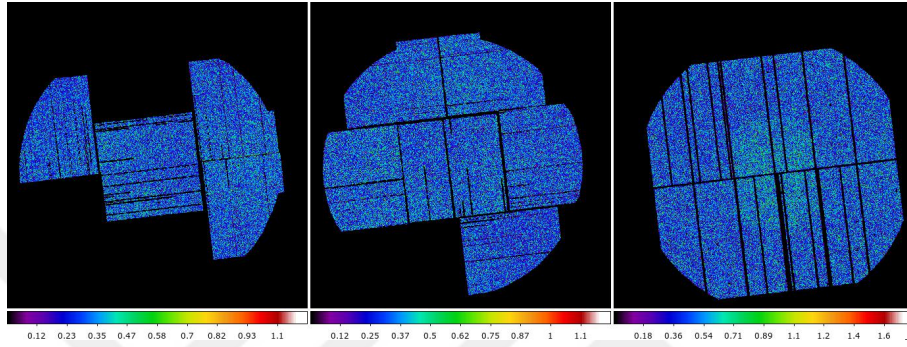


Figure 3.8 QPB background images of Mrk1216 for each camera (mos1, mos2 and PN, respectively).

Images are produced from the filtered event files. The corresponding background images (Quiescent Particle Background, see Section 3.2.3 for details) for each camera are also shown in Figure 3.8. Finally, the mask files for filtering the point sources detected by the *wavdetect* tool are shown in Figure 3.9. The adaptively smoothed and combined image of the Mrk1216 is shown in Figure 3.10.

3.2.2 Surface Brightness Profile

Following the standard data reduction steps, we extracted the surface brightness profile of Mrk1216. One of the purposes of using the surface brightness profile is to determine

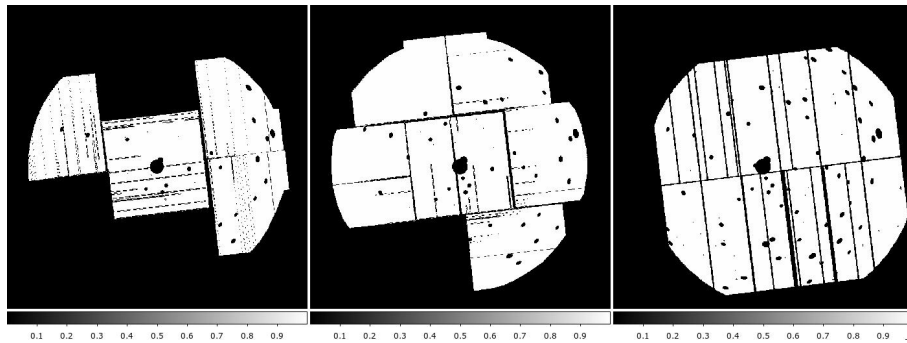


Figure 3.9 Mask files for filtering detected point sources by *wavdetect* tool.

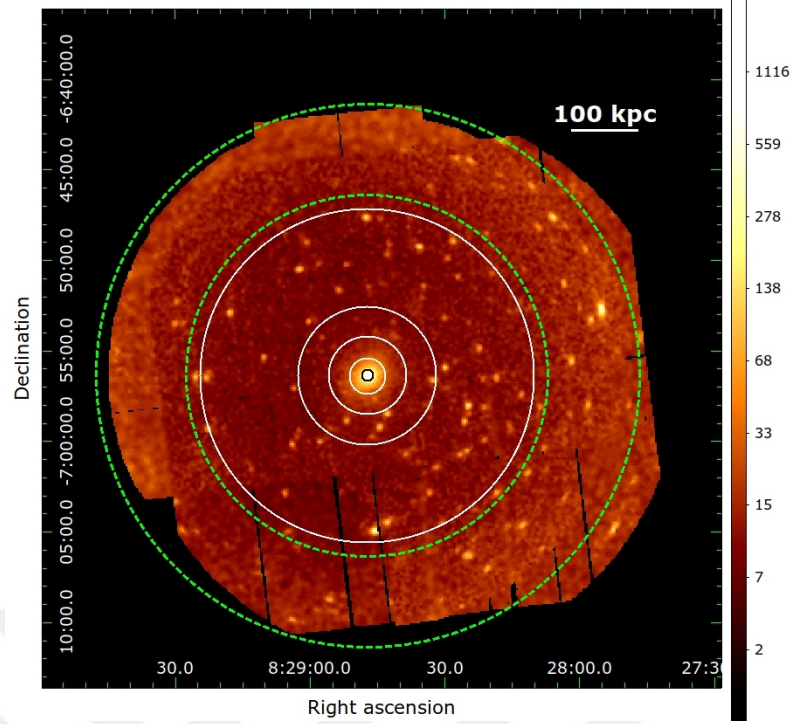


Figure 3.10 Adaptively smoothed and combined image of Mrk1216. Solid white annuli show the selected regions for analysis, extends up to R_{500} . The central region has a black color for the sake of visualisation. The green dashed annulus shows the background region.

how the brightness of ISM changes from the center of the galaxy outskirts. This allows modeling and characterization of the radial brightness changes. Another purpose is to calculate the distance within the field of view where the galaxy's ISM emission drops to the background emission level. This provides a measure of the radius up to which the galaxy's emission should be examined. We derived β model [68] to represent the ISM emission and a constant model for background emission. The fit results are reported in Section 4.

$$S(r) = S_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta+0.5} \quad (3.1)$$

3.2.3 Spectral Analysis

By modeling the spectrum of Mrk1216's ISM, we can calculate parameters such as electron density, temperature, elemental abundance, and luminosity. However, the observed data presents multiple components originating from various sources, each possessing distinct characteristic features. Therefore, to achieve accurate modeling, a meticulous examination and modeling of each component are essential. Fundamentally, these components

can be categorized into three groups: Non X-ray Background (NXB), Cosmic X-ray Background (CXB), and Source Emission (SE). Details of each component are described in the following sections.

3.2.3.1 NXB (Non-X-ray Background)

The NXB is mainly a result of energetic particles interacting directly with the detector or with the materials surrounding the detector, generating fluorescent X-rays that subsequently hit the detector [69]. NXB has 3 components: Fluorescent instrumental lines for each MOS and pn detector, QPB (Quiescent Particle Background) and SP (Soft Proton) contamination. Fluorescent instrumental lines are taken into account as Gaussian models with given energies, as described in [66].

ESAS spectrum extraction tasks generate the QPB spectra of the interested region. Therefore, we modelled it with a combination of multiple Powerlaws as continuum and additional Gaussian components when needed. For each spectral region, we calculated the fit parameters and kept them fixed in the main model.

Although the SP contamination is filtered by the light curve filtering during the data reduction process as mentioned in Section 3.2.1, we added a Broken-Powerlaw component for the possible residual soft proton contamination as described in [66]. During the fitting, we initially set the normalisations of the residual SP components to zero. After reaching a stable fit status, we set them free to account the residuals.

Since these NXB components are not originated from X-ray photons, the usual response files are not suitable for them. We used diagonal response files provided within ESAS CALDB (Calibration Database) as suggested by [66].

$$NXB = QPB + SP \quad (3.2)$$

3.2.3.2 CXB (Cosmic X-ray Background)

CXB has 3 components, LHB (Local Hot Buble), GH (Galactic Halo) and UPS (Unresolved Point Sources) [69, 70]. In order to model these 3 components, we extracted spectrum for 600-900 arcsec region as background area, show in the Figure 3.10 as white dashed annuli. We also used the ROSAT All-Sky Survey (RASS) spectrum to fit our background spectra simultaneously with it. The RASS spectrum is obtained from X-ray background tool provided by the *HEASARC* (High Energy Astrophysics Science Archive Research Center) web site⁵. We chose an annulus with radii of 1° and 2°, centering the Mrk1216.

Table 3.4 Best fit parameters for The CXB (Cosmic X-ray background) emission.

Component Name	Parameter (Unit)	Measured Value
LHB	kT (keV)	0.11
	Norm (cm ⁻⁵)	2.03×10^{-7}
GH _{Cold}	kT (keV)	0.10
	Norm (cm ⁻⁵)	4.22×10^{-6}
GH _{Hot}	kT (keV)	0.30
	Norm (cm ⁻⁵)	2.56×10^{-7}
UPS	Γ	1.45
	Norm (cm ⁻⁵)	8.78×10^{-7}

LHB is modelled with a thermal emission model (APEC) with fixed temperature value (0.11 keV). GH is modelled with double thermal emission models (APEC+APEC) for a cold and a hot component. UPS is modelled with a Powerlaw with fixed index ($\Gamma = 1.45$). All thermal models metal abundance values are fixed to 1.0 and redshift value fixed to zero. Finally additional absorption model is added for GH and UPS components.

After all these model components are fitted with both RASS and EPIC spectrum simultaneously, the obtained CXB parameter values are used in the main model for source regions. These values are shown in Table 3.4.

$$CXB = LHB + Abs(GH_{cold} + GH_{hot} + UPS) \quad (3.3)$$

3.2.3.3 Source Emission

The final component consists of ISM and LMXB (Low Mass X-ray Binary) emissions. LMXBs create a hard continuum emission mostly seen as point sources in the observation and their cumulative spectra are almost constant through different galaxies [71, 72]. Although detectable point sources were filtered from the data, the X-ray emission of the ISM might contain a considerable amount of unresolved LMXB emissions [29]. Even though the contribution of unresolved LMXB for Mrk1216 is relatively small [6], we included it as an additional component due to the necessity for detailed modeling and the possibility of a higher rate of undetected point sources, given the relatively low spatial resolution of XMM. Consequently, the Source Emission component can be modeled as follows: ISM can be represented with a thermal emission model, and LMXB with a Powerlaw model

¹heasarc.gsfc.nasa.gov/cgi-bin/Tools/xraybg/xraybg.pl

with a fixed index [71, $\Gamma = 1.6$]. Both components are multiplied with an absorption model to account for Galactic column density (n_H).

In order to accurately measure the elemental abundances of the ISM, proper modeling is essential. Assuming a single-temperature plasma, as an example, may lead to inaccurate measurements, especially in the case of a multi-phase plasma [73, 74]. An illustrative instance of this situation is the phenomenon known as 'Fe-bias' [75]. To address this, we utilized a multi-temperature model called VGADEM from the XSPEC package (refer to section 3.2.5.1, [76]). The VGADEM model operates on the assumption of a Gaussian distribution of emission measure, implying that the plasma is represented by multiple temperature components distributed in a Gaussian manner. This model allows the derivation of mean (μ_{kT}) and sigma (σ_{kT}) values for the temperature distribution, along with their associated uncertainties. Additionally, the model enables the measurement of abundance values for various elements in relation to Solar values (He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, Ni).

$$Source = Abs(ISM + LMXB) \quad (3.4)$$

3.2.4 RGS Analysis

Finally we extracted high resolution spectra by using RGS instrument of XMM-Newton, following the standard procedure described by official guide book⁶. The working mechanism of RGS is different from EPICs, as described in Section 3.1. Therefore, the selected spectral region is not a radial profile consisting of rings, but a thin strip whose two ends extend along the field of view (FOV). The width of the region is selected as 40 arcsec, which is the diameter of the central region selected for EPIC analysis (20 arcsec radius), in order to focus to the core of the galaxy.

3.2.5 Spectral Fitting

3.2.5.1 EPIC

Spectral fitting were performed by X-ray Spectral Fitting Package (XSPEC) 12.11.1 [76] and AtomDB (Atomic Database) version 3.0.9 [77, 78]. Energy range of MOS spectra were restricted in 0.3 – 6.5 keV and pn spectra in 0.4 – 6.5 keV. C-statistics [79] were adopted for fitting process. Therefore, we didn't bin any of the spectra nor subtract background from the spectra, as required by the selected statistic. Finally, *LPGS* [80] abundance table is selected for calculating the elemental abundances the Solar unit.

⁶<https://heasarc.gsfc.nasa.gov/docs/xmm/abc/abc.html>

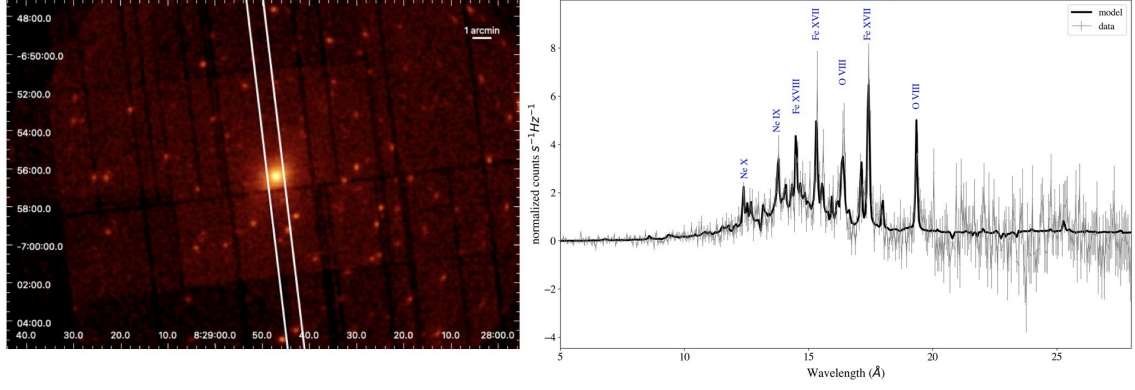


Figure 3.11 *Left*: Adaptively smoothed and combined image of Mrk1216. White lines show the selected spectral region for RGS analysis. *Right*: Spectral fit of the selected RGS region.

The final EPIC spectral model is shown in Eq. 3.5. The *FL* component represents the fluorescent lines for mos and PN cameras. We added a *Gaussian* component for each line as described in [66]. The first of the two *Const* parameters added to represent the small deviations between mos1, mos2 and PN detectors. The second one is the area value of each spectral region. Since the areas are not equal for the 3 detectors, it is added to scale the emissions to equalize them with the RASS spectra, as described in [66]. The *Abs* expression stands for the galactic absorption in terms of hydrogen column density (n_H). The *PHABS* model from *XSPEC* is used for calculating the absorption in spectral modelling. Value of the n_H is taken from [81]. Due to the fact that the *NXB* component is a particle background, standard response files can not be used for them. Therefore we modelled them separately from the main part of the model with a diagonal response file provided by *ESAS* calibration files, as described in [66].

$$S = [FL + Const \times Const \times Abs(CXB + Source)] + [NXB] \quad (3.5)$$

3.2.5.2 RGS

Spectral fitting of RGS spectra were also performed by using the same tools and statistics. We restricted RGS spectra in 7-22 Angstrom where most complex X-ray lines are located. In the fitting process, elemental abundances of O, Ne, and Fe within the *VGADDEM* model vary freely. Modelling the RGS spectra is a straightforward process, relative to the EPIC spectral fitting as described in Section 3.2.5.1. The derived spectral model consist of an absorption model (*TBABS*) to take into account for hydrogen column density additional to the multi-temperature plasma emission model. Finally, RGS spectral region and modelled spectra are shown in Figure 3.11.

3.3 SNIa Ratio Calculations

Hot inter-stellar X-ray plasma in elliptical galaxies is recognized for its substantial metal content, primarily originating from explosions of core-collapse supernovae (SNcc) and Type Ia supernovae (SNIa). Determining the fractional contribution of each supernova type involves a comparison between measured element abundances and expected nucleosynthesis yields from progenitor models. These models simulate supernova explosions, predicting mass production for each element based on specific initial conditions. Theoretical yields are typically provided in units of Solar mass ($M_{\odot}$). SNcc yields, which depend on factors such as stellar mass, explosion energy, and metallicity, necessitate integration for each element. This integration is performed using a function for stellar mass distribution called IMF (Initial Mass Function). Salpeter IMF [46] and top-heavy IMF [82] are some of the viable options. The IMF characterizes the expected star frequency at birth relative to their mass [45]. Integrated yields (Y_i) for a specific element i are calculated by:

$$Y_i = \frac{\int_{m_l}^{m_u} Y_i(m) m^{-(1+x)} dm}{\int_{m_l}^{m_u} m^{-(1+x)} dm} \quad (3.6)$$

Here, the lower and upper mass limits of the integration are m_l and m_u , denotes for initial masses of stars that eventually expected to explode as SNcc. These limits are typically set to $10 M_{\odot}$ for low mass limit and $50 M_{\odot}$ for high mass limit. Therefore, throughout this study, SNcc yields were integrated using a Salpeter IMF with the mass limits of 10-50 $M_{\odot}$. The slope for the Salpeter IMF is $x = 1.35$. Unlike SNcc, SNIa yields do not require integration.

Abundance of an element (X) relative to Fe (Iron) can be calculated for a single supernova type using equation (3.7):

$$\langle X/Fe \rangle = \frac{Y_X/M_X}{Y_{Fe}/M_{Fe}} \times \frac{1}{(X/Fe)_{\odot}} \quad (3.7)$$

Here, Y denote the yield of an element and M is its mass number (e.g., $M_{Fe} = 56$). As both SNcc and SNIa contributed to the ISM enrichment, their fractional/relative contributions are combined in equation (3.8):

$$\langle X/Fe \rangle = \left(\frac{a(N_X)Ia + b(N_X)cc}{a(N_{Fe})Ia + b(N_{Fe})cc} \right) \times \frac{1}{(X/Fe)_{\odot}} \quad (3.8)$$

Here, $N_x = Y_x/M_x$. The fractions of SNIa and SNcc contributions are represented with a

Table 3.5 Implemented Yield Tables in SNeRatio

Reference	Reference Table ^a	Initial Metallicity ^b	SN Type
[83]	Table 2	–	SN Ia
[84]	Table B1	–	SN Ia
		0.0	
		0.001	
[43]	Table ^c	0.004	SN cc
		0.008	
		0.02	
		0.05	

^a This column refers to cited table numbers.

^b This column is given in units of $Z_{\odot}$.

^c <http://star.herts.ac.uk/chiaki/works/YIELDCK13.DAT>

and b respectively. They are also subject to the condition in equation (3.9):

$$a + b = 1.0. \quad (3.9)$$

3.4 SNeRatio Code

For this study and future research, we have developed Python tool called SNeRatio. This well-tested tool is published as an open-source project, specifically designed to estimate the relative contributions of supernova types. In the calculation process it models the given element abundances in the Interstellar Medium (ISM) or Intra-Cluster Medium (ICM) using a selected combination of SN Ia and SN cc progenitor yield models. The details of these models are summarized in Table 3.5. The code calculates the SN Ia fraction (denoted as the a value in equation (3.8)) relative to the total number of contributing supernovae (SN Ia + SN cc). This estimation is made by comparing elemental abundances obtained from X-ray spectra for ISM or ICM enrichment with the implemented supernova yields. Thus, the SN Ia fraction is defined as follows:

$$R_{(Ia)} = \frac{SN Ia}{SN Ia + SN cc}. \quad (3.10)$$

The SNeRatio code uses the least squares fitting algorithm and find the best set of parameters. This approach has proven effective in determining the SN Ia ratio in the chemical enrichment process of A1837's Intra-Cluster Medium (ICM) [14], identifying the most

suitable combination of progenitor models among those implemented `SNeRatio` source code is publicly available at the following web page⁷ with a user manual. Contributions, feature requests, and bug reports are all welcomed.



⁷<https://github.com/kiyami/sneratio>

4

RESULTS

In this work, we investigate the chemical properties of the isolated elliptical galaxy Mrk 1216 in detail using X-ray spectral analyzing techniques. The spectral analysis of Mrk1216 extends up to the R_{500} radius as 5 concentric circular annuli and a single circular region that covers the area as a whole, with an additional background region beyond the R_{500} . After calculating the background emission parameters carefully, the ISM emission was modelled for each region as described in Section 3.

During the spectral modelling, an unidentified excess is detected at ~ 1.2 keV for the central two regions. Curiously, [6] also detected the same emission from the Chandra observations of Mrk1216 and discussed the possible explanations in detail. The detection of the same excess from different observatories suggests that this is not an instrument related emissions. The identification of this excess emission might require detailed analysis and additional observations, which is beyond our scope. For the sake of avoiding the possible biases that this excess might introduce, the 1.17 - 1.25 keV energy range is removed from the spectra for the mentioned regions. This energy range was carefully selected and checked if it effects the modelling of both continuum emission and elemental abundances.

We should also note that, we observed slight S shaped residuals at the spectra of R_{500} region. Possibly, ISM of the R_{500} region contains huge amount of plasma with different phases, e.g. mixture of elemental lines of different ionisation stages due to wide temperature range, as mentioned by [29] with a similar trend. It is reasonable to assume that this effect becomes more noticeable as the area increases in size. Considering that we modeled the entire R_{500} region as a whole, even using a multi-temperature model (VGADEM) might not compensate for this effect, given the wide abundance range. Therefore, our spectral analysis results for the R_{500} region (e.g., plasma temperature and elemental abundances) appear to be affected by a similar situation and should be treated with caution. We did not observe this trend in any of the other regions.

The analysis results of the selected regions includes radial profiles of X-ray luminosity, plasma temperatures, elemental abundances and SNIa ratios. Some of these properties

were analysed and reported within previous studies by using Chandra X-ray observations of Mrk1216 [4–6]. We made our most comparisons with [6] due to the fact that this work covers the data with the longest exposure, by including the latest Chandra observations of Mrk1216.

While the higher spatial resolution of the Chandra satellite allows the central areas to be examined in more detail, higher spectral resolution of the XMM satellite gave us the advantage of measuring element abundance values with more precision. In addition, XMM’s wider field of view allowed us to expand our analysis up to R_{500} radius. Therefore, it would be useful to make this comparison, taking into account the fact that different analysis and modelling methods were used.

4.1 Surface Brightness Profile

In order to study the ISM emission accurately, point sources were extracted using the procedure with the mask file described in Section 3.2.1. We derived β model [68] for modelling the ISM emission and a constant model for background emission. However, single- β model was not able to model the data adequately. Adding an additional β model greatly improved the fit, thus the final emission model became double- β with a constant background model. The equation of the total emission model is presented in Eq. 4.1. The first β -model corresponds to the main emission component of the galaxy and has a brighter peak with a slightly steeper decline, while the second β -model is fainter in the center and starts to dominate approximately starting from the 4th source region ($\sim 65kpc$). The r_{c1} and β_1 values (3.41 ± 0.34 kpc and 0.55 ± 0.02) are consistent with the analysis results of [6] which are $6.2^{+2.0}_{-1.3}$ arcsec ($2.8^{+0.9}_{-0.6}$ kpc) and $0.52^{+0.03}_{-0.02}$ respectively. Fit parameters are reported in Table 4.1 and the modelled surface brightness profile is shown in Figure 4.1.

$$S_{Total} = S(r)_1 + S(r)_2 + bkg. \quad (4.1)$$

Double- β model is usually needed for modelling the Cool-Core galaxy clusters (CC) where the single- β model is inadequate to represent their emission. The added model is needed for the excess emission comes from the dense cores of these type of clusters [85]. In our case, the necessity might be originated from the complex emission mechanisms of the galaxy or the ISM having multi-phase plasma analogues to the over-dense cores of CC clusters. These possibilities are discussed in Section 5.

For the sake of specifying spectral regions, we defined a hard limit for the radius where the brightness value drops to the modelled background level within 3σ uncertainty. We noticed that the R_{500} value of the Mrk1216 stays inside this radius limit. (R_{500} is defined as

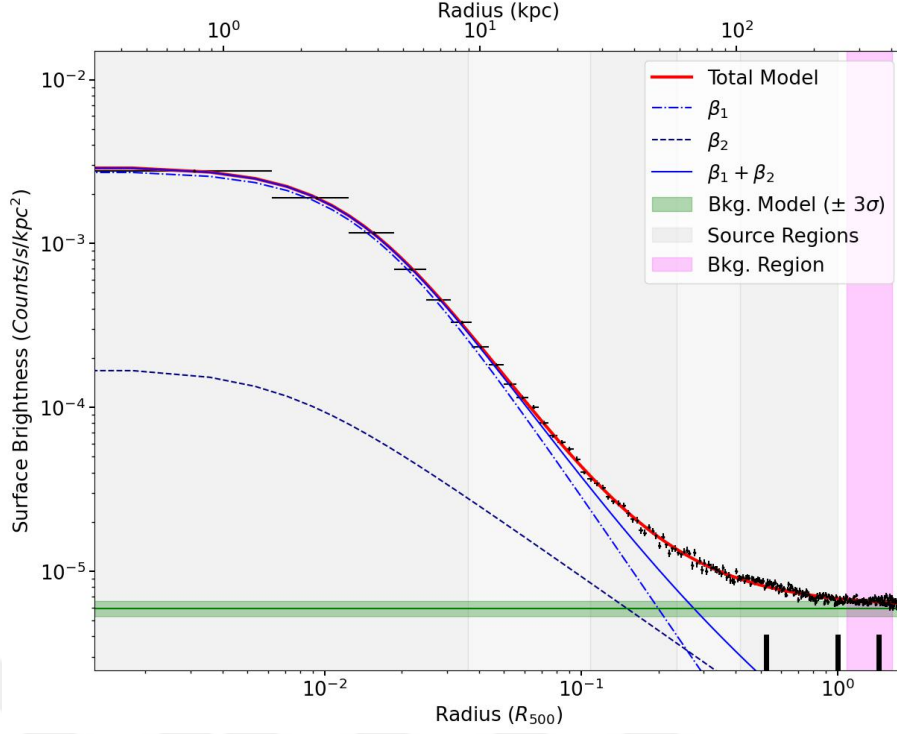


Figure 4.1 Mrk1216 Surface Brightness Profile.

the radius at which the mean mass density is 500 times the critical density of the universe at the galaxy redshift.) Therefore, for further analysis, we defined the radius limit as the R_{500} ($\sim 248kpc$) value to ensure the comparability of our results on an R_{500} scale.

After setting the radius limit, we split this area (R_{500}) into 5 concentric annuli for spectral analysis. We also defined a background annulus for modelling the background emission, with radii of $268.8kpc$ and $403.2kpc$, beyond the R_{500} . The background region was selected as far as possible, in order to get a better representation of its emission, spectrally. Source regions are shown as white solid circles and background region is shown as green dashed annuli in Figure 3.10. The black short vertical lines at the right bottom of the Figure 4.1 represents the R_{2500} ($\sim 130kpc$), R_{500} ($\sim 248kpc$) and R_{200} ($\sim 358kpc$) radius values of Mrk1216 [6].

4.2 Temperature Profile

We extracted spectra for 5 source regions and 1 background region. Selected regions are shown in Figure 3.10. We calculated the temperature values as described in section 3.2.5.1. The extracted spectra for each region and the temperature values calculated from these spectra are plotted in Figure 4.2 and Figure 4.3, respectively. The black data points indicates the mean temperature value (μ_{kT}) of the multi-temperature model (VGADeM) with uncertainties, while the green boxes indicates the associated sigma values of the tem-

Table 4.1 Surface Brightness Profile.

Parameter	Value		Unit
S_1	2.77 ± 0.43	$(\times 10^{-3})$	$(cts/s/kpc^2)$
r_{c1}	3.41 ± 0.34		(kpc)
β_1	0.55 ± 0.02		-
S_2	0.17 ± 0.50	$(\times 10^{-3})$	$(cts/s/kpc^2)$
r_{c2}	1.72 ± 3.06		(kpc)
β_2	0.35 ± 0.06		-
<i>Bkg.</i>	5.91 ± 0.21	$(\times 10^{-6})$	$(cts/s/kpc^2)$

perature distribution (σ_{kT}). Uncertainties of the μ_{kT} for the 2 central regions cannot be seen in Figure 4.3 due to their small values, can be seen in Table 4.2. Uncertainties of the σ_{kT} values are shown as green strips.

We observed a slight radial decrement trend in the μ_{kT} values starting from ~ 0.77 keV down to ~ 0.61 keV up to R_{500} . The difference is significant for the first 3 regions, the rest is consistent within the uncertainties (σ_{kT}). Central region has the largest σ_{kT} value (~ 0.16), indicating that it covers a larger temperature range. Although it is not significant due to the increasing uncertainties (green stripes on the Figure 4.3), σ_{kT} value is decreasing for the following regions. The last region has near zero σ_{kT} value, which means that the plasma can be approximately represented by a single-temperature model. Unfortunately both uncertainties (μ_{kT} and σ_{kT}) on the last region is the largest, therefore single-temperature approximation is not significant. High background contamination and low source counts might have made it difficult to determine the ISM continuum, resulting in large uncertainties for this region.

[6] measured temperature values up to ~ 110 kpc by using *Chandra* observations of Mrk1216. The temperature peaks at the center and decreases with radius, ranging between ~ 0.6 - 1.0 keV (Table 6 of the mentioned paper). This radius value approximately covers the central 4 regions of this work (~ 103 kpc). Although these results are not directly comparable due to being measured by different instruments and modelled with single-temperature model, taking the average temperature values for the corresponding radius bins gives consistent results.

4.3 Luminosity Profile

As mentioned in Section 3.2.3, the source model consist of two components, ISM and LMXB. We calculated the $0.3 - 8.0$ keV ISM and LMXB luminosity of R_{500} region which are $L_{ISM, R_{500}} = 5.43 \pm 0.06 \times 10^{39}$ erg/s and $L_{LMXB, R_{500}} = 0.67 \pm 0.05 \times 10^{39}$ erg/s,

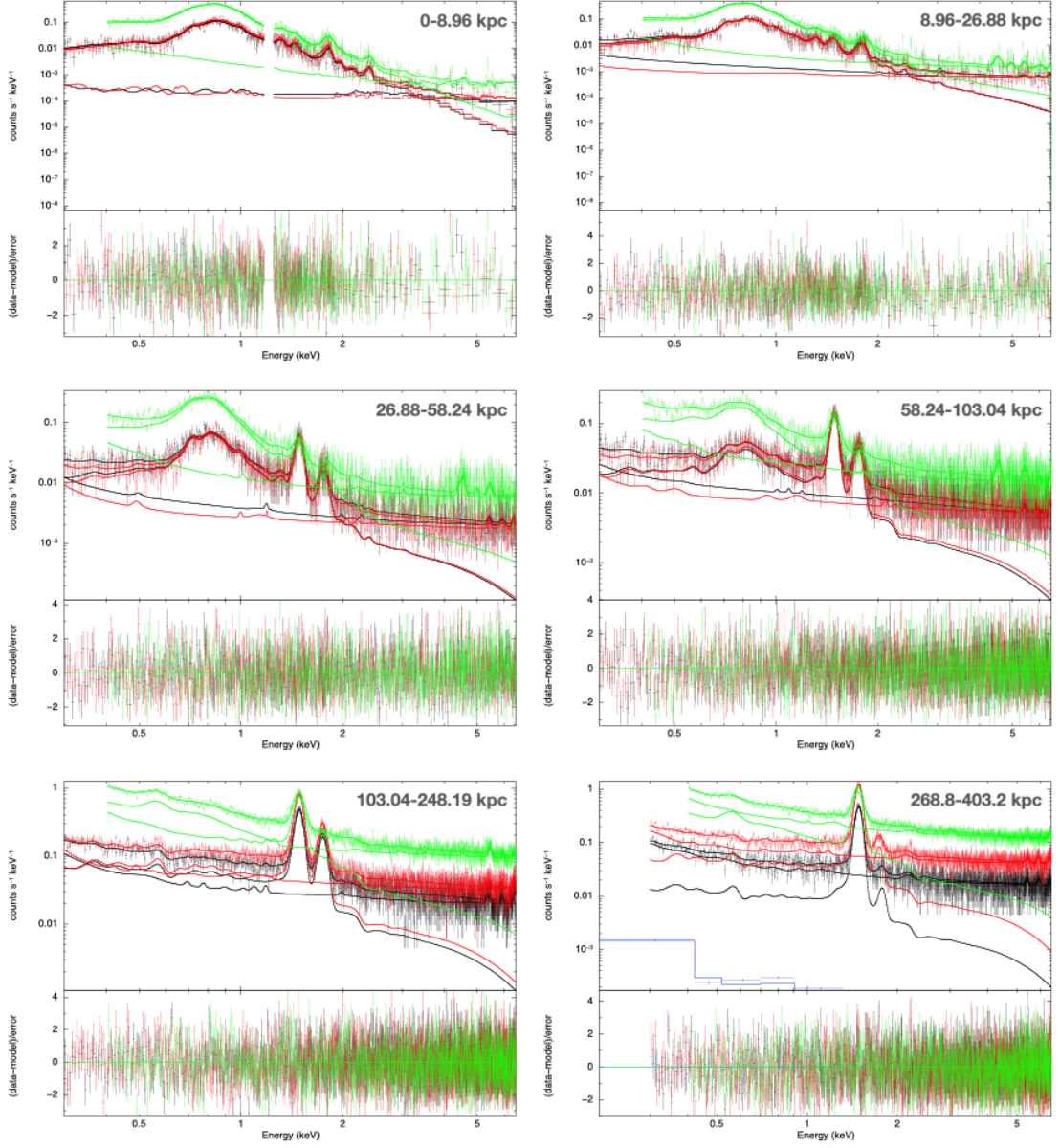


Figure 4.2 Modelled spectra of Mrk1216 for each region. Lower panels of each spectrum shows the deviation between the data and the best-fit model. The radius intervals of the regions are written at the upper-right side of each panel. The bottom-right panel shows the spectra of the background annuli.

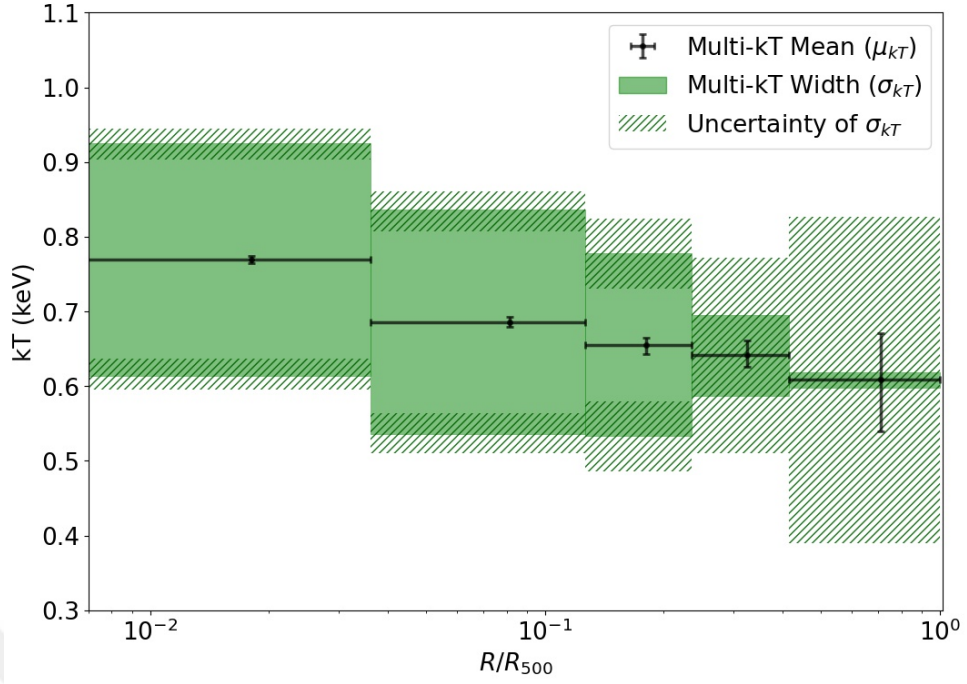


Figure 4.3 Radial temperature profile of Mrk1216. The derived multi-temperature plasma emission model (VGADEM) calculates the mean (μ_{kT}) and standard (σ_{kT}) deviation of temperature values for a region.

respectively. The visually detectable point sources were removed from the spectral regions as mentioned before (see Section 3.2.1). Therefore, this LMXB luminosity contribution comes from the unresolved sources. The measured values corresponds to $\sim 0.12 L_{\text{LMXB}}/L_{\text{ISM}}$ ratio for the R_{500} radius.

Additionally we calculated the luminosity values for the 5 source regions in order to see how the ISM and LMXB profiles changes with radius. Unfortunately, we were not able to determine LMXB luminosity values for the 5 source regions, since they are measured as being consistent with zero. Nonetheless we were able to set an upper limit by calculating their uncertainties within 3σ confidence interval. These upper limit values are shown in Figure 4.4 as red dotted horizontal lines.

4.4 Abundance Profile

We were able to measure the Fe abundance successfully up to R_{500} radius, with XMM-EPIC instruments. For Mg and Si, the spectral data quality allowed us to measure up to region 4 ($\sim 0.42R_{500}$). High S/N ratio of the central 2 regions ($\sim 0.11R_{500}$) allowed us to measure also S. The abundance profiles are shown in Figure 4.5. Additionally, we measured O, Ne and Fe abundances with XMM-RGS instrument. Since the RGS's spectral regions covers a slit along the field of view, we tuned the width as 20 arcsec (~ 8.96 kpc) to match with the central region. All the measured abundance values are listed in Table

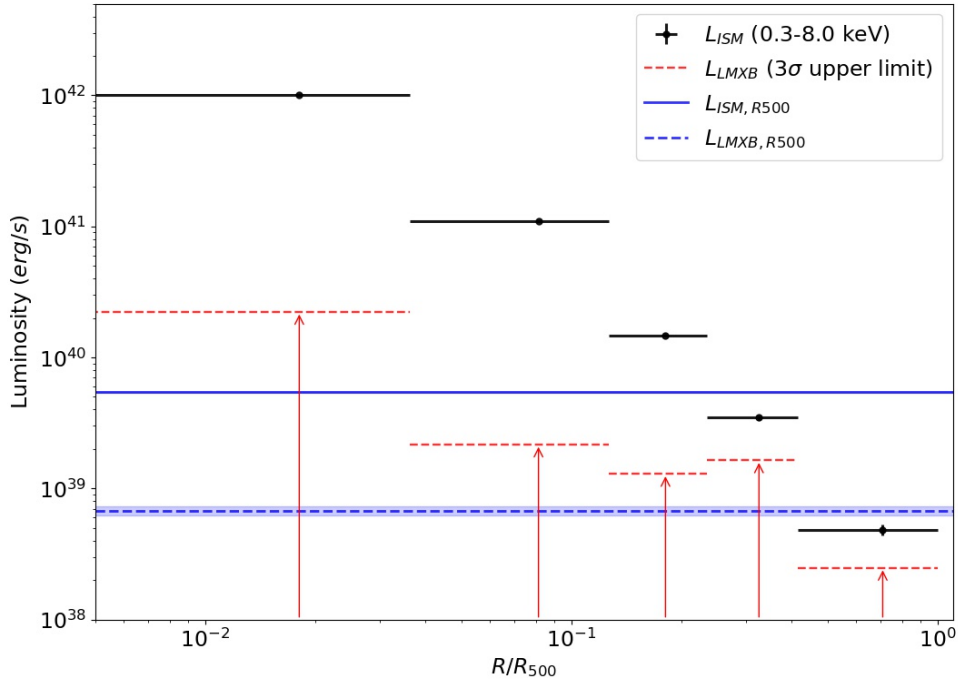


Figure 4.4 Radial luminosity profile of Mrk1216. Black data points corresponds to the ISM emission and red dashed lines corresponds to the $3\text{-}\sigma$ upper limit of LMXB (Low Mass X-ray Binary) emission. Blue horizontal line shows the ISM luminosity and blue dashed line shows the LMXB luminosity for R_{500} region.

4.2.

In addition, we detected high Si-K fluorescence line emission contamination in the spectra of regions 3 and 4. As is well known, this line emission is present only in MOS1 and MOS2 cameras, but not in pn [66]. Therefore, in order to test whether this contamination affects the measured Si element abundance, we unlink the Si abundance parameters during the fit for the MOS1, MOS2 and pn data. As we expected, the Si abundances for the MOS1 and MOS2 data were inconsistent with each other and reached suspiciously high values ($\text{Si} \gtrsim 2$). Consequently, in order to prevent this additional excess from affecting our abundances measurements, we have taken the Si abundances in these two regions only from the pn data.

In the case of EPIC measurements, we observed a steady decline for both Mg, Si and S. The Fe abundances starts with a peak and shows an almost flat profile at the middle, and ends with a dramatic drop at the final region. The Mg profile is showing a flattening at the last region, similar with the Fe profile at that radius, but the large uncertainties prevents us to confirm this trend.

The abundance ratios are more reliable for inspecting chemical enrichment, rather than their absolute values [29]. Therefore we calculated the abundance ratios with respect to

Table 4.2 Spectral fit results of Mrk1216.

Instrument	Radius (kpc)	kT_{μ} (keV)	kT_{σ} (keV)	O	Ne	Mg	Si	S	Fe	C-Stat./dof
RGS	0-8.96	$0.800^{+0.021}_{-0.019}$	$0.232^{+0.054}_{-0.051}$	$0.45^{+0.16}_{-0.11}$	$0.35^{+0.19}_{-0.14}$	-	-	-	$0.517^{+0.155}_{-0.105}$	1729.21/1468
	0-8.96	$0.770^{+0.004}_{-0.004}$	$0.155^{+0.019}_{-0.022}$	-	-	$1.11^{+0.14}_{-0.11}$	$0.80^{+0.11}_{-0.08}$	$1.06^{+0.24}_{-0.20}$	$0.891^{+0.082}_{-0.061}$	2638.47/3639
	8.96-26.88	$0.686^{+0.007}_{-0.007}$	$0.150^{+0.025}_{-0.029}$	-	-	$0.77^{+0.08}_{-0.09}$	$0.56^{+0.09}_{-0.08}$	$0.71^{+0.28}_{-0.23}$	$0.630^{+0.059}_{-0.050}$	3657.81/3640
EPIC	26.88-58.24	$0.655^{+0.009}_{-0.013}$	$0.122^{+0.047}_{-0.046}$	-	-	$0.57^{+0.17}_{-0.12}$	$0.47^{+0.15}_{-0.13}$	-	$0.592^{+0.117}_{-0.073}$	4032.11/3690
	58.24-103.04	$0.641^{+0.020}_{-0.016}$	$0.054^{+0.077}_{-0.054}$	-	-	$0.56^{+0.19}_{-0.23}$	$0.35^{+0.34}_{-0.33}$	-	$0.543^{+0.048}_{-0.052}$	3975.01/3690
	103.04-248.19	$0.608^{+0.062}_{-0.069}$	$0.010^{+0.208}_{-0.010}$	-	-	-	-	-	$0.129^{+0.048}_{-0.042}$	3918.67/3690
	0-248.19	$0.713^{+0.006}_{-0.003}$	$0.123^{+0.012}_{-0.012}$	-	-	$0.52^{+0.04}_{-0.04}$	$0.22^{+0.05}_{-0.05}$	$0.41^{+0.22}_{-0.22}$	$0.375^{+0.003}_{-0.004}$	3879.53/3689

Fe. Mg/Fe ratios starts with a slightly higher value from unity, then became consistent with zero. The mean values of Si/Fe ratios decreases but they are all consistent with unity within error bars. S/Fe values are also consistent with unity with large uncertainties. The abundance ratios are plotted in Figure 4.6

Finally, the abundance measurements of the overall R_{500} region are also listed in Table 4.2. However, these values might not be reliable due to the mentioned residuals on the modelled spectra (see Section 4). The elemental abundance measurements are highly sensitive to the determination of other spectral components, especially the ISM continuum. Even small fluctuations might effect the measured abundances dramatically. Hence the reported R_{500} abundance values should be treated cautiously.

[86] is one of the most comprehensive and up to date study for chemical enrichment of elliptical galaxies, groups and clusters, with large sample size of 44 nearby objects. In this study, they split the sample into two categories. The first category contains the galaxy clusters, and the second category contains elliptical galaxies and galaxy groups. The separation was made by the objects temperature (below or above 1.7 keV), which is related to its mass. The analysis results of Mrk1216 can be compared with the second category (<1.7 keV) to check if it follows the expected average behaviour of the mentioned sample or has any distinct features that can be related to its special evolution process. We should note that, both studies used the same solar table (LPGS, [80]), therefore the systematic differences between solar tables are eliminated when comparing the measured abundance values.

Initially, we made a comparison between the abundance values of 4 elements that we measured, Mg, Si, S and Fe (Figure 4.7). We observed a centrally peaked Mg profile, rather than a near flat behaviour as in [86]. We measured significantly higher values in the central 2 regions. The rest are also higher in terms of mean values but not significant within uncertainties. In case of Si, both profiles fits well together with a slight insignificant sep-

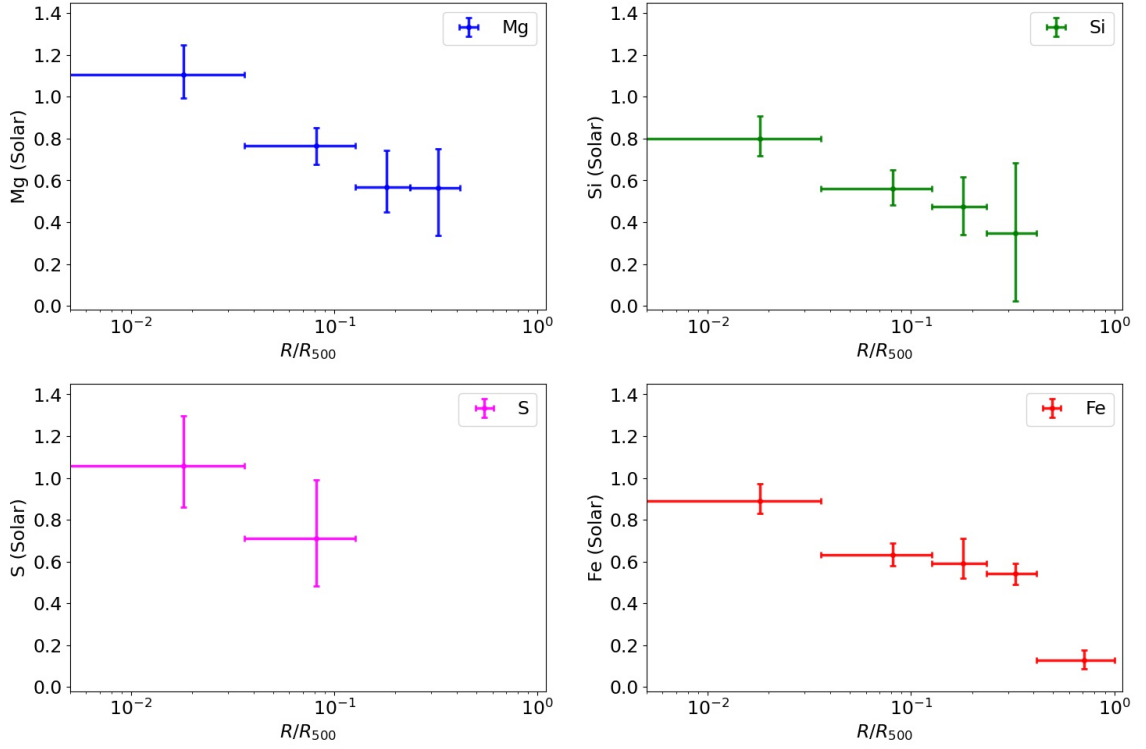


Figure 4.5 Radial Mg, Si, S and Fe abundance profiles of Mrk1216.

ation at the end, that our Si profile is flatter. Our S profile covers only 2 central regions and have higher values with a similar slope, but not significant with large errors. The overall Fe profile is also have insignificant higher values in the center and this becomes significant with regions 3 and 4. This separation corresponds to the previously mentioned Fe flattening. In the last region, our Fe value drops sharply and has a lower mean value than the [86] profile, but consistent within uncertainties.

In the case of abundance ratios, the only significant difference is the central area of our Mg/Fe profile. The profile starts with super-solar ratio (significant within 1σ confidence) and decreases with radius, becoming consistent with solar ratio. Reversely, the Mg/Fe profile of the [86] starts from a much lower ratio (almost 0.5) and increase with radius, up to above unity. The Si/Fe and S/Fe profiles shows a good match. Unfortunately, we were not able inspect the effect of Fe drop at the last region, since we could not measure the other elements at that radius. The abundance ratio profiles are plotted in Figure 4.8.

4.5 SNIa Ratio Profile

SNIa ratio profiles are important tools for inspecting chemical evolution of galaxies, galaxy groups and clusters. Radial variation of SNIa ratio as well as its value provides important clues about the evolution history of these objects. Therefore, we calculated SNIa ratios from the measured abundance ratios up to $\sim 0.42R_{500}$ (central 4 regions),

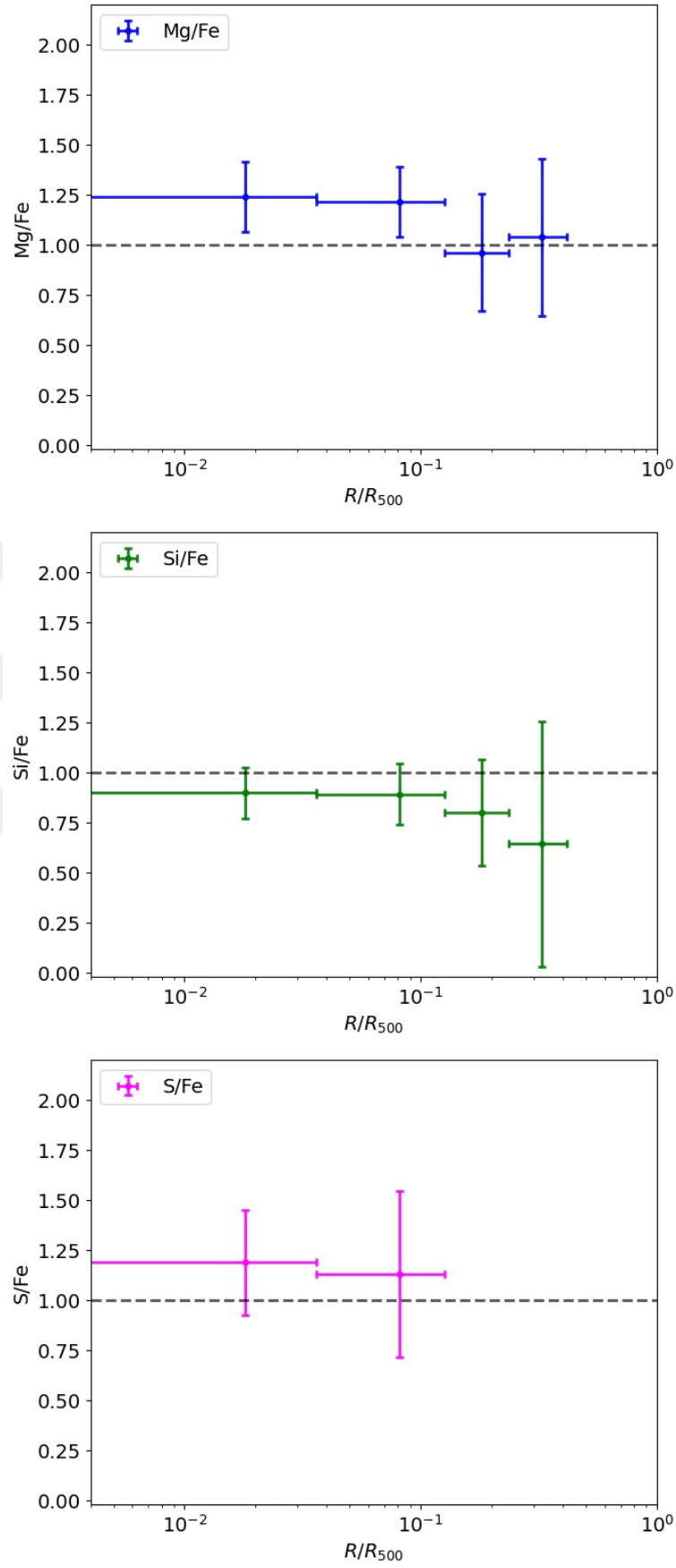


Figure 4.6 Radial Mg/Fe, Si/Fe and S/Fe abundance ratio profiles of Mrk1216.

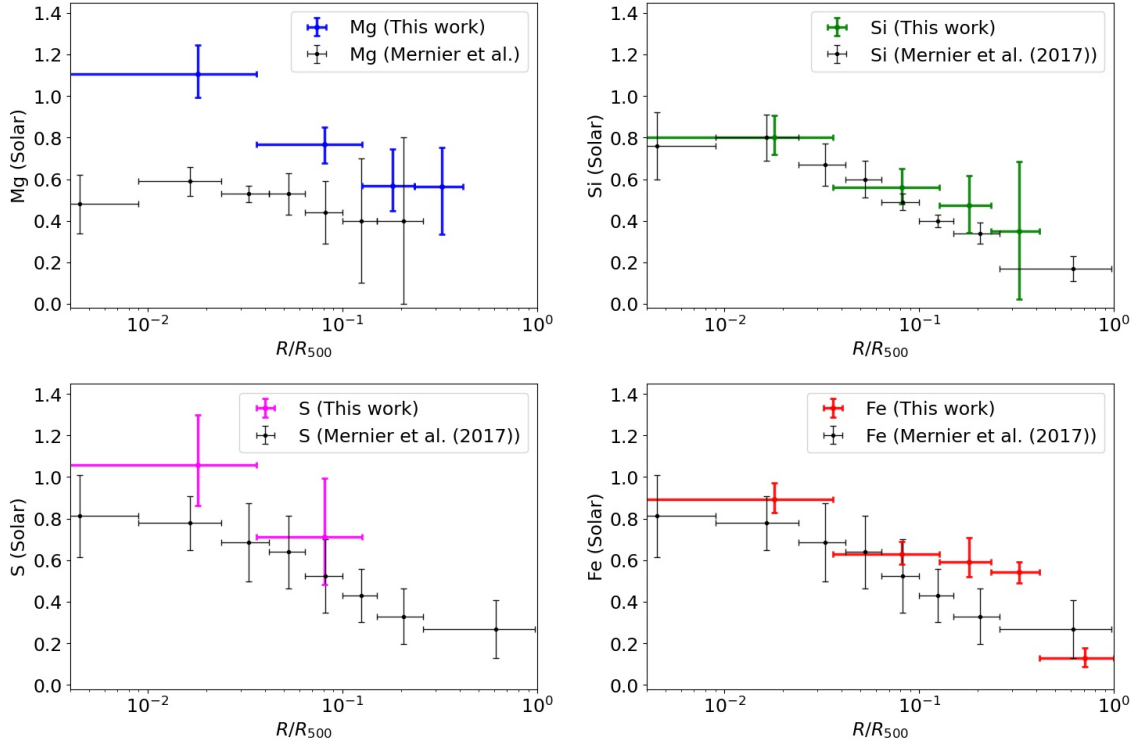


Figure 4.7 Radial Mg, Si, S and Fe abundance profiles of Mrk1216 and results from [86], plotted for comparison.

by using SNeRatio software [14]. We performed the SNIa ratio fit with Mg/Fe, Si/Fe and S/Fe abundance ratios for central 2 regions and only Mg/Fe, Si/Fe for the rest. In addition, we performed a separate fit using the O/Fe and Ne/Fe values obtained from the XMM-RGS analysis. The SNeRatio fits of 4 EPIC regions are shown in Figure 4.9 and fit of the RGS region is shown in Figure 4.10.

We selected our SNeRatio fit parameters as *N100H* yield table [83] for SNIa, *Z0.008* yield table [43] for SNcc, Salpeter IMF [46] with 10-40 solar mass range and LPGS as solar table [80]. The rationale behind these choices is to ensure consistency with studies for which our results will be compared (see Section 5). Significant systematic differences may emerge when there are variations in model selections [14]. Additionally, highlighting a particular model combination is not one of the goals of this study. The fit results for the selected model combination are reported in Table 4.3 and plotted in Figure 4.12.

As seen in the Figure 4.9, Region 1 and Region 2 have relatively worse fits due to the underestimated Mg and overestimated Si abundance by the yield model. We repeated the fittings for these 2 regions without Mg to see how much it affected the results. As a result, the SNIa ratios were slightly increased into $0.233^{+0.056}_{-0.041}$ and $0.250^{+0.081}_{-0.055}$ with much better fit statistics (c-stat./dof) as 1.73/1 and 0.56/1, respectively. Removing Si from the fits even improved the statistics better and reduced the SNIa ratios significantly. The new ratios became $0.103^{+0.023}_{-0.018}$ and $0.102^{+0.025}_{-0.019}$, while statistics (c-stat./dof) became 0.72/1 and

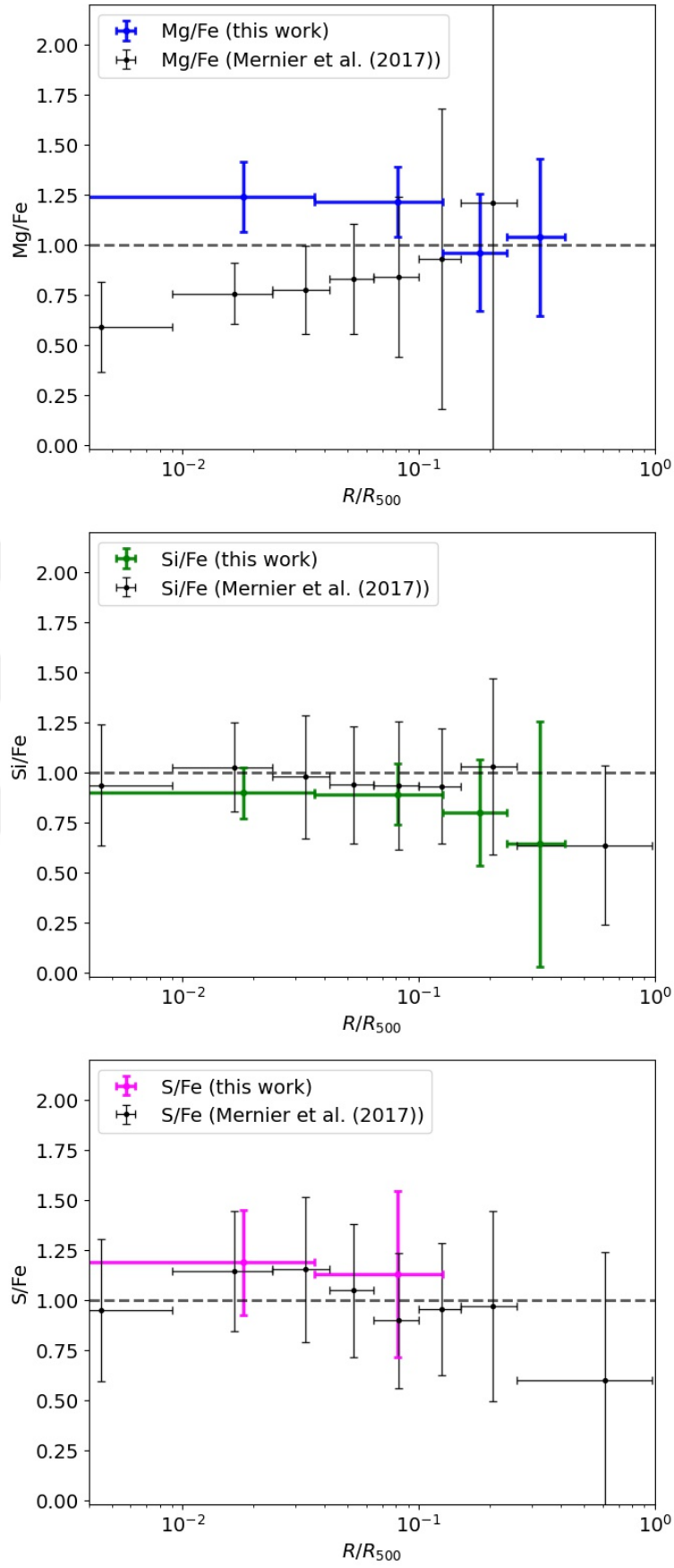


Figure 4.8 Radial Mg/Fe, Si/Fe and S/Fe abundance ratio profiles of Mrk1216 and results from [86], plotted for comparison.

Table 4.3 SNeRatio fit results of Mrk1216.

Instrument	Radius (kpc)	SN Ia Ratio	C-Stat./dof
RGS	0-8.96	$0.210^{+0.089}_{-0.055}$	0.17/1
	0-8.96	$0.167^{+0.027}_{-0.022}$	10.8/2
EPIC	8.96-26.88	$0.160^{+0.030}_{-0.024}$	8.65/2
	26.88-58.24	$0.205^{+0.084}_{-0.053}$	1.78/1
	58.24-103.04	$0.165^{+0.119}_{-0.061}$	1.07/1

0.45/1. Possible explanations of such underestimation/overestimation will be discussed in Section 5. Region 3 and Region 4 have better statistics with data being consistent with model expectations.

In order to measure the radial change, we fit a linear model to the SN Ia ratio profile. The fitted line was almost flat with a small slope value of 0.046 ± 0.106 and intercept value of 0.164 ± 0.10 , as shown in Figure 4.11. Additionally we repeated the fit with a constant model to quantify the average SN Ia ratio value for $\sim 0.42R_{500}$ radius, which is 0.167 ± 0.006 .

When comparing the SN Ia ratio results, we should remind that theoretical selections (yield models, IMFs and solar tables) can change the derived ratios dramatically. Different yield models causes systematic differences in the estimated ratio levels, but might be compatible within characteristics of a profile, as discussed in [14] for some yield tables. Similar effects are expected for IMFs and solar tables as well. Consequently, it is essential to compare results with compatible selections. In this study, our selected parameters matches the [86]. Thus, we eliminate the major systematic differences as we did in elemental abundance comparison in the previous section.

The SN Ia ratio profile of Mrk1216 from this work and average profile of groups and ellipticals from [86] are plotted in Figure 4.12. The results of Mrk1216 is located in the left panel, plotted as black data points with error bars. The average value is also plotted as green solid line with a shaded area around, but not clearly visible due to being small. The results from [86] is plotted in the right panel. The plot contains two different results for different model combinations. The blue colored data is compatible with Mrk1216. The blue dotted line indicates the average central SN Ia ratio (see the paper for details). Additionally we added the Mrk1216's average ratio line (green solid) into the right panel and central average ratio line (blue dotted) of groups into the left panel for making a better visual comparison.

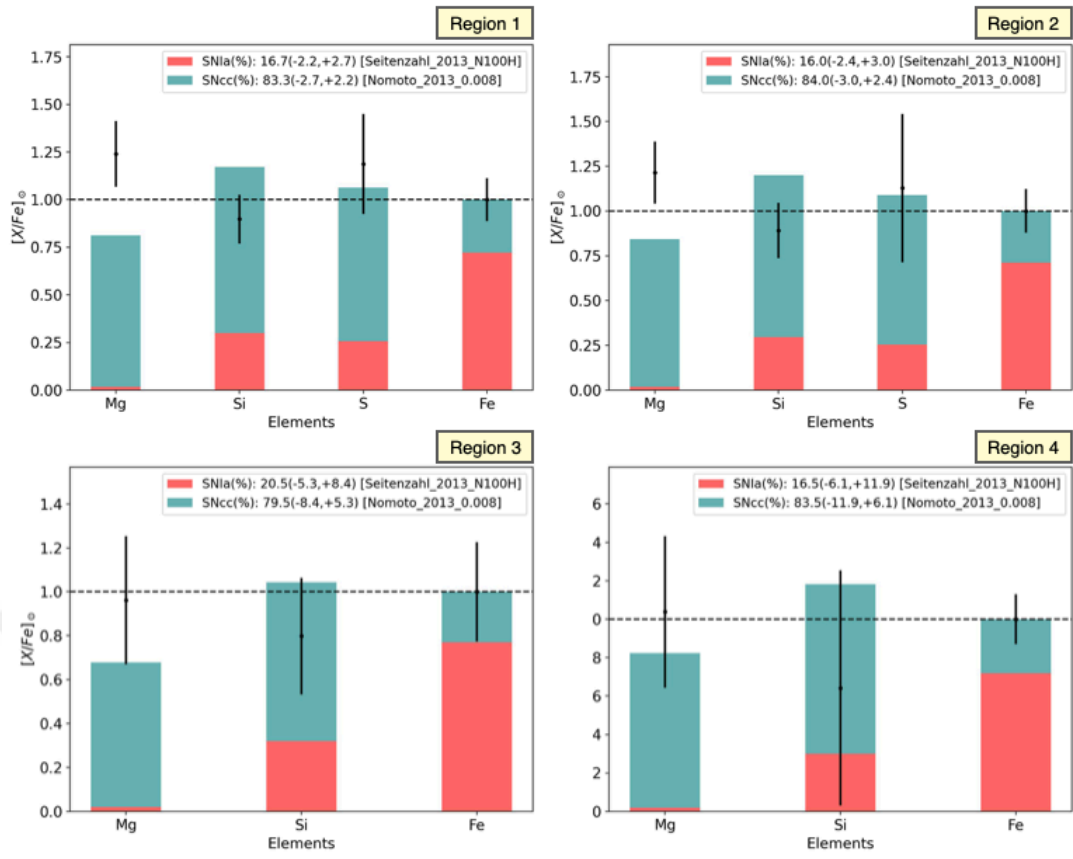


Figure 4.9 Mrk1216 SNeRatio fits of 4 source regions.

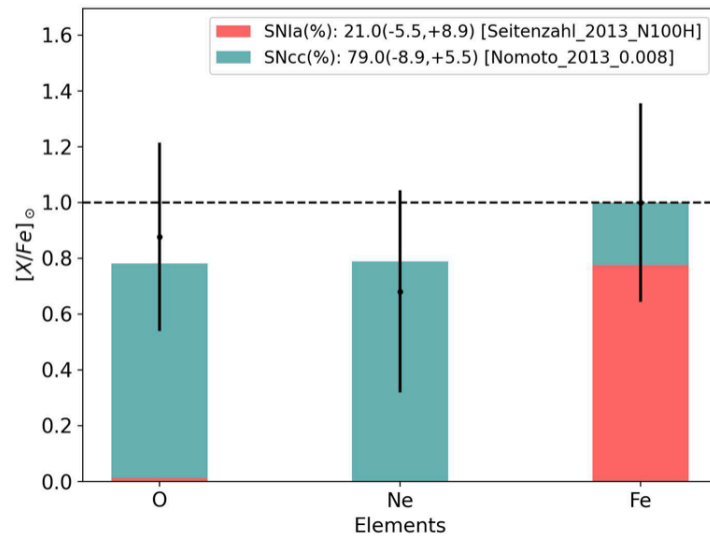


Figure 4.10 Mrk1216 SNeRatio fit of RGS region.

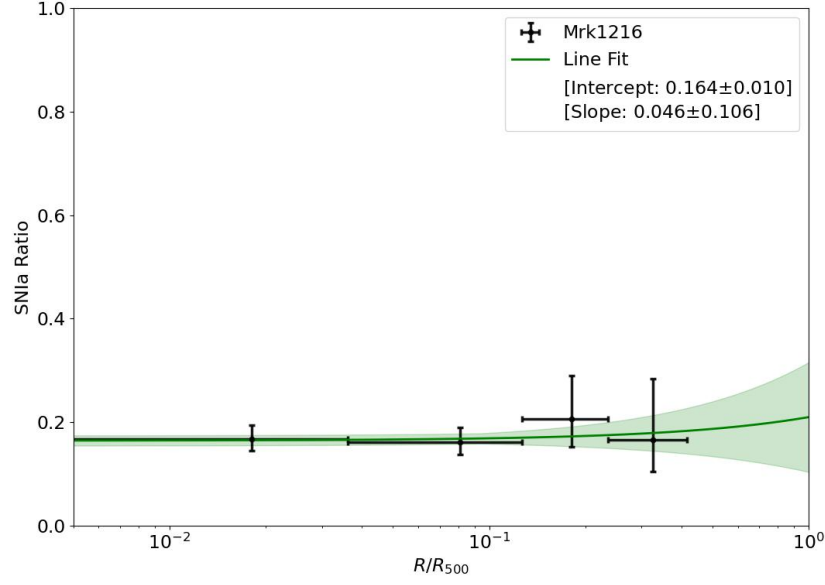


Figure 4.11 Mrk1216 SNIa profile, line fit.

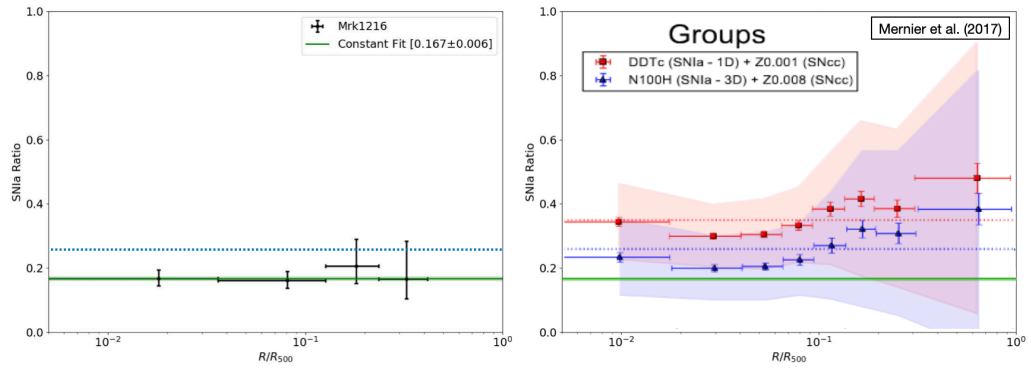


Figure 4.12 Relative SNIa ratio profile of Mrk1216.

As can be seen from the Figure 4.12, SNIa ratio profile of Mrk1216 in the central region ($\lesssim 9kpc$) is significantly lower than the average profile of [86] in terms of mean values (blue data points with error bars at the right panel of Figure 4.12), but the differences is not significant considering their scatter (blue shaded area). The mean values of group profile shows a slight decline near center and increase with radius up to R_{500} . The Mrk1216 does not show any increase significantly, up to $\sim 0.42R_{500}$.

5 DISCUSSION

In this section, we will briefly summarize the analysis results of Mrk1216 and discuss their implications in the context of galaxy formation and chemical evolution scenarios. Additionally, we will compare our findings with relevant observational results from the existing literature.

In general, abundance measurements of all elements (Mg, Si, S, Fe) shows centrally peaked profiles. The most noticeable difference is the Mg profile of the Mrk1216, as plotted with the results of [86] in Figure 4.7. Highly peaked Mg abundance in the center significantly differs from the almost flat sample average, and start to converge with increasing radius. The second interesting feature is the flatter Fe profile of the Mrk1216 up to the 4th radial bin, and drop sharply at the last region. The bottom Fe values are consistent within the uncertainties but the inner side of the sharp edge has significantly higher Fe abundance. Besides these distinctive features, although not significant, the overall abundance values of radial bins are also slightly higher in average, comparing the mean values.

When considering the $[X/Fe]$ ratios (Figure 4.8), the $[Mg/Fe]$ profile differs significantly in the center, exhibiting a slightly super-solar ratio that converges with increasing radius. $[Si/Fe]$ and $[S/Fe]$ profiles are consistent with CHEERS average [86] as well as solar ratio. The $[Si/Fe]$ profile has slightly lower ratios and the $[S/Fe]$ profile has slightly higher ratios but the difference is not significant due to large uncertainties.

Lastly, we compare the SNIa ratio profile of the Mrk1216 with the CHEERS average, shown in the Figure 4.12. The left panel shows the SNIa ratio profile of Mrk1216 with a green solid line showing the average value, and the right panel shows the SNIa ratio profile of CHEERS average for $< 1.7keV$ objects [86] for two different sets of SNe yield models for SNIa and SNcc. As described in Section 4, in order to avoid significant systematic differences, it is essential to select same yield models when making a comparison [14]. The derived model combination is *SeitenzahlN100H* for SNIa yields [83] and *NomotoZ0.008* for SNcc yields [43]. The results for this combination is plotted in blue

colors in the right panel of the Figure 4.12 (blue dotted line for the central value, blue data points for the radial ratio values and blue shaded area for the deviation). In order to provide a better visual aid, we plot the green average value line of Mrk1216 into the right panel and the blue dotted line of CHEERS’s central average to the left panel.

Considering the radial SNe contribution, the main difference of Mrk1216 is that the SNIa ratio throughout the profile is lower than the CHEERS’s average. The difference is statistically more significant at the center due to smaller uncertainties. Unfortunately, the difference becomes insignificant with increasing radius due to the large deviations (blue shaded area). As a result, the least we can deduce certainly is that the central SNIa ratio of Mrk1216 ($\lesssim 9kpc$) is significantly lower (comparing with the blue dotted line) and the overall profile lies at the lower limit of the sample variation range. Beyond making a comparison, Mrk1216 show remarkably flat SNIa ratio profile for the $\sim 0.42R_{500}$ radius, which is a strong indication of early enrichment scenario, suggesting that metal production processes begin in the early phase of structure formation at epoch $z \geq 2$ [14, and references therein].

5.1 Temperature Structure

Previous studies, based on Chandra observations, have reported the temperature profile of Mrk1216 [5, 6]. Benefiting from higher spatial resolution, these Chandra-based findings provided a more detailed temperature examination of the central region, employing annuli with smaller radii. Despite the use of different plasma emission models and data from various instruments in each study, all the results, including ours, are in agreement, revealing a centrally peaked (negative gradient) radial temperature profile.

On the other hand, [87] analyzed 60 ETGs and proposed a universal temperature profile. In the study, ETGs are categorized into six types based on their temperature profile characteristics: Hybrid-bump, hybrid-dip, double-break, positive, negative, and irregular (see [87] for detailed definitions and respective features). Among these types, Mrk1216 can be categorized as the “negative” type due to its negative gradient radial temperature profile. The notable point here is that these “negative” type ETGs are characterized as dynamically disturbed systems and show similar features to NCC (Non Cool-Core) clusters. In contrast, Mrk1216 is a highly relaxed system with no signs of dynamical disturbance [5, 6, 10], making it incompatible with the sample characteristics.

Remarkably, the sample in the mentioned study also has an exception: NGC6482. Despite being a relaxed fossil system [88], NGC6482’s temperature profile has a negative gradient. This distinct temperature structure of relaxed fossil systems, compared to normal ETGs (i.e., Mrk1216 and NGC6482), might reveal an uncommon behavior of heating-cooling

mechanisms in galaxies and emphasize the importance of their evolutionary path.

[5] proposed radio-mechanical AGN feedback as a central heating source, connecting it with Mrk1216 as an outlier of the black hole mass–bulge mass relation, and the physical process called "Chaotic Cold Accretion" (CCA) [89] of the AGNs. Further details about heating mechanisms are beyond the scope of this thesis.

5.2 Metallicity Structure

According to the two-phase galaxy formation scenario, structures are formed via gas-rich (wet) and dissipative mergers ($z \gtrsim 2$), and then passively evolves through gas-poor (dry), non-dissipative and collisionless mergers ($2 \gtrsim z \gtrsim 0$), as mentioned before [90, and references therein]. The wet mergers from the first phase initiates rapid and efficient star formation episodes [2, 5, 6, 91]. In this process, α -elements, such as Mg, predominantly originating from the cores of massive stars, are expelled through core-collapse supernovae (SNcc). The short lifespan of these massive stars results in the rapid release and recycling of Mg, which serves as a reliable tracer for overall enrichment. In contrast, Type Ia supernovae (SNIa), originating from remnants of long-lived, low-mass stars, predominantly contribute to the production of Fe-peak elements [92]. Due to a time delay between SNcc and SNIa, the rapidity of star formation leads to α -elements (from SNcc) surpassing Fe-peak elements (from SNIa). As a result, enhanced $[\alpha/Fe]$ elemental abundance ratios serve as indicators of the intensity and rapidity of the star-formation process [8]. In a red-nugget formed through such wet-mergers, which has not yet transitioned to the second phase, the dense SNcc activity would yield a relatively high $[\alpha/Fe]$ ratio. The observed relatively high Mg abundance and $[Mg/Fe]$ ratio in Mrk1216 align with these expectations, given its red-nugget-like characteristics.

In previous studies, [93] identified the most Mg enhanced massive quiescent galaxy observed to date at $z = 2.1$ ($[Mg/Fe] = 0.59 \pm 0.11$), while [94] also documented a lensed quiescent galaxy at $z = 2$ exhibiting enhanced Mg. Both investigations highlight an unusually short star formation timescale when compared to local early-type galaxies (ETGs) and propose that further chemical evolution is driven by mergers up to $z \sim 0$. Consequently, the high $[Mg/Fe]$ ratio observed in Mrk1216 aligns with the findings of these studies thus supporting its resemblance to red-nuggets.

Furthermore, the relationship between the mass of a system and its metallicity has been extensively studied in the literature, known as the mass-to-metallicity relation (MZR). It has been observed that metallicity tends to increase with galactic mass [95, 96]. The underlying reason for this correlation is believed to be that massive systems more efficiently enrich the accreted gas [8]. However, following studies also brought forward the idea that

the compactness is a more prominent cause within this regard. The gravitational potential is regulating the metallicity of galaxies, hence, smaller galaxies with equal masses (i.e., more compact) have steeper potential well, therefore have higher metallicity [92, 97–99]. Although not significant at all data points within the uncertainties, the observation that the abundance values of Mrk1216 tend to be mostly higher than the average of the ETGs within the analysed radius seems to resonate with the gravitational potential regulation scenario. This alignment is particularly noteworthy given Mrk1216’s status as an extremely compact object.

There is also an additional effect that might cause the observed higher abundance. It is known that ‘dry-mergers’ (gas-poor) in the second-phase of formation significantly increase the sizes of galaxies, also breaks the compactness of CEGs [11]. Semi-analytical models and cosmological simulations show that galaxies can increase their sizes up to ~ 7 times within this dry merger phase [3]. Since the size increase would reduce the compactness, hence flattens the steep gravitational potential in CEGs, the long-term metal production efficiency could be influenced (i.e., reduced). While the compact nature of Mrk1216 suggests protection from minor mergers, it also implies an influence on the chemical enrichment process in this direction, being consistent with its abundance measurements.

Moreover, the Mg profile of Mrk1216 exhibits a steeper trend compared to other abundance profiles (Si, S, and Fe). Considering the absence of disruptive AGN feedback and the flattening effect of dry minor mergers [8], it becomes reasonable to anticipate steeper profiles for metal abundances. AGN feedback can impact metallicity by dispersing the highly enriched central Inter-Stellar Medium (ISM) to the outskirts [100, 101]. [100, 102] confirmed this by studying 28 galaxy groups and showed that the central regions ($\sim 0.03R_{500}$) less affected by feedback are, on average, more metal-rich. AGN feedback can also suppress star formation, reducing the [Mg/Fe] ratio [86, 103]. To sum up, both effects can lead to a flatter abundance ratio profile. In situations where these effects are absent, such as in Mrk1216, steeper profiles can be expected. Considering the fact that SNcc appears to dominate over SNIa, this steepening effects should be more effective for particularly for SNcc products like Mg. The compact nature of Mrk1216 may further reinforce this trend through a steep gravitational potential, making it harder to distribute plasma through galactic winds from the center to the outskirts [104, 105].

Nevertheless, it’s important to acknowledge the limited radial coverage by our analysis (R_{500}). Consequently, a second consideration emerges: If we were able to extend our measurements to the virial radius, the overall metal content might not exhibit significant differences. In other words, what we may be observing is a plasma with a steeper metallicity gradient rather than higher overall enrichment. In this scenario, the disparity could be attributed not to variations in production quantity but rather to the inefficient distribution

of existing elements. Unfortunately, arriving at a definitive conclusion within this context remains challenging given our current data constraints.

5.3 Relative SNe Contributions

The observed abundance ratios in Mrk1216 suggest a predominant contribution from SNcc compared to SNIa in the overall enrichment process. The *SNeRatio* fit results, displayed in Table 4.3 and plotted in Figures 4.9 and 4.10, show the calculated ratios. However, the measured $[\text{Mg}/\text{Fe}]$ ratio in the central two regions significantly exceeds the prediction of the selected model combination. There could be several explanations for this discrepancy, aside from possible spectral errors. We employed a simple and uniform Initial Mass Function (IMF), specifically the Salpeter IMF [46], to calculate SNcc yields. The IMF describes the expected frequency of stars at birth based on their mass [45]. As can be clearly seen from the definition, changing the IMF directly affects the calculated element abundances. It is already known that canonical IMFs often fail to reproduce the enrichment patterns in galaxies, as they should be in a more complex and variable form [106, 107]. Therefore, the requirement for more realistic IMF calculation methods, might be come forward within our case significantly, especially due to the dominance of SNcc in the abundances of Mrk1216.

In this context, the Integrated Galaxy-wide Initial Mass Function (IGIMF) model emerges as a more realistic IMF approach, as it suggests that the IMF changes over time based on the star formation rate, providing a more realistic enrichment model [107–113]. One might speculate that, if we were to use a IGIMF and obtain a well represented Mg abundance fit, relatively low SNIa ratios of Mrk1216 might become higher and more consistent with the average of compared systems. However we should remember that the studies that we make comparison are also using the same IMF. Therefore we can confirm that there is a difference between SNIa ratios, but since our system seems SNcc dominated, unrealistic IMF might have a stronger effect, compared to less SNcc dominated systems. Thus, changing into IGIMF might still decrease the discrepancy to some degree. Additionally, a better representation of $[\text{Mg}/\text{Fe}]$ for the central 2 regions might also solve the overestimated $[\text{Si}/\text{Fe}]$ abundance by releasing the extra burden on the fit constraints. Finally, these results strongly suggests that more realistic IMF models are essential for future studies, in order to draw a more accurate picture of chemical evolution [114].

Beyond the considerations of IMF selections, from a nucleosynthesis perspective, the observed ratio in Mrk1216 may result from either enhanced core-collapse supernovae (SNcc) or suppressed Type Ia supernovae (SNIa). Considering the previously discussed highly efficient star-forming period leading to elevated $[\alpha/\text{Fe}]$ levels in Mrk1216, the derived SNIa

ratio might directly correlate with this outcome.

In addition to that, the distinctive evolutionary trajectory of Mrk1216, as suggested by studies [3, and references therein], may lead to a more top-heavy Initial Mass Function (IMF), resulting in an increased SNcc occurrence and a reduction in SNIa progenitors [94]. A top-heavy IMF implies a higher contribution from high-mass stars, causing the IMF to be weighted more heavily toward the upper (high-mass) region. Given that SNcc progenitors are massive stars, a top-heavy IMF enhances the prevalence of SNcc over SNIa [101]. Additionally, considering the evolution of Mrk1216 characterized by a rapid star-forming period with the absence of AGN feedback quenching, the efficiency of SNcc may surpass that of SNIa.

Alternatively, the distinctive environment of Mrk1216 could influence the efficiency of SNIa occurrences. Factors such as a high central velocity and the absence of dry minor mergers, which may imply fewer SNIa progenitors, could decrease the likelihood of SNIa events. The association between dry minor mergers and a reduced number of SNIa progenitors is based on the premise that dry minor mergers should be expected to bring and mix stellar-mass with more bottom-heavy IMF owing to lower star formation efficiency resulting from a flatter gravitational potential. This, in turn, would lead to the low-mass systems with relatively higher quantities. Consequently, with an increased abundance of SNIa progenitors, the occurrence rate of SNIa might rise, contrary to Mrk1216.

If these results are indeed attributed to the efficiencies of supernovae, each factor may contribute to a varying extent, leading to this cumulative behaviour on the chemical enrichment of Mrk1216.

Clearly, SNe ratio calculations with the abundance values of more elements also becomes more reliable. However, the limitations of observations and instrument constraints have led us to use a small number of ratios ($[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{S}/\text{Fe}]$), increasing the uncertainty. Especially in low-temperature systems like galaxies, where the emission lines used to determine element abundance are more limited compared to clusters, due to low emissivity (i.e., Ar, Ca, Ni). With increased resolution of the next generation satellites, these calculations can be performed more comprehensive. Nevertheless, in order to utilize the available data most efficiently, we also calculated the SNe ratio using the spectrum obtained from the RGS instrument. This allowed us to include some extra elements that RGS can measure, but EPIC can not ($[\text{O}/\text{Fe}]$, $[\text{Ne}/\text{Fe}]$). Although the selected spectral region may not be equivalent, we can expect similar results in the calculations with RGS, since the radial SNe contribution profile calculated from EPIC spectra is nearly flat. Despite being somewhat higher with a $0.21^{+0.09}_{-0.06}$ value, we obtained a consistent SNIa ratio within the margin of error, as expected.

5.4 Enrichment Scenarios

In the context of Large-Scale Structure (LSS), variations arise in the chemical enrichment processes between galaxies and galaxy clusters. Notably, smaller systems such as galaxies experience a dominance of baryonic effects and interactions throughout their evolution (e.g., AGN feedback, galaxy-scale winds, cooling flows, X-ray cavities, filaments, shells, tidal features, and cold fronts). In contrast, larger systems such as galaxy clusters are predominantly influenced by gravitational effects [87, 90, and references therein]. Another crucial factor is that clusters operate as closed-box systems. Galaxies, on the other hand, can lose enriched mass through outbursts, winds, and ram-pressure strippings [15]. Consequently, our understanding of the overall enrichment scenario for galaxies is incomplete if we solely consider observable data, as we are observing the remnants of an open system. Lastly, Mrk1216, with its uncommon evolutionary trajectory, is expected to exhibit even more significant differences in this regard. While these sources of variation are applicable to most galaxies, the potential under-dense environment of Mrk1216 during its formation and evolution may amplify these effects, making them more noticeable. Therefore, the study of such objects as Mrk1216 holds value in enhancing our comprehension of baryonic interactions in galaxies, closing the gap between small and large scales [101].

Another noteworthy aspect is Mrk1216's prominently flat radial SNIa ratio profile with an average ratio of ~ 0.17 , particularly up to $\sim 0.42R_{500}$. This flat relative SNIa contribution is often regarded as a strong indication of the "early-enrichment" scenario [13, 14, 86, 101, 115]. According to this perspective, a significant portion of the enrichment occurs prior to clustering, before the formation of large systems such as galaxies or galaxy clusters ($z \sim 2$) [116]. Consequently, both central and outskirts plasmas, evolving under distinct physical conditions, exhibit a similar relative SNe contribution. Furthermore, the "pre-enrichment" scenario implies that the gas enriched within proto-groups and proto-cluster galaxies may have been displaced beyond their shallower potential wells at even earlier times (at $z \geq 3$) [15, 101, and references therein]. In our case, the indication of a flat profile becomes more pronounced due to the lack of efficient mixing mechanisms in Mrk1216. Consequently, plasma from the outskirts predominantly represents the most recently accreted matter, which is distinct from the plasma that accreted earlier [101].

Lastly, most chemical enrichment studies observe a global "floor-abundance" value at the outskirts of galaxy clusters [101, 117–119]. Although we are only able to measure Fe up to R_{500} , our floor value (~ 0.1 solar) is lower than the clusters' ($Z \sim 0.3$ solar). There are also other studies that measure low abundances at the outskirts of galaxies and groups [120]. One way to interpret this result is that if the universal near 0.3 "floor abundance" value might be a outcome of the density of the environment of pre-clustering times, systems at the under-dense regions, thus environments of isolated systems like Mrk1216 might

have a lower "floor-abundance" value [3]. Another possibility is that this floor abundance might be most likely observable within closed-box systems, where all the enriched gas stays within, unlike galaxies [99]. In the case of Mrk1216, although there are no signs of strong activities capable of expelling a large amount of enriched gas from the galaxy, the presence of weaker outflows (e.g., from supernova winds) might contribute to the decrease in metallicities in the outskirts, where the gravitational potential is shallow. In this regard, future studies and observation up to virial radius, or even beyond, could provide invaluable information for a comprehensive understanding on this subject.

5.5 Future Works

Concerning the metallicity profiles, the sharp drop in Fe abundance in the last region is difficult to interpret due to potential systematic or statistical uncertainties, such as limited counts and statistical difficulties associated with low-temperature systems (i.e., Fe abundance is determined using only L shell emissions [29]). However, assuming the accuracy of these results, a possible explanation emerges. Mrk1216 has two faint neighbouring galaxies detected, and this system is most likely a fossil group as mentioned in Section 1. In this case, the source of the extended X-ray emission covering Mrk1216 is most likely not only the ISM, but also the IGrM (Intra-Group Medium). It may not be easy to determine where the ISM ends and the IGrM begins to dominate. Nevertheless, we may be observing this transition, possibly different levels of enrichment between the two environments. In the case of Mrk1216, the absence of effective mixing mechanisms may have made this transition more apparent.

Additionally, the surface brightness profile of Mrk1216 fits better with a double- β model. Typically, a second β model is required when the system has a cool-core, incorporating an extra emission component in the central area (one narrow β for the center and one wide β for more extended emission) [85, 121, 122]. In the case of Mrk1216, there is no cool-core, and the second β component does not represent a narrow emission located in the center. Instead, both models are wide, with one starting to dominate from the end of the fourth radial bin ($\sim 103\text{kpc}$). This is consistent with the assumption of an ISM-IGrM transition, since the Fe drop is observed at approximately this radius. In this case, the second β might be representing the IGrM emission.

Another point to consider about the measured abundances, particularly when unexpectedly low values are observed (as seen in the low Fe content at the outskirts), is the potential influence of metal depletion into dust. Metals locked in the dust, thus depletion, is a major source of uncertainty of measuring ISM abundance [99]. It's important to note that not every element experiences the same rate of depletion, and the efficiency of depletion

can vary with plasma temperature [99, 123]. Therefore, neglecting the depletion effect may introduce biases into our fits. Some studies discussed the possible outcomes of metal depletion [15, and references therein]. In our case, the overestimated model expectation of Si is most likely an artefact of high Mg value, that the current model (IMF, yield table etc.) can not compensate. However, some of this discrepancy may be attributed to the unaccounted depletion effects, as an example. Future studies could also offer improved frameworks for accounting for depletion and estimating more accurate patterns of abundances and SNe contributions.



6

CONCLUSION

In this thesis, we presented the analysis results of X-ray observations of the IsoCEG Mrk1216 made with XMM-Newton Observatory. Our results are compared with the properties of massive compact ellipticals reported in the literature. Additionally we interpreted our results and comparisons in terms of galaxy formation and chemical enrichment scenarios. We can summarize our main findings and remarks as follows:

- Radial temperature profile of Mrk1216 shows a negative gradient. This outcome is an unexpected behaviour relative to the universal temperature profile for ETGs reported by [87]. Interestingly, a relic galaxy named NGC6482 [88], an outlier of this 60 galaxy sample, also has similar temperature profile. These results indicates that the observed temperature structure might be caused by a rarely seen feature of complex heating-cooling mechanisms that take place in the relic galaxies, possibly related to passive AGN evolution [5, 89].
- According to the two-phase galaxy formation model, galaxies form through gas-rich mergers in the early phase, leading to rapid star formation. Elements like Mg, originating from massive star cores, are expelled during core-collapse supernovae (SNcc). This results in enhanced $[\alpha/Fe]$ ratios, indicating intense and rapid star formation. The observed high Mg abundance in Mrk1216 aligns with its red-nugget-like characteristics, suggesting it has not transitioned to the second phase.
- The studies propose that metallicity is regulated by gravitational potential, meaning a higher gravitational potential correlates with increased metallicity. The exceptionally compact nature of Mrk1216, and consequently its steep gravitational potential, aligns with this scenario, explaining the observation of higher abundance values, particularly within the analyzed radius. The preservation of its compactness is likely due to the absence of minor mergers during its evolution. This is crucial, as dry-mergers in the second formation phase tend to enlarge galaxies significantly, leading to a flattening of the potential, thus reducing metallicity.

- The absence of disruptive AGN feedback in Mrk1216 is evident in the literature. The centrally peaked radial abundance profiles are consistent with this observation, as AGN feedback mechanisms typically transport a significant amount of enriched gas to the outskirts. Additionally, AGN feedbacks play a role in quenching star formation. Hence, the steeper Mg profile in comparison to other elements may be a consequence of the lack of AGN feedback, as efficient star formation tends to yield high [Mg/Fe] ratios.
- The observed disparities in metal content could be attributed to a steeper metallicity gradient rather than increased enrichment. However, the limited radius covered by the analysis raises considerations about the efficiency of element distribution. Extending measurements to the virial radius would provide a more comprehensive understanding of overall metal content and distribution within Mrk1216.
- Abundance ratios in Mrk1216 indicate a significant contribution from core-collapse supernovae (SNcc) compared to Type Ia supernovae (SNIa) in the enrichment process ($R_{Ia} \approx 0.17 \pm 0.01$). *SNeRatio* fit results demonstrate calculated ratios, but the measured [Mg/Fe] ratio in central regions exceeds the model prediction, raising the need for further investigation. The use of a simple and uniform Initial Mass Function (IMF), such as the Salpeter IMF, might contribute to the discrepancy. Employing more realistic IMF models, like the Integrated Galaxy-wide Initial Mass Function (IGIMF), is suggested for accurate chemical evolution modeling.
- The observed ratio in Mrk1216 could result from enhanced SNcc or suppressed SNIa, with a potential correlation between the derived SNIa ratio and the efficient star-forming period. The unique evolutionary trajectory of Mrk1216, possibly featuring a top-heavy IMF, could increase SNcc occurrence and decrease SNIa progenitors. The absence of AGN feedback quenching and specific environmental factors might enhance SNcc efficiency and reduce SNIa likelihood in Mrk1216.
- The distinctive environment, including high central velocity and the absence of dry minor mergers, might reduce SNIa occurrences due to fewer SNIa progenitors. Dry minor mergers could bring stellar-mass with a more bottom-heavy IMF, leading to increased SNIa progenitors and potentially higher SNIa occurrence rates. Cumulative effects of these factors contribute to the varying efficiencies of supernovae, impacting the chemical enrichment of Mrk1216.
- The limitations of observations and instrument constraints result in using a small number of ratios, increasing uncertainty. Despite limitations, SNe ratio calculations using the RGS instrument provide consistent results with EPIC, supporting the reliability of the calculated SNIa ratio.

- In the context of LSS, chemical enrichment processes vary between galaxies and galaxy clusters. Smaller systems like galaxies are influenced by baryonic effects (e.g., AGN feedback, winds, cooling flows), while larger clusters are predominantly affected by gravitational effects. Galaxies operate as open systems, losing enriched mass through various processes, making the overall enrichment scenario incomplete based on observable data. Mrk1216 and similar galaxies, with their unique evolutionary trajectory and potentially under-dense environment, might provide insights into baryonic interactions, bridging the gap between small and large scales.
- Mrk1216 exhibits a prominently flat radial SNIa ratio profile, suggesting an "early-enrichment" scenario. The scenario implies significant enrichment occurring before clustering, with similar relative SNe contributions in both central and outskirt plasmas. Lack of efficient mixing mechanisms in Mrk1216 emphasizes existence of the flat profile even further, indicating that plasma from the outskirts represents the most recently accreted matter.
- Chemical enrichment studies often observe a global "floor-abundance" value at the outskirts of galaxy clusters. Mrk1216 shows a lower floor value (~ 0.1 solar) than clusters (~ 0.3 solar) at R_{500} . Interpretations include under-dense regions having lower floor abundance and the possibility that this value is observable mainly within closed-box systems. Weaker outflows, such as from supernova winds, might contribute to decreased metallicities in Mrk1216's outskirts, where the gravitational potential is shallow. Future studies and observations up to the virial radius could provide comprehensive insights into this subject.
- The sharp drop in Fe abundance in the outermost region is difficult to interpret due to potential systematic or statistical uncertainties, including limited counts and statistical difficulties in low-temperature systems. Assuming accurate measurements, the reason for this drop could be that the observed X-rays are not only from the ISM, but also from the less enriched IGrM of the fossil group dominated by Mrk1216.
- Mrk1216's surface brightness profile fits better with a double- β model, commonly associated with systems having a cool-core. However, Mrk1216 lacks a cool-core, and both models in the fit are wide, with one dominating from the end of the fourth radial bin ($\sim 103\text{kpc}$). Since this radius value aligns with the Fe drop, the second β component might be representing the IGrM emission.
- Measured abundances, especially unexpectedly low values (e.g., low Fe content at the outskirts), may be influenced by metal depletion into dust. Metal depletion into dust is a major source of uncertainty in measuring ISM abundance. Different elements experience varying rates of depletion, and efficiency can vary with plasma

temperature. Neglecting depletion effects may introduce biases into fits, and future studies could provide improved frameworks for accounting for depletion and estimating more accurate abundance patterns and SNe contributions.

As a result of this thesis, it can be asserted that the structural and chemical properties of the IsoCEG Mrk1216, with a red-nugget-like and relic nature, align with the predictions of the hierarchical formation model. The strength of interpretations based on the results from a single object will be limited. However, this study emphasizes how future research, adopting a similar perspective, can yield valuable insights. The identification of similar objects and the collective examination of deep observations are crucial in this regard. Additionally, many details that have eluded us with the current generation of missions will come to light with the high resolutions of upcoming missions like Athena X-IFU (X-ray Integral Field Unit) [124] or XRISM (X-ray Imaging and Spectroscopy Mission) as successor ASTO-H/HITOMI [125]. Finally, there is a need to enhance our existing theoretical assumptions. For instance, the incorporation of more realistic IMF models, the inclusion of the 'dust depletion' effect in chemical modeling, and the resolving the uncertainties related to SNIa progenitors. Certainly, this list is not exhaustive. Every progression in these topics will contribute significantly to the advancement of chemical enrichment and structural formation scenarios, and thus related fields.

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PUBLICATIONS FROM THE THESIS

Papers

1. M. K. Erdim, C. Ezer, O. Ünver, F. Hazar, M. Hudaverdi, "The relative supernovae contribution to the chemical enrichment history of Abell 1837," Monthly Notices of the Royal Astronomical Society, vol. 508, no. 3, pp. 3337–3344, 2021.

Conference Papers

1. M. K. Erdim, M. Hudaverdi, "Asymmetric uncertainties in measurements: SOAD a Python package based on Monte Carlo Simulations," American Institute of Physics Conference Proceedings, AIP Publishing, vol. 2178, no. 1, 2019.

Projects

1. "Eliptik Galaksilerde Süpernova Kimyasal Element Sentezi İzlerinin Araştırılması", TÜBİTAK-1001 Projesi, 2021 - Present
2. "Süpernova Nukleosentezi ile Evrendeki Yapıların Metal Zenginleşme Evrimi", TÜBİTAK-1001 Projesi, 2018 - 2021