

Broadband Spectral Analysis and Variability of AGNs

Thesis submitted to the
University of Calicut
for the award of the Degree of
Doctor of Philosophy in Physics
under the Faculty of Science

by
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CERTIFICATE

This is to certify that the thesis entitled '**Broadband Spectral Analysis and Variability of AGNs**' is the original work carried out by **Akhila K.**, under my supervision and guidance at the Department of Physics, Providence Women's College (Autonomous), University of Calicut. No part of this thesis has been included previously for the award of any other degree, either in this university or any other institution. The thesis has been checked for plagiarism, using the 'iThenticate' software, at C.H.M.K. Library, University of Calicut and the similarity index found within the permissible limit. The thesis is free from AI generated contents.

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I hereby declare that the work presented in the thesis entitled '**Broadband Spectral Analysis and Variability of AGNs**' is based on the original work done by me under the guidance of **Dr. Jeena K.** and has not been included in any other thesis submitted previously for the award of any degree. The contents of the thesis are undergone plagiarism check using 'iThenticate' software at C.H.M.K. Library, University of Calicut and the similarity index found within the permissible limit. I also declare that the thesis is free from AI generated contents.

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This is to certify that all the corrections/suggestions recommended by the adjudicators have been incorporated in the thesis entitled '**Broadband Spectral Analysis and Variability of AGNs**' submitted to the University of Calicut for the award of the degree of Doctor of Philosophy in Physics by **Akhila K.**, Department of Physics, Providence Women's College (Autonomous), University of Calicut and the content in this thesis and the soft copy are one and same.

Supervisor: Dr. Jeena K.
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To my
AMMA & ACHAN
whom I love to the far end of the Universe and back.

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Journal Publications

- **Akhila, K.**,* Misra, R., Sarma, R., Ezhikode, S.H., and Jeena, K. (2025): Modelling the energy dependent X-ray variability of Mrk 335. In: Journal of High Energy Astrophysics, Volume 45, Pages 418-427.
- **Akhila, K.**, Misra, R., Ezhikode, S.H., and Jeena, K.* (2024): Long term X-ray spectral variations of the Seyfert-1 galaxy Mrk 279. In: Research in Astronomy and Astrophysics, Volume 24, no. 6, Pages 065025.

Conference Presentations

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- **Conference On Blazars and Restless AGNs**, July 2024, Oral presentation: ‘X-ray variability to distinguish Comptonisation & reflection scenarios for the soft excess in Mrk 335.’
- **Young Astronomer’s Meet 2024**, March 2024, Oral presentation: ‘X-ray variability to distinguish warm Comptonisation and reflection scenarios of NLS1 galaxy Mrk 335.’

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Abstract

Active Galactic Nuclei (AGNs) are among the most powerful persistent sources of electromagnetic energy in the Universe, powered by accretion of mass onto supermassive black holes. Studying their broadband spectra and variability patterns can provide information on the geometry, physical conditions and energetics of the accretion disk-corona system. This thesis investigates the physical processes governing AGN mechanism through a combination of broadband spectral modelling and variability informed X-ray analysis using data from *AstroSat*, *NuSTAR* and *XMM-Newton*. Long term spectral analysis of the Seyfert 1 galaxy, Mrk 279, using multi-epoch data was conducted to examine the evolution of the source's flux state and the associated variations in individual components. The study revealed significant source variability without consistent correlation between photon index and continuum intensity. Variations in spectral shape follows only the long term flux state variability and not short timescale variabilities. Flux variability without accompanying spectral shape variability can undermine small changes in physical parameters, necessitating variability analyses along with broadband spectroscopy. Incorporating temporal information with spectral modelling, a novel method for modelling the energy dependent variability is introduced. The method is demonstrated by applying to an *XMM-Newton* observation of the NLS1 galaxy, Mrk 335, whose spectrum can be described by (i) a partial covering absorber modifying the primary emission, (ii) a warm and hot coronal model and (iii) gravitationally blurred reflection along with primary emission. The source's intrinsic variability, quantified through fractional rms variability amplitude can be utilised to break the degeneracy between the spectral models. The study presents a technique to estimate fractional rms from the spectral model and identify the model parameters that best recreates the observed variability pattern. Together the studies consider the different complementary aspects of AGN behaviour, demonstrating that a multi-domain approach combining long term spectral evolution along with variability-informed modelling provide a powerful tool to understand AGN physics.

Keywords: Astronomy:Astrophysics; galaxies:active; methods:observational; X-rays:galaxies; relativistic processes

സംഗ്രഹം

ആക്റ്റീവ് ഗാലക്റ്റിക് ന്യൂക്ലിയസ് (AGNs) പ്രപഞ്ചത്തിലെ വൈദ്യുതകാന്തിക ഊർജത്തിന്റെ ഏറ്റവും ശക്തവും സ്ഥിരവുമായ സ്രോതസ്സുകളിൽ ഒന്നാണ് - സൂപ്പർമാസ്സീവ് തമോഗർത്തങ്ങളിലേക്ക് പിണ്ഡം ആർജിക്കുന്നതിലൂടെ ഇവ ഊർജ്ജം ഉല്പാദിപ്പിക്കുന്നു. ഇവയുടെ ബ്രോഡ്ബാൻഡ് സ്പെക്ട്രവും വ്യതിയാന രീതികളും പഠിക്കുന്നത്, അക്രിഷൻ ഡിസ്ക്-കൊറോണ സിസ്റ്റത്തിന്റെ ആകൃതി, ഭൗതിക സാഹചര്യങ്ങൾ, ഊർജ്ജ പ്രവണതകൾ എന്നിവയെക്കുറിച്ചുള്ള വിവരങ്ങൾ നൽകാൻ കഴിയും. ആസ്ട്രോസാറ്റ്, ന്യൂസ്റ്റാർ, എക്സ്.എം.എം.-ന്യൂട്ടൺ എന്നീ ഉപഗ്രഹങ്ങളിൽ നിന്നുള്ള ഡാറ്റ ഉപയോഗിച്ച് ബ്രോഡ്ബാൻഡ് സ്പെക്ട്രൽ മോഡലിംഗും, വേരിയബിലിറ്റി-റിസോൾവ്ഡ് എക്സ്റേ വിശകലനവും സംയോജിപ്പിച്ച് AGN മെക്കാനിസത്തെ നിയന്ത്രിക്കുന്ന ഭൗതിക പ്രക്രിയകളെ ഈ പ്രബന്ധം വിശകലനം ചെയ്യുന്നു. സെയ്ഫെർട്ട്-1 ഗാലക്സിയായ എം.ആർ.കെ.279 (Mrk 279) -ന്റെ ഫ്ളക്സ് അവസ്ഥയുടെ പരിണാമവും വ്യക്തിഗത ഘടകങ്ങളിലെ അനുബന്ധ വ്യതിയാനങ്ങളും പരിശോധിക്കുന്നതിനായി വിവിധ കാലഘട്ടങ്ങളിലെ ഡാറ്റ ഉപയോഗിച്ച് ഒരു ദീർഘകാല സ്പെക്ട്രൽ വിശകലനം ചെയ്തു. ഫോട്ടോൺ ഇൻഡക്സും, കണ്ടിന്യൂവം ഇന്റൻസിറ്റിയും തമ്മിലുള്ള സ്ഥിരമായ ബന്ധത്തിന്റെ അഭാവത്തിലും, കാര്യമായ ഉറവിട വ്യതിയാനം പഠനം വെളിപ്പെടുത്തി. സ്പെക്ട്രൽ ആകൃതിയിലുള്ള വ്യതിയാനങ്ങൾ ദീർഘകാല ഫ്ളക്സ് സ്റ്റേറ്റിന്റെ വ്യതിയാനങ്ങളെ മാത്രമേ പിന്തുടരുകയുള്ളൂ, ഹ്രസ്വ സമയ വ്യതിയാനങ്ങളെയല്ല. സ്പെക്ട്രൽ ഷേപ്പ് വ്യതിയാനങ്ങളുടെ അഭാവത്തിലുള്ള ഫ്ളക്സ് സ്റ്റേറ്റ് വ്യതിയാനങ്ങൾക്ക് ഫിസിക്ക് പാരാമീറ്ററുകളിലെ ചെറിയ മാറ്റങ്ങളെ നിഷ്പ്രഭമാക്കുവാൻ കഴിയും, അതിനാൽ ബ്രോഡ്ബാൻഡ് സ്പെക്ട്രോസ്കോപ്പിക്കൊപ്പം തന്നെ വ്യതിയാന വിശകലനവും ആവശ്യമാണ്. സ്പെക്ട്രൽ മോഡലിംഗിനൊപ്പം കാലസംബന്ധമായ വിവരങ്ങളും ഉൾപ്പെടുത്തിക്കൊണ്ട്, ഊർജ്ജാവലംബമായ വ്യതിയാനങ്ങളുടെ മോഡലിംഗ് ചെയ്യുന്നതിനുള്ള ഒരു പുതിയ രീതി ഈ ഗവേഷണത്തിൽ അവതരിപ്പിക്കുന്നു. ഈ രീതി എൻ.എൽ.എസ്.1 (NLS1) ഗാലക്സിയായ എം.ആർ.കെ.335 (Mrk 335) -ന്റെ എക്സ്.എം.എം.-ന്യൂട്ടൺ നിരീക്ഷണ ഡാറ്റയിൽ പ്രയോഗിച്ച് ഉദാഹരിച്ചു കാണിക്കുന്നു. ഇതിന്റെ സ്പെക്ട്രം (i) പ്രാഥമിക വികിരണത്തെ ബാധിക്കുന്ന ഒരു പാർഷ്യൽ കവറിംഗ് അബ്സോർബർ, (ii) ചൂടും (warm) ഉഷ്ണവും (hot) ആയ രണ്ടു കൊറോണയോടു കൂടിയ മോഡൽ, (iii) പ്രാഥമിക വികിരണത്തോട് കൂടി ഗുരുത്വാകർഷണ ബലത്താൽ ബാധിക്കപ്പെട്ട പ്രതിഫലനം ഉൾപ്പെടുത്തിയ മോഡൽ, എന്നിവയാൽ വ്യാഖ്യാനിക്കാം. സ്പെക്ട്രൽ മോഡലുകൾ തമ്മിലുള്ള ഈ ഡീജനറസി ഇല്ലാതാക്കാൻ വ്യതിയാന സൂചികയായ ഫ്രാക്ഷണൽ ആർ.എം.എസ്. (fractional r.m.s variability amplitude) -നെ ഉപയോഗപ്പെടുത്താം. സ്പെക്ട്രൽ മോഡലിൽ നിന്നും ഫ്രാക്ഷണൽ ആർ.എം.എസ്. കണക്കാക്കുവാനും, നിരീക്ഷണത്തിൽ കണ്ടെത്തിയ വ്യതിയാന രീതി ഏറ്റവും കൃത്യമായി പുനർനിർമ്മിക്കുന്ന മോഡൽ പാരാമീറ്ററുകൾ തിരിച്ചറിയുവാനുമുള്ള ഒരു സാങ്കേതിക വിദ്യ ഈ പ്രബന്ധം അവതരിപ്പിക്കുന്നു. ഈ പഠനങ്ങൾ AGN പ്രവർത്തനത്തിന്റെ പരസ്പര-പൂരകങ്ങളായ വ്യത്യസ്ത വശങ്ങളെ പരിഗണിച്ച്, ദീർഘകാല സ്പെക്ട്രൽ പരിണാമവും, വ്യതിയാന-നിർദ്ദേശിത മോഡലിംഗിനെയും സംയോജിപ്പിക്കുന്ന ബഹുമേഖല സമീപനം AGN ഫിസിക്സ് മനസിലാക്കാനുള്ള ശക്തമായ ഉപകരണമാണെന്ന് തെളിയിക്കുന്നു.

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Abbreviations

AGN	Active Galactic Nucleus
BLR	Broad Line Region
CCD	Charge-Coupled Device
EPIC	European Photo Imaging Camera
FPMA/FPMB	Focal Plane Module (A & B)
FWHM	Full-Width at Half-Maximum
ISCO	Innermost Stable Circular Orbit
LAXPC	Large Area X-ray Proportional Counter
LINER	Low-Ionization Nuclear Emission-line Region
NLR	Narrow Line Region
NLS1	Narrow-Line Seyfert 1
NuSTAR	Nuclear Spectroscopic Telescope Array
RMS	Root Mean Square
SED	Spectral Energy Distribution
SMBH	Super Massive Black Hole
SXT	Soft X-ray Telescope
XMM	X-ray Multi-Mirror Mission

Physical Constants

Boltzmann Constant	$k_B = 1.38 \times 10^{-23} \text{ J K}^{-1}$
Parsec	$\text{pc} = 3.086 \times 10^{16} \text{ m}$
Planck's Constant	$h = 6.626 \times 10^{-34} \text{ kg s}^{-1}$
Solar Luminosity	$L_{\odot} = 3.826 \times 10^{33} \text{ erg s}^{-1}$
Solar Mass	$M_{\odot} = 1.989 \times 10^{30} \text{ kg}$
Speed of Light	$c = 2.99 \times 10^8 \text{ m s}^{-1}$

Chapter 1

Introduction

Astronomy and Astrophysics are among the oldest, yet very rapidly evolving branches of science, dedicated to understanding the origin, composition and evolution of the Universe. From the very early naked-eye observations to the current generation of space and ground-based telescopes and precision instruments, human beings have always been trying to comprehend the physical processes that govern the celestial phenomenon. Astronomy involves observing these celestial bodies, while Astrophysics uses the principles of Physics to explain the nature and evolution of these bodies and phenomena they display. Over the past century, exceptional progress in observational technology over the entire electromagnetic spectrum has revolutionized our understanding of the Universe.

Active Galactic Nuclei (AGNs) are fascinating discoveries of modern Astrophysics - compact regions of extreme luminosity found at the centres of certain galaxies. Being the most persistently luminous sources in the known Universe, AGNs have captured the human attention and have widely been studied in the last few decades. The study of AGNs connect together several fundamental areas of Physics and Astrophysics, including that of accretion and ejection, high energy radiation mechanisms and galaxy evolution. By examining the AGN phenomenon, astronomers gain valuable insights into the processes in the ambient regions of supermassive black holes (SMBHs) and their role in the evolution of galaxies and other cosmic objects.

1.1 Historical Background

AGN studies began in the early twentieth century when Carl Seyfert reported that the optical spectra of six galaxies showed high ionization nuclear emission

lines superimposed on a bright continuum (Seyfert, 1943). Some of these galaxies showed broad emission lines, while the other only had narrow ones - these objects were later named Seyfert galaxies in his honour. The next major breakthrough was the discovery of extragalactic radio sources, called quasars (Schmidt, 1963; Matthews & Sandage, 1963). In optical images, quasars appear like point objects. However, their luminosities were often found to exceed that of entire galaxies. Redshift measurements revealed that these objects lie at cosmological distances. Radio galaxies, with giant lobes and very long jets extending beyond the host galaxy were discovered at around the same time (Baade & Minkowski, 1954; Fanaroff & Riley, 1974).

A common hypothesis that a large number of stars could produce AGN phenomenon was disregarded when Woltjer (1959) estimated that the observed emission within the central 100 pc of the galaxies would require a mass of a few $10^8 M_{\odot}$. The idea that the central portion of AGNs could host a black hole was proposed by Salpeter (1964) and Zel'dovich & Novikov (1964). The concept of black hole had been put forward long before, but remained ignored until Albert Einstein formulated the General Theory of Relativity (Einstein et al., 1916). AGN phenomena and others such as the fact that massive stars have to collapse into a black hole, gave theoretical evidence for the existence of black holes. By 1970s, theoretical models agreed on the idea that the extreme luminosities of quasars and Seyferts were powered by accreting matter onto supermassive black holes (Lynden-Bell, 1969; Rees, 1984; Begelman et al., 1984).

Accretion can efficiently convert gravitational potential energy into radiation, thereby explaining both the high luminosity and observed variability of AGNs. AGNs have been observed to emit at almost all the wavelengths of the electromagnetic spectrum and these observations reveal compact emission regions, rapid variability and accretion-consistent spectral features that characterise the AGN phenomenon (Elvis et al., 1978; Mushotzky et al., 1993).

1.2 AGN Classification

AGNs exhibit great diversity in their observed features such as luminosity, spectral features, variability and radio morphology. These differences reflect a diversity in the physical conditions, orientation and evolutionary states of the nuclei. Multiple classification schemes are employed to account for these differences - typically based on spectral types and radio loudness. Spectral classification sep-

arates Type 1 AGNs with both broad and narrow emission lines from Type 2 AGNs where broad lines are not present. Independently, AGNs are also divided into radio-quiet that includes the vast majority lacking any relativistic powerful jets and radio-loud classes having jets with significant kinetic power. Each scheme highlights a different aspect of AGN phenomenon and along with physical models, aids our understanding of the central engine.

1.2.1 Optical Classification

In this scheme, AGNs are classified based on their features in the rest frame optical spectra. It primarily uses the presence and relative strengths of the permitted and forbidden emission lines, which are used to understand the structure and physical conditions of the nuclear region. Optical surveys revealed that some galaxies show very broad emission lines with typical widths exceeding 1000 km s^{-1} , while others display only narrow lines. Thus two primary classes were introduced, Type 1 and Type 2 AGNs - based on the visibility of broad line regions in their spectra (Khachikian & Weedman, 1974).

- **Type 1 (Broad-Line) AGNs:** These are characterised by strong, blue non-stellar continuum with two distinct types of emission lines:
 - Broad Emission Lines: Permitted lines, such as $\text{H}\alpha$ and $\text{H}\beta$, with very large Doppler broadening - corresponding gas velocities range between $1000 - 10,000 \text{ km s}^{-1}$. Forbidden lines, such as O[III] , are never broad.
 - Narrow Emission Lines: Forbidden lines and narrow components of permitted emission lines. The full-width at half-maximum (FWHM) typically range between 100 to 1000 km s^{-1} .
- **Type 2 (Narrow-Line) AGNs:** This category of AGNs lack broad emission lines in their spectra. They only exhibit narrow lines for both permitted and forbidden transitions.

A quantitative basis for Seyfert subclasses was introduced by Osterbrock (1977). He proposed intermediate sequence between the above two extreme classes, according to relative strengths of broad to narrow component of Balmer emission lines. In Type 1, the broad components dominate while it is entirely absent in Type 2. Other intermediate classes are:

- **Type 1.2:** Broad component of $H\beta$ is much stronger than the narrow one.
- **Type 1.5:** Broad and narrow components of $H\beta$ are of comparable strength.
- **Type 1.8:** Broad $H\beta$ is weak but still visible; broad $H\alpha$ is more prominent.
- **Type 1.9:** Broad component is visible only in $H\alpha$, $H\beta$ appears purely narrow.

NLS1 Galaxies

A special subclass of Type 1 AGNs were identified by Osterbrock & Pogge (1985), known as the Narrow Line Seyfert 1 (NLS1) galaxies. In accordance with their Type 1 behaviour, they show prominent permitted lines; however the spectra has characteristic unusually narrow Balmer lines with FWHM widths of $H\beta$ being less than 2000 km s^{-1} . The optical spectra show strong Fe II emission complex and weak O[III] lines, distinguishing them from typical Seyfert 1 galaxies. The spectra often have pronounced Fe II lines in the $4400\text{--}5500 \text{ \AA}$ range, resulting in a false continuum dominating the optical region.

1.2.2 Luminosity-based Classes

AGNs have a wide range of luminosities, span more than ten orders of magnitude and hence can be classified based on their total power output. Quasars dominate the higher luminosities with bolometric outputs reaching as high as $10^{45} - 10^{48} \text{ erg s}^{-1}$. Often in cases of quasars, the nuclear regions are so bright that they outshine the host galaxies entirely. Quasars are typically found at moderate to high redshifts. Seyfert galaxies are the moderate-end of this classification with typical bolometric luminosities of $10^{42} - 10^{44} \text{ erg s}^{-1}$ (Seyfert, 1943; Osterbrock, 1989).

Low-Ionization Nuclear Emission-line Regions (LINERs) are the low luminosity class of AGNs, with luminosities around $10^{40} - 10^{42} \text{ erg s}^{-1}$ (Heckman, 1980; Ho, 2009). LINER spectra are dominated by low ionization forbidden lines. Their optical continuum are faint and the nuclear contribution is often difficult to be separated from that of the host galaxy's stellar background. LINERs are often associated with massive elliptical galaxies in the early Universe.

Some AGNs occupy the intermediate positions, blurring the boundary between Seyferts and LINERs. Their optical spectra show both moderately strong high-ionization lines (as in Seyferts) and significant low-ionization features (as in

LINERs). These objects are called transition objects and their presence suggest that AGN activity spans a continuous luminosity sequence rather than a set of sharply divided classes.

1.2.3 Radio Classification

Another important observational difference in active galaxies appear in their radio loudness. Early surveys showed that while some AGNs are extremely powerful radio sources, a vast majority of them are relatively faint or even undetectable at radio wavelengths. This led to the division between radio-loud and radio-quiet active galaxies (Kellermann et al., 1989, 1994; Wilson & Colbert, 1995).

The radio loudness parameter (R) is defined as the ratio of flux densities in the radio (5 GHz) and optical (B-band, 4400 Å) bands:

$$R = \frac{F_{5GHz}}{F_B} \quad (1.1)$$

Kellermann et al. (1989) classifies sources with $R > 10$ as radio-loud while the ones having $R < 10$ are often considered radio-quiet.

Radio-loud AGNs have powerful synchrotron emission extending from radio to the millimetre regime - often associated with relativistic jets arising from the central nucleus. The radio structures can extend from parsec to megaparsec scales, forming lobe structures and hotspots that are visible in the interferometric radio maps. Important subclasses include radio galaxies, blazars and radio-loud quasars. Based on their morphology, radio galaxies are further divided into Fanaroff-Riley Classes (Fanaroff & Riley, 1974) :

- **FR I** sources are low luminosity objects with jets that fade and broaden as they move outwards, showing edge-darkened morphology.
- **FR II** sources are high luminosity objects whose jets end in very bright outer lobes or hotspots, with edge-brightened morphology.

Despite the terminology, ‘radio-quiet’ does not mean a complete absence of radio emission; rather for a given optical luminosity, these objects are several orders of magnitude fainter in radio than their radio-loud counterparts. Radio-quiet AGNs lack any extended radio jets and display very weak radio emission which is often restricted to the nuclear region.

1.3 Physical Structure

In a typical AGN, matter accretes onto a central black hole from a rotating accretion disk, releasing enormous energy. This radiation powers the different constituents in the ambient environment - broad and narrow emission line regions, dusty molecular torus and in some cases, relativistic jets and winds. Each of these components have their own signature features across the electromagnetic spectrum of the AGN and together they form the complex multiwavelength appearance of the AGN.

1.3.1 Central Engine and Accretion Disk

The centre of every active galactic nuclei is occupied by a supermassive black hole of mass ranging between $10^6 - 10^8 M_{\odot}$. The extraordinary luminosity of AGN, that can even exceed $10^{46} - 10^{48} \text{ erg s}^{-1}$, is powered by converting gravitational potential energy into radiation when matter falls onto these central objects. With an efficiency of 10 %, accretion is the most-efficient known astrophysical energy source and can generate energies several orders of magnitude greater than nuclear fusion (Lynden-Bell, 1969; Rees, 1984).

Since the infalling matter has angular momentum, it cannot directly fall onto the black hole, instead the matter forms a rotating accretion disk. Shakura & Sunyaev (1973) proposed a geometrically thick, optically thin disk model with viscous forces enabling transport of angular momentum outwards and matter towards the inside. The gravitational energy in the disk is dissipated due to viscous forces thus, heating up the disk. The resulting thermal emission can be represented by a series of blackbodies at different temperatures. The effective temperature varies with radius by the relation,

$$T(r) \propto r^{-3/4}$$

The result is a multi-colour blackbody spectrum peaking at UV temperatures. This emission component give rise to the ‘big blue bump’ observed in many AGN spectra (Shields, 1978; Malkan & Sargent, 1982). The inner regions of the accretion disk closer to the black hole can have temperatures several times of 10^5 K . The emission profile is mainly shaped by general relativity effects. Rapid variability have been observed in optical and UV bands, suggesting that the disk extends inward upto just a few gravitational radii. Studies on time

lags between X-ray and UV signals also support the X-ray illumination and reprocessing picture inside a compact disk-corona system (McHardy et al., 2014; Edelson et al., 2015).

The actual mechanism for the transport of angular momentum is still a topic of study. Currently, the viscous force is thought to be generated by magneto-rotational instability (MRI) (Balbus & Hawley, 1991). MRI creates magnetic turbulence which not only helps in energy dissipation in the disk, but also connect to the formation of the X-ray producing corona.

The observational evidence for the accretion disk in AGNs are many. Optical-UV spectral analysis show multi-colour blackbody thermal emission, consistent with the disk model. Time lag studies reveal that the variations in UV continuum precede those in optical by few hours to days, suggesting that the UV emission originates from inner, hotter regions of the accretion disk while optical emission is from the cooler, outer regions (Cackett et al., 2007; Fausnaugh et al., 2016). Many AGNs show a relativistically broadened and skewed Fe K α line at 6.4 keV with an extended red wing. This is caused by Doppler shift and gravitational red shift of materials orbiting at relativistic velocities near the black hole - which form the accretion disk (Tanaka et al., 1995). Together these results strongly support the presence of accretion disk as the primary radiation sources in active galactic nuclei.

1.3.2 X-ray Emitting Corona

AGNs are bright at almost all wavelengths that they have been observed, especially in the X-ray energies. The accretion disk primarily emits in the optical and UV bands, corresponding to gas temperatures of $\sim 10^5$ K. Even at the innermost stable circular orbit (ISCO), for a $10^8 M_\odot$ black hole, the temperature ranges between $10^5 - 10^6$ K, peaking at UV energies. Thus the observed X-ray flux cannot be explained by disk emission.

This high energy emission is now attributed to the corona - a compact region of hot, optically thin plasma in the vicinity of the black hole and the inner accretion disk (Haardt & Maraschi, 1991, 1993; Done et al., 2012). Soft optical and UV photons from the accretion disk reaches the corona and undergo inverse Compton scattering thereby getting upscattered into X-ray energies. This produces a power law continuum extending upto hundreds of keV (Sunyaev & Titarchuk, 1980). Typically the photon index ranges from $\Gamma = 1.5 - 2.5$ with an exponential cut-off at $\sim 100 - 300$ keV. These spectral parameters provide

crucial information on the coronal temperature and optical depth (Fabian et al., 2015; Tortosa et al., 2018). The overall X-ray luminosity constitutes $\sim 10\%$ of the bolometric luminosity in AGNs (Lusso & Risaliti, 2016).

Despite decades of in-depth studies, the geometry and structure of the corona is not completely understood. Early models proposed a ‘sandwich’ or ‘slab’ configuration for the corona, with the hot plasma lying above and below the accretion disk (Haardt & Maraschi, 1993). Recent evidences from time lag and microlensing studies suggest a ‘lamppost’ geometry. In this model, the compact plasma is located close to the rotational axis of the black hole, within a few gravitational radii of the event horizon (Wilkins & Fabian, 2012; Kara et al., 2016). The height and compactness of the corona significantly affect the reflection spectrum: X-rays from the corona illuminate the disk and a fraction of this radiation gets absorbed and re-emitted as the reflection spectrum. Major components of the reflection spectrum are (i) the iron $K\alpha$ emission line at 6.4 keV due to fluorescent transitions in the cold or mildly ionized iron atoms and (ii) the Compton hump - broad excess in the spectrum peaking at 20 - 30 keV caused by the scattering of high energy photons by the dense disk (Fabian et al., 1989, 1995; Mushotzky et al., 1995; Magdziarz & Zdziarski, 1995).

Moreover, the corona seems to be dynamically linked with the accretion flow and it might be the base of a failed jet (Markoff et al., 2005). AGN X-ray emission shows variability on very short timescales, even a few light hours. Thus the emission should be from a region of small physical size, within ~ 10 gravitational radii (Wilkins & Gallo, 2015; Fabian et al., 2017b). These rapid variability, along with the correlated variability between optical/UV and X-ray bands provide crucial constraints on the physical conditions and energy coupling in the disk-corona system.

1.3.3 Broad and Narrow Line Emission Regions

The radiation from the accretion disk photoionizes gas cloud lying beyond the corona, at larger distances from the black hole. These regions produce the many emission lines characteristic of the AGN spectra. The broad line region (BLR) and narrow line region (NLR) represent two distinct regions of density, ionization state and kinematics (Osterbrock & Ferland, 2006).

BLR lies closer to the central engines, about few light days to light weeks from the black hole corresponding to a radius of $\sim 0.01 - 0.1$ pc. It consists of dense gas ($n_e \approx 10^9 - 10^{11} \text{ cm}^{-3}$), moving at very high velocities (thousand of

km s⁻¹). This causes the Doppler broadening of permitted lines such as H β , Mg II and C IV. Measuring the width of these lines can give an estimate on the virial velocities. Along with the radius estimates from reverberation map techniques, it gives one of the most direct methods for black hole mass estimation (Peterson, 1993; Kaspi et al., 2000; Bentz & Katz, 2015). Very often the emission lines show asymmetries or sometimes multiple components indicating very complex dynamics in the emitting regions.

NLR lies farther outside, at distances of tens to hundreds of parsecs. This region has lower density gas ($n_e \approx 10^3 - 10^6 \text{ cm}^{-3}$) and is photoionized by the AGN continuum. Due to its larger distance from the black hole, this region experience far lesser Doppler broadening (few hundred km s⁻¹), producing narrow permitted and forbidden emission lines seen in Seyfert 2 and Type 2 quasars. Some prominent forbidden lines often observed are O[III], N[II] and S[II]. Thus the BLR and NLR together represent the structure of ionized gas surrounding the central engine in AGNs. BLR represent the inner, high velocity region while NLR characterises the far, slow moving gas.

1.3.4 Dusty Torus

A doughnut-shaped, thick obscuring structure of gas and dust surrounds the central engine and the broad line region and is referred to as the dusty torus. The torus is thought to consist of molecular gas and dust grains, at a distance of a few parsecs from the black hole. The dust temperature ranges from several hundred kelvins at the outer edges to sublimation temperatures ($\approx 1500 \text{ K}$) in the inner regions. The inner portions are heated by the intense radiation energy from the accretion disk (Barvainis, 1987). This warm dust will re-emit the absorbed UV and optical photons as IR radiation, giving rise to the mid-infrared bump observed in AGN spectra.

High resolution interferometry observations suggest that the torus is clumpy or filamentary, rather than a uniform continuous structure (Nenkova et al., 2008a,b; Bartscher et al., 2013). Each dust cloud will absorb and scatter light independently, which allows some light to escape even when the line of sight passes through the torus. The covering fraction of the torus is defined as the fraction of solid angle around the nucleus that it obscures. The covering fraction is found to vary with luminosity, decreasing in more powerful AGNs - this is called the receding torus model (Lawrence, 1991; Simpson, 2005; Hoenig & Beckert, 2007). Recent models suggest that the torus maybe a dynamic, multiphase structure

and can be linked to the outflows from the disk that gets condensed into dusty clouds (Wada, 2012; Hönig & Kishimoto, 2017).

The torus can also act as source of material feeding the process of accretion. It, therefore, serves as an interface between the nuclear region and the host galaxy's interstellar medium, controlling the exchange of materials and angular momentum between the two. Gas inflow from the host galaxy may accumulate in the torus before being given into the accretion disk, feeding the accretion for extended time periods (Storchi-Bergmann & Schnorr-Müller, 2019). Oppositely, feedback from the accretion disk in the form of radiation pressure, jets and winds can shape the structure and dynamics of the torus.

1.3.5 Jets

Some AGNs show the presence of relativistic jets and outflows which are among the most energetic phenomena in the observable Universe. AGN jets are collimated stream of plasma moving along the rotational axis of the supermassive black hole. These jets extend outside the host galaxies, over kiloparsec to megaparsec scales and emit in almost all energies from radio to γ -rays (Blandford et al., 2019). The jets are thought to be powered by the accretion energy and rotational energy extracted from the black hole through magnetohydrodynamic processes.

In the radio-loud AGNs, the synchrotron radiation dominates at radio to optical wavelengths while inverse Compton scattering dominates at higher X-ray and γ -ray energies. The jets often appear one-sided in observations. This is caused by relativistic beaming where emission from the approaching jet gets enhanced while the other one is down boosted. Interferometric observations reveal that the jets have complex structures such as knots, shocks and helical patterns indicating magnetic collimation and instabilities within (Laing & Bridle, 2014).

The launching, acceleration and collimation of AGN jets are not completely understood. Magnetic fields in the inner accretion disk are essential for extracting energy and focusing the plasma. Observing the variability and polarization of jets can provide constraints on the composition, speed and geometry. The composition may consist of either electron-positron pairs or a mixture of electrons and protons. The interaction of jets with the surrounding interstellar and intergalactic medium can create hotspots and lobes which affect galaxy evolution and produce extended radio emission.

In addition to the collimated jets, AGNs also show outflows such as ionized winds, ultrafast X-ray outflows and molecular or neutral gas outflows seen in the infrared observations. Outflows are observed in both radio-loud and radio-quiet AGNs. These outflows maybe driven by radiative forces or by magnetic effects. They carry mass, energy and momentum into the host galaxy and thus play a role in the feedback process that controls star formation and black hole growth.

1.4 The Unification Theory

The unification theory propose that the different observational classes of AGNs are a single type of physical object viewed under different physical conditions, specifically their orientation. Apparent differences between the classes are simply manifestations of their different orientations with respect to the observer. According to this model, all AGN types share a common structure consisting of the central black hole, an accretion disk, a hot X-ray corona, a broad line region, a narrow line region, surrounding dusty torus and in some cases, relativistic jets. The differences in observational properties are due to the angle at which the system is observed, rather than any intrinsic variation (Antonucci, 1993; Urry & Padovani, 1995).

In this scheme, Type 1 AGNs are viewed with a direct line of sight to the central engine and BLR. Unobscured by the dusty torus, the spectra will have features coming from these regions such as the strong optical/UV continuum from the disk along with prominent X-ray emission and broad emission lines from the BLR. On the other hand, Type 2 AGNs happen when observed through the obscuring torus. This blocks the direct view of the BLR and central region. As a result, only the narrow permitted and forbidden lines from NLR are seen in the spectra and the continuum appears to be attenuated at optical and UV energies (Lawrence, 1991; Netzer, 2015). Furthermore, obscured Type 2 AGNs show strong IR emission from dust reprocessing and heavily absorbed X-ray emission, as compared to their Type 1 counterparts. In the case of radio-loud AGNs, the orientation determines whether we see a blazar with the jet pointed towards the observer or a radio galaxy with the jet at a large angle (Urry & Padovani, 1995; Blandford & Rees, 1974). This is further supported by the observed superluminal motion in blazars and the one-sided jet asymmetry due to relativistic beaming. The schematic diagram in Figure 1.1 summarises the unification model, showing the central black hole and accretion disk at the core, surrounded by BLR and

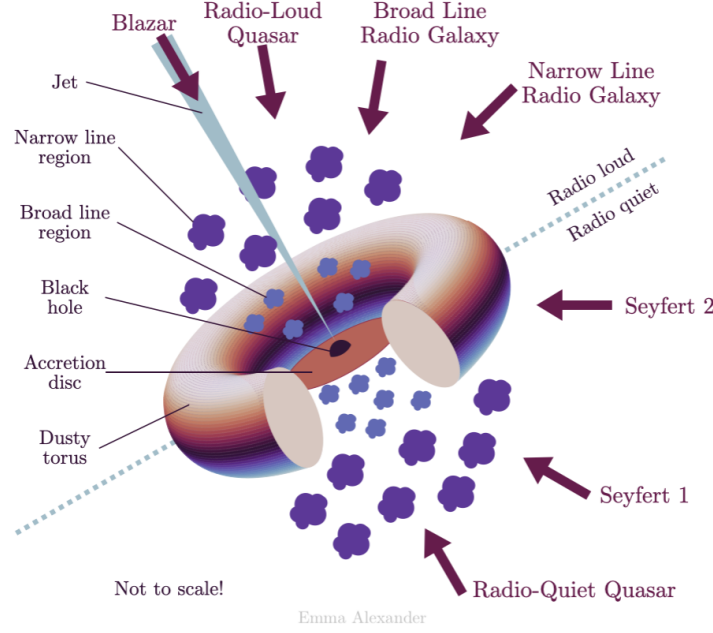


Figure 1.1: Schematic representation of the AGN unification model showing how the observed characteristics depend upon the viewing angle with respect to the observer. Image Credit: GitHub/Alexander.E.L.

the torus, while the NLR lies outside, extending to larger distances.

This basic model explains most of the observed diversity in the properties. However, the unification model does have certain limitations. Some refinements are required to accommodate intermediate objects such as Seyfert 1.2-1.9 galaxies, LINERs and AGNs with varying obscuration. Modern unification theory proposes a clumpy torus, luminosity dependent obscuration and the effect of host galaxy structure to have effects on the AGN's appearance (Nenkova et al., 2008a; Netzer, 2015). Intermediate Seyferts such as Type 1.8/1.9 show weak broad lines, possibly due to partial obscuration or a clumpy torus. LINERs with low ionization emission lines and weak continuum could represent transitional objects between active and inactive nuclei or systems with inefficient accretion flow. Another category of objects, called the changing look AGNs, switch between Types 1 and 2 over timescales of a few months to years and requires phenomena such as variable obscuration and changes in accretion rates to be explained. Thus the unification theory provides a comprehensive framework to include the subclasses of AGNs, emphasizing that along with orientation, torus clumpiness, host galaxy effects and intrinsic variability are all fundamental in shaping the observed AGN population.

1.5 Spectral and Temporal Properties of AGNs

The various structural components of AGNs are observationally evident through their individualistic features in the broadband spectrum and variability patterns. Each region contributes at different wavelength, giving the observed multiwavelength broadband spectral energy distribution (SED). Thermal emission from the accretion disk dominates the optical/UV energies, while the dusty torus reprocesses a fraction of this radiation and re-emits at IR wavelengths. The corona produces X-rays through Comptonization and relativistic jets give out non-thermal synchrotron emission and inverse Compton emission that extends from radio and γ -ray energies.

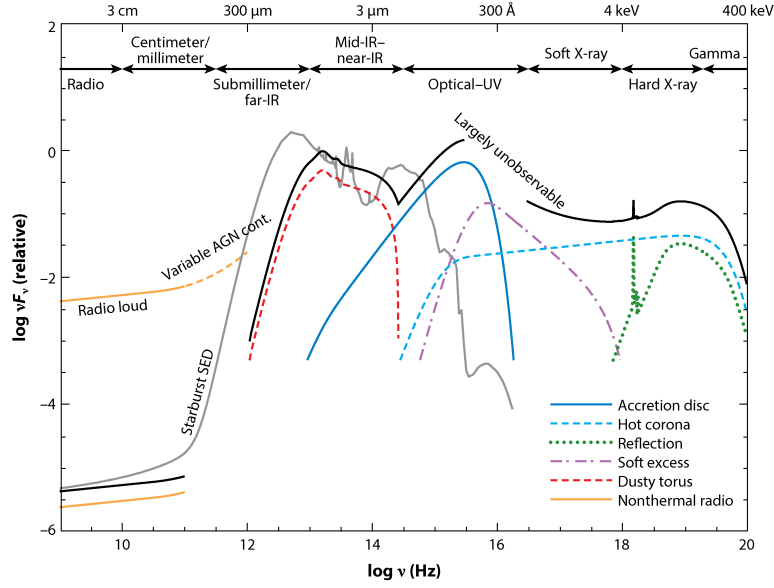
AGNs are also characterised by their distinct variability patterns. They have been observed to exhibit variability at almost all wavelengths on timescales ranging from hours to years. The variability pattern contains information about the size and dynamics of the corresponding emission region. Studying the spectro-temporal properties of AGNs is therefore crucial in understanding their structure and the physical processes that govern AGN mechanism.

1.5.1 Spectral Characteristics

The overall spectral energy distribution of AGNs is characterised by the combined emission from all its components and extends over more than ten orders of frequency magnitudes from radio to IR, through optical/UV and extending upto X-rays and γ -rays. Despite the differences in individual classes, AGNs show some common features that describes the underlying physical processes. In radio-quiet AGNs, the dominant components are thermal and Comptonized emission from the disk-corona system, while in radio-loud AGNs, there is additional non-thermal emission from the relativistic jets at radio to γ -ray energies (Elvis et al., 1994; Padovani, 2017). Figure 1.2 sums up the spectral energy distribution with individual components marked.

Continuum Emission

The continuum emission arises from the combination of thermal and non-thermal processes happening in different regions of the AGN. Typical AGN SED contains the ‘big blue bump’ at optical/UV region, produced by the multi-coloured accretion disk (Shields, 1978; Malkan & Sargent, 1982). The optical/UV continuum



Hickox RC, Alexander DM. 2018.
Annu. Rev. Astron. Astrophys. 56:625–71

Figure 1.2: Broadband spectral energy distribution of a typical AGN showing the components at different wavelengths. Image Credit: Hickox & Alexander (2018).

from the accretion disk is caused by the conversion of gravitational potential energy into radiation. In the geometrically-thin optically-thick disk, each annular region emits like an individual blackbody at a different temperature, resulting in the observed multi-colour blackbody spectrum (Shakura & Sunyaev, 1973). The overall peaked UV emission can be studied for estimating the accretion rates and radiating efficiency. At IR energies, a secondary bump maybe caused by the re-emission of optical/UV light into longer wavelengths by the dust clouds in the torus (Pier & Krolik, 1992; Sanders, 1999; Netzer, 2015). The obscuring torus absorbs a fraction of the disk emission and reprocesses it, at IR wavelengths.

At higher energies, inverse Compton scattering in the corona give rise to a power law emission continuum extending upto hundreds of keVs. This X-ray power law has a spectral slope that depends mainly on the temperature and optical depth of the corona (Haardt & Maraschi, 1993; Fabian et al., 2015). The X-ray continuum is modified by the reflection of X-rays from the accretion disk, giving rise to features such as Fe $K\alpha$ line emission and the Compton hump (George & Fabian, 1991; García et al., 2014).

In radio-loud AGNs, non-thermal emissions dominate the spectra. These are produced by the synchrotron mechanism of the relativistic electrons spiralling inside the magnetic fields of the jets (Blandford & Königl, 1979). Sometimes,

these electrons can also upscatter their synchrotron photons to X-rays and γ -rays through the synchrotron self Compton processes (Ghisellini & Tavecchio, 2010). This is commonly seen in blazars.

Relative strengths of the individual components depends on several factors including black hole mass, accretion rate and orientation. In systems with high accretion rates, including several NLS1 galaxies, a strong optical/UV continuum is seen along with a steep X-ray power law. Low luminosity AGNs, on the other hand, often have weak disk emission and a hard X-ray spectrum (Vasudevan & Fabian, 2007). Hence, the shape of the spectrum can give us information on the radiative efficiency, geometry and energy budget of the central engine.

Emission and Absorption Features

Superimposed on the continuum, AGNs have several emission and absorption features particular to their physical structure. Broad and narrow emission lines arise from clouds in the BLR and NLR region discussed in Section 1.3. These lines provide valuable tools for understanding the ionization state and gas dynamics in this region. Their widths and shifts provide information about velocity fields and black hole masses while the line ratios can be used to distinguish AGN excitation from stellar photoionization. The relative strengths of permitted and forbidden lines may also be used to constrain gas density, temperature and the ionization parameter.

X-ray bands are also characterised by several emission features. Many Seyfert galaxies and quasars show an additional soft X-ray excess below ~ 2 keV (Arnaud et al., 1985; Crummy et al., 2006). The origin of this smooth excess component is still debated with many interpretations such as thermal Comptonization in a warm optically thick corona or a blurred reflection from the ionized accretion disk (Magdziarz et al., 1998; Done et al., 2012; Ross & Fabian, 2005). At 6.4 keV, we see the Fe $K\alpha$ emission line, a prominent feature in the AGN X-ray spectrum, caused by illumination of cold material in accretion disk or the torus by X-ray photons (George & Fabian, 1991). Sometimes, relativistic Doppler effects and gravitational broadening can cause an asymmetric profile reaching upto ~ 4 keV. The Compton reflection hump, at ~ 20 keV, is caused by backscattering and absorption in optically thick material.

Absorption features are another common characteristics of AGN spectrum. They are produced due to warm absorbers - ionized outflows characterised by edges and lines from O VII, O VIII and Fe L transitions. Their existence prove

the presence of winds that can move at hundreds to thousands of km s^{-1} , carrying away significant kinetic energy (Reynolds, 1997; George et al., 1998).

1.5.2 Temporal Variability

Observations show that emission from the active galactic nucleus vary over a wide range of timescales from minutes to decades, at almost all wavelengths. The variability provides a direct method to study the compact regions close to the supermassive black holes, that are otherwise too small to be spatially resolved (Ulrich et al., 1997; Collier & Peterson, 2001). Since the light travelling time across the emission region limits the speed of flux exchange, variability timescales can offer a way to estimate the size and structure of emitting zones.

Variability Timescales

AGNs exhibit variabilities of a range of timescales:

- **Short Term (Hours to Days):** Commonly seen in X-ray and UV bands, short term variabilities involve processes occurring in the innermost accretion disk and corona (e.g., McHardy et al., 2006). The rapid variability indicates extremely compact emission regions, only a few gravitational radii in size.
- **Intermediate (Weeks to Months):** Optical and UV bands show these variabilities and are attributed to changes in accretion disk, reprocessing of X-ray illumination and/or instabilities travelling through the disk (e.g., Krolik et al., 1991; Ulrich et al., 1997).
- **Long Term (Years to Decades):** Long term variabilities involve changes in the overall luminosity or spectral state, caused by uniform evolution of accretion flow and changes in obscuration over a large scale. Changing look AGNs could be considered as examples of long term variability (e.g., LaMassa et al., 2015).

Energy Dependence

AGN variability amplitudes and patterns are strongly energy dependent. X-ray emissions show the most rapid and pronounced variations while optical and infrared band show delayed and smoother variations. This energy dependent behaviour helps us to understand the causal links between AGN components. The

cross-band correlations can provide additional information on the physical coupling of emitting regions. In many Seyfert galaxies, the optical and UV variations lag behind the X-ray by several days (Edelson et al., 2015). These delays can be thought of as proofs for the model where varying coronal emission illuminate the disk and are re-emitted at longer wavelengths after a time delay corresponding to the light travelling time between the two regions - this phenomenon is known as reverberation. At even longer wavelengths, IR emission trails behind optical proving the reprocessing by the circumnuclear dust in the torus.

The energy dependence of variability indicates a strong correlation between the disk and corona. As already mentioned, variable coronal emission can illuminate and heat the disk, driving the delayed UV/optical emission. Conversely, fluctuations in the accretion rate may first appear in the disk emission and then propagates inward, modifying the coronal emission. This will produce correlated variations in X-ray but with a time lag (Arévalo & Uttley, 2006). This two-way interaction give rise to complex energy dependent AGN lightcurves and measuring the time delays between energy bands makes it possible to study the geometry of the reprocessing regions and estimate the separation between emitting zones.

Tools for Variability Analysis

Several diagnostic tools are used for analysing the AGN variability, including:

- **Flux-Flux Correlations and Lag Spectra** between the different energy bands constrain the coupling between the disk and the corona to estimate the light travel time or propagation delays within the accretion flow (Nowak et al., 1999; Arévalo et al., 2009).
- **Fractional Root Mean Square (rms) Variability:** Measure the intrinsic variability of the source, excluding the contribution from measurement error (Vaughan et al., 2003). The method can be utilised to identify components driving the variability and to distinguish between spectrally degenerate models.
- **Reverberation Mapping:** Measure time delays between variations in the continuum and emission lines to estimate the size and geometry of broad line region. With knowledge of the velocity profile, this provides a direct tool for black hole mass estimation (Blandford & McKee, 1982; Peterson, 2014).

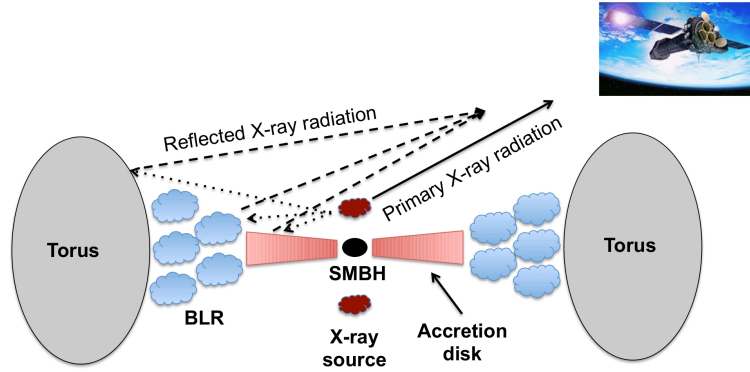


Figure 1.3: AGN X-ray reprocessing. Image Credit: Ricci.

1.5.3 X-ray Reflection

An important aspect of AGN X-ray regime is the phenomenon of X-ray reflection. It plays an important role in shaping the observed X-ray spectra and is among the most direct probes of the innermost regions around supermassive black holes. Reflection happens when the primary continuum emitted by the corona illuminates the optically thick accretion disk and these photons are then re-emitted by the accretion disk (Fabian et al., 1989; Laor, 2005; Fabian & Ross, 2010). Thus the observed AGN X-ray spectrum will have contribution from both the primary emission and the reflected component, see Figure 1.3.

When the hard X-rays from the corona falls on the disk surface, part of the radiation is absorbed and re-emitted, while the rest undergoes Compton scattering and photoelectric absorption. This combination of processes results in a reflected spectrum that is different from the incident power law. One of its most important features is the Fe $K\alpha$ emission line in the 6.4 – 6.9 keV energy range. These emission lines are produced by fluorescence in iron atoms and are prominent in observed spectra due to the high cosmic abundance of iron and the high fluorescent yield. Another important feature is the soft excess, the smooth enhanced emission below ~ 2 keV which could result from a blend of numerous reprocessed features. At higher energies, repeated Compton scattering of reflected photons produces the Compton hump peaking around 20 – 30 keV. These features together form a complex signature on the AGN X-ray spectrum.

The reflection processes occur very near to the central supermassive black hole and hence, the observed features are strongly affected by relativistic effects. The orbital motion of the inner disk causes Doppler broadening and boosting, while the gravitational field causes redshift and bending of light. As a result, the

iron line will have a broad profile continuing upto lower energies, as mentioned in the previous section and it will modify the continuum curvature of the reflection spectrum (Matt et al., 1991; Fabian et al., 1989). Thus, studying the emission line shape and width can give information about the disk’s inner radius, black hole spin and the distribution of coronal illumination (Brenneman, 2013; Reynolds, 2014).

The reflection features also depend on the ionisation state of the disk, the radial emissivity profile and the source’s inclination. For e.g., a highly ionised disk produces softer emission and weaker neutral lines, whereas a colder disk enhances the 6.4 keV Fe $K\alpha$ line. The emissivity profile, which tells us how strongly is the disk illuminated at different radii, determines the contribution from the inner and outer disks - providing a link to the coronal geometry. Inclination affects the width and shape of reflection features by affecting the line-of-sight velocity. Thus reflection features contain a lot of information regarding the structure and mechanism of the central engine.

AGN X-ray reflection also has some temporal properties (Uttley et al., 2014; Fabian et al., 2017a). The reflected photons travel paths longer than primary continuum and hence take longer to get observed. Hence, variations in the coronal emission appear in the reflected emission after a short time delay. The reverberation lags have an amplitude and frequency dependence as well, which can be measured to infer the distance between the corona and the disk. Additionally, fractional variability measurements shows characteristic dips or enhancements in the reflection dominated energy bands, giving us more evidence of disk re-processing. Being a natural means to study the innermost regions around the supermassive black holes, X-ray reflection is a fundamental component in understanding the AGN emission.

1.5.4 Current Challenges in AGN X-ray Studies

Despite significant advances in both observations and theoretical modelling, several fundamental questions regarding the physical processes governing AGN X-ray emission remain unresolved. While the broad framework of accretion onto supermassive black holes is now well established, physical properties of the innermost regions continue to be debated. In particular, the size, geometry and physical conditions of the X-ray emitting corona remain poorly constrained and the nature of its interaction with accretion disk is still not fully understood. Similarly, the physical origin of soft X-ray excess and relative contributions of

relativistic reflection, warm Comptonisation and ionised absorption to the observed X-ray spectrum remain active areas of research (Haardt & Maraschi, 1991; Reynolds, 2019; García et al., 2019).

A major challenge in AGN X-ray studies arises from the inherent degeneracies between competing spectral models. Broadband X-ray spectroscopy has revealed the presence of continuum emission, relativistic reflection and complex absorption with unprecedented detail. However, different physical scenarios can often reproduce similar spectral signatures. For example, relativistic reflection, warm Comptonisation and partial-covering absorption can all explain the soft X-ray excess and broadband spectral curvature observed in many Seyfert galaxies (Crummy et al., 2006; Done et al., 2012; Parker et al., 2014). Consequently, spectral fitting alone cannot uniquely identify the dominant physical mechanism or accurately constrain key parameters such as the geometry of the corona, ionisation state of the accretion disk or properties of the absorbing material.

Temporal variability provides a complementary tool capable of overcoming many of these limitations. Since different emission components respond differently to changes in the central engine, variability analyses techniques such as flux-resolved spectroscopy, time-resolved spectroscopy, fractional rms analysis and lag spectroscopy can be utilised for the separation of variable and relatively stable spectral components, thereby providing stronger constraints on the physical origin of observed emission (Uttley et al., 2014; Kara et al., 2016). Moreover, using observations obtained over multiple epochs long-term evolution of AGNs can be investigated, helping distinguish persistent changes in the accretion flow from short-term variability. The combination of broadband spectral modelling with variability studies across different timescales therefore provides a more comprehensive understanding of the physical processes governing AGN emission than either approach alone.

1.6 Motivation and Thesis Outline

Powered by accretion, active galactic nuclei are among the most luminous and dynamic astrophysical sources. This immense energy output influence the surrounding interstellar medium, thereby regulating star formation and feedback processes that determine the large scale structure of the host galaxies (Fabian, 2012; Heckman & Best, 2014; Harrison et al., 2018). Thus AGNs are fundamental to our understanding of black hole growth and galaxy evolution. They also

act as natural laboratories for studying physics in extreme conditions of strong gravity, relativistic motion and high energy radiation - environment that cannot be recreated on Earth.

The challenges outlined in the previous section demonstrate that a comprehensive understanding of AGNs requires a broadband approach that simultaneously studies the spectral and temporal domains. Combining detailed spectral fitting with variability analysis, we can test the different models and infer the geometry and energetics of central engine. Availability of high quality X-ray observations from instruments such as India's *AstroSat*, ESA's *XMM-Newton* and NASA's *NuSTAR* telescopes has enabled us to carry out such comprehensive analyses.

This thesis is motivated by the need to explore the same through broadband spectral analysis and variability studies of AGNs. It combines broadband spectral modelling with variability-resolved analyses to investigate the geometry and physical conditions of the X-ray emitting corona, examine the origin of spectral variability and reduce the degeneracies associated with purely spectral modelling. Long-term multi-epoch observations are used to investigate the evolution of spectral components, while variability-informed modelling is employed to distinguish between competing physical scenarios and obtain stronger constraints on the accretion disk-corona system.

The remaining chapters of this thesis are organised to provide a systematic study of the AGN broadband spectra and variability, building on the concepts introduced in this Chapter. The next Chapter 2, introduces the X-ray observational facilities used in our analysis. It describes the space telescopes, their detectors, energy coverage, spectral resolution and sensitivity, setting the observational context for the analyses undertaken.

Chapter 3 focuses on the detailed spectral analysis of a Seyfert 1 galaxy, Mrk 279. It presents the spectral modelling based on observations taken at multiple epochs. The long term analysis of spectral variations provide information on how the X-ray power law changes over time and the contributions of individual emission components therein.

Chapter 4 presents a novel method to predict the energy dependent fractional rms variability for linearly correlated variations of a pair of spectral parameters. By linking the variability patterns to spectral parameters for a test case of Mrk 335, the analysis investigates the physical processes driving the X-ray variability. The study demonstrated the potential of the developed method to be applied

to other datasets of different AGNs, providing us with a new approach to understand the energy dependent X-ray variations and the underlying physical processes.

Chapter 5, summarises the key conclusions and contributions of the thesis, highlighting the insights gained on AGN emission and variability. The chapter discusses the major results emphasizing how it improves our understanding of the physics of active galaxies. Chapter 6 provides recommendations for future works.

Chapter 2

Observational Facilities

Active galactic nuclei emit enormous radiation across the electromagnetic spectrum, with the X-ray energies providing a direct window for studying the processes governing the innermost regions. The X-ray band, from ~ 0.3 keV to > 50 keV contains emission from the hot corona, inner disk and relativistic jets, making it essential for studying high energy emission of AGNs. However, the Earth's atmosphere is opaque to X-ray photons (See Figure 2.1). This causes a fundamental limitation by making ground-based observations impossible. X-ray observations require space-based missions having specialized detectors capable of imaging, spectroscopy and/or timing at high energies.

Astronomical X-ray observations dates back to 1960s beginning with rocket-based experiments. This was followed by dedicated missions such as *Uhuru*, *Einstein* and *ROSAT*. These missions mapped the sky at X-ray wavelengths and revealed the variability and spectral complexity of AGNs. The observational capabilities have since improved drastically and now we have high resolution, high sensitivity observatories such as *XMM-Newton*, *NuSTAR* and *IXPE* (for polarimetric studies). Multi-instrument, broadband observations are particularly valuable as different instruments cover complementary energy ranges. For our analyses, we have used data from different instruments onboard the *AstroSat*, *XMM-Newton* and *NuSTAR* space telescopes.

2.1 AstroSat

AstroSat, launched by the Indian Space Research Organisation (ISRO) in September 2015, is India's first dedicated multiwavelength space observatory. The satellite is designed to provide simultaneous observations in the X-ray and UV bands,

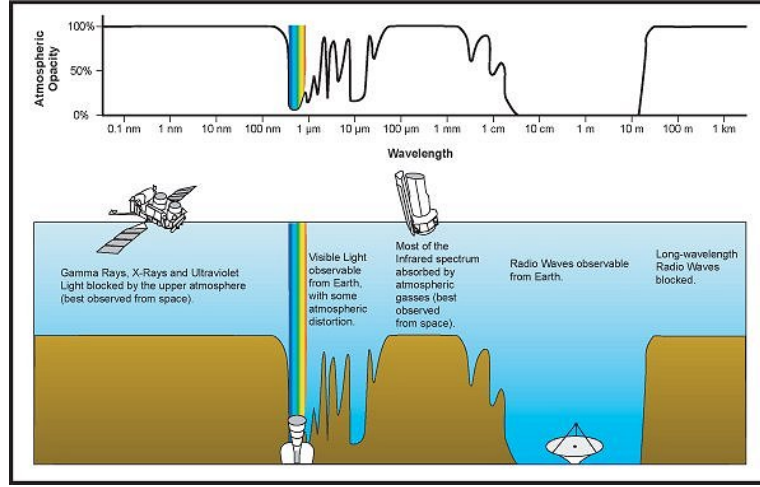


Figure 2.1: Opacity of Earth's atmosphere to different energies of the electromagnetic spectrum. Image Credit: NASA-IPAC

making it possible to have comprehensive observations of astronomical objects including AGNs. There are five payloads onboard: the Soft X-ray Telescope (SXT), Large Area X-ray Proportional Counter (LAXPC), Cadmium Zinc Telluride Imager (CZTI), Ultra Violet Imaging Telescope (UVIT) and the Scanning Sky Monitor (SSM). Together, these instruments cover a wide range of energies from ~ 130 nm UV to ~ 150 keV hard X-rays.

Figure 2.2 shows the different payloads onboard the satellite. SXT and LAXPC operate in X-ray energies, with the former being sensitive to soft X-rays of 0.3 - 8 keV, providing imaging and moderate resolution spectroscopy. The latter consists of a set of three identical proportional counters covering the 3 - 80 keV range and offers larger effective area and excellent timing capabilities. CZTI extends the X-ray coverage to 20 - 150 keV and is capable of hard X-ray imaging, spectroscopy and polarization measurements. The UVIT telescope observes in the far-UV, near-UV and visible bands. It allows us to conduct high resolution imaging and studies of star formation and accretion disks. There is also the SSM unit which continuously scan the X-ray sky in the 2.5 - 10 keV band in order to detect and track variable and transient sources. For the purpose of this thesis, we use data from both SXT and LAXPC instruments to obtain the broadband coverage required for spectroscopic and timing studies.

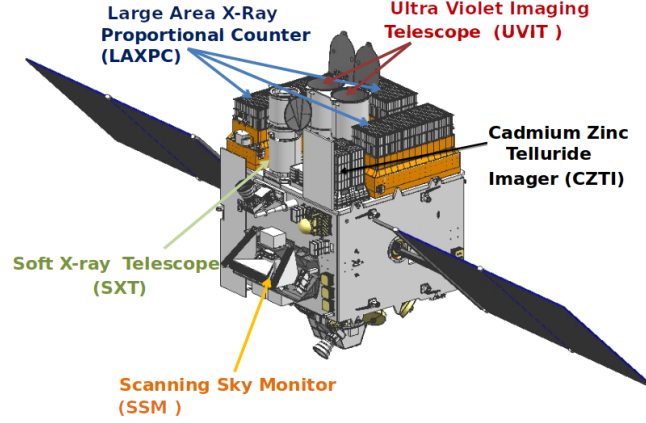


Figure 2.2: ISRO's *AstroSat* Mission Payloads. Image Credit: ISRO/AstroSat

2.1.1 SXT

The Soft X-ray Telescope (SXT) is designed for imaging and moderate resolution spectroscopy in the 0.3 - 8 keV energy range (Singh et al., 2016, 2017). The telescope has Wolter-I configuration of 41 nested mirrors that focus incoming X-rays onto a charge-coupled device (CCD) detector. The telescope has a focal length of ~ 2 m providing a field of view of about $\sim 40'$ in diameter. The effective area peaks at 90 cm^2 at 1.5 keV (See Figure 2.3). It provides an energy resolution of ~ 140 eV at 6 keV. SXT telescope can operate in multiple modes:

- **Photon Count** mode is the default mode and is used to observe faint to moderately bright sources. Each CCD frame, ≈ 2.4 s exposure, is read out completely, preserving both spatial and spectral information. Almost all AGN observations use this mode.
- **Fast Window** mode is used for very bright sources where the chances of pileup are higher. In this mode, only a region of the CCD is read out. This provides an increased timing resolution of ~ 0.278 s but at the cost of field of view.

Data from SXT is processed through the SXTPIPELINE software. The standard procedures include the following steps:

1. **Event Level 1 to Level 2 Processing:** Raw telemetry files are converted into calibrated event files with appropriate gain corrections, removal of flickering pixels and time tagging.

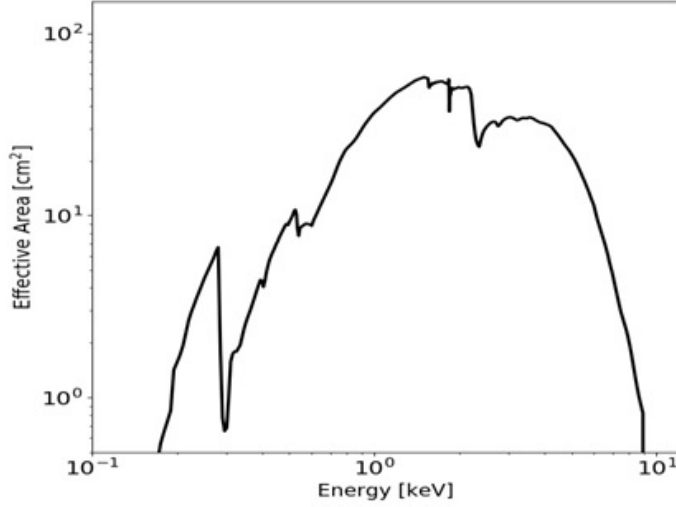


Figure 2.3: SXT telescope effective area as a function of energy. Image Credit: Singh et al. (2017).

2. **Filtering of Events:** Good Time Interval (GTI) file is generated to identify periods such as the South Atlantic Anomaly (SAA) passage, Earth occultation and times of increased background radiation. The event file is then filtered for this gti using standard screening parameters. For bright sources, check for any pileup by comparing the observed psf with calibration models, affected inner regions will be excluded if necessary.
3. **Image and Spectrum Extraction:** Using the cleaned event file, source image can be generated. Source spectrum is generated from a central circular region, usually of radius $15''$. Detector response files are generated using the SXTARFMODULE.
4. **Generating Lightcurve:** Lightcurves can be generated for the required energy range, using bin sizes suited for scientific purpose, corrected for exposure, vignetting and dead time.

SXT's soft X-ray coverage is important for studying the soft excess emission and reflection features in AGN spectra. Along with simultaneous LAXPC observations it provides a seamless broadband coverage of X-ray energies.

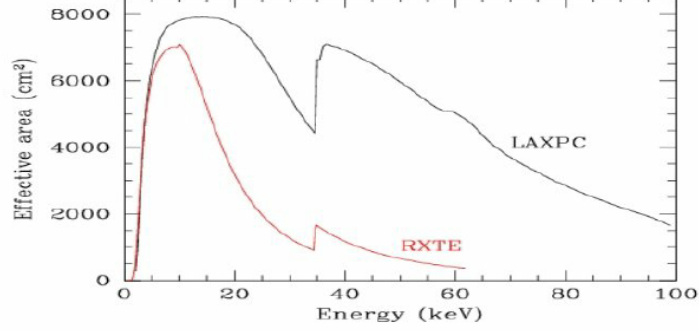


Figure 2.4: Combined effective area of all three units of LAXPC. The same for *RXTE* is also shown for comparison. Image Credit: AstroSat-LAXPC.

2.1.2 LAXPC

Large Area Proportional Counter (LAXPC) provides observations of high time resolution and moderate spectral resolution in the 3 - 80 keV band (Yadav et al., 2016; Agrawal et al., 2017; Antia et al., 2017; Misra et al., 2017; Antia et al., 2021). Its large effective area, wide energy coverage and millisecond time resolution makes it an ideal complement to the SXT telescope. The instrument consists of three identical co-aligned proportional counter units - LAXPC10, LAXPC20 and LAXPC30, aligned along the same optical axis. It has an effective area of $\sim 8000 \text{ cm}^2$ in the 5 - 20 keV range (See Figure 2.4). The energy resolution is about 12 % at 22 keV.

LAXPCSOFT is used for processing LAXPC data. It converts Level 1 telemetry to Level 2 calibrated event files. The standard steps of data reduction are as follows:

1. **Event Extraction:** Events are selected based on standard screening criteria, excluding the South Atlantic Anomaly (SAA) passages.
2. **Background Estimation:** Background files are modelled using the blank sky background, for the same orbital conditions.
3. **Generation of Science-ready Products:** Spectrum and lightcurves are generated over user-defined energy bins and with time bins as small as 0.01 s. Instrument's response matrices and ancillary files are also generated, which are required for spectral analysis.

LAXPC's hard X-ray sensitivity make it a powerful instrument for investigating coronal emission and reflection features in AGNs - being particularly effective

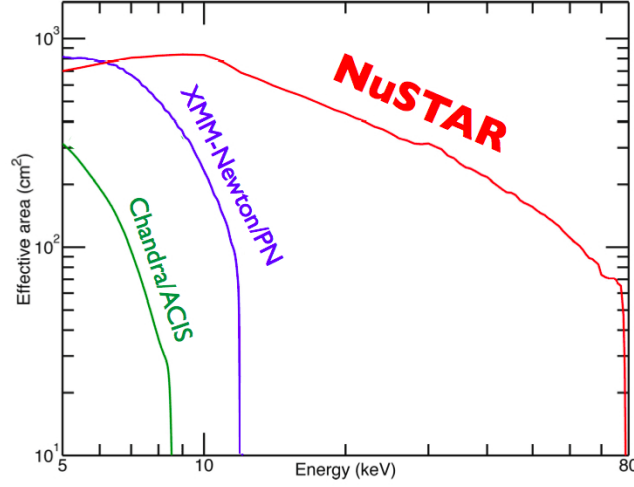


Figure 2.5: *NuSTAR* effective area, in red, compared to previous X-ray missions. Image Credit: HEASARC-*NuSTAR*.

in studying spectral variability and time lag phenomena.

2.2 NuSTAR

NUclear Spectroscopic Telescope ARray (*NuSTAR*), is a NASA mission, operating in the hard X-ray 3 - 79 keV band (Harrison et al., 2010, 2013; Madsen et al., 2015). The telescope marks a major advancement in X-ray astronomy by providing focusing capabilities at high energies. It was able to achieve two orders of magnitude improvement in sensitivity and has an angular resolution of 18'' FWHM. Launching of *NuSTAR* revolutionised observations of faint and distant X-ray sources including AGNs.

NuSTAR contains two identical co-aligned telescopes with Wolter-I grazing incidence optics. Each of them are connected to a focal plane module - FPMA and FPMB. It has a focal length of 10.14 m, with a combined field of view $\sim 12' \times 12'$ FWHM. The telescope's effective area peaks $\sim 900 \text{ cm}^2$ at 10 keV (See Figure 2.5). It provides a good energy resolution of $\sim 400 \text{ eV}$ at 10 keV and fast timing $\sim 2.5 \mu\text{s}$.

NuSTAR data reduction is performed using the NUSTARDAS software package integrated within HeaSoft, along with the calibration database CALDB, managed by NASA/HEASARC. The standard procedure is:

1. **Pipeline:** The NUPIPELINE converts raw Level 1 data into cleaned Level

2 data following standard practices.

2. **Product Extraction:** NUPRODUCTS task is used to extract source and background spectra, lightcurves and instrument response files. Source regions are selected, typically circular with a radius of 30''-35'', depending upon the source's brightness. Background regions are selected from nearby blank sky regions on the same detector for accurate subtraction.

NuSTAR allows exact measurements of coronal temperatures, high energy cut-off and reflection fractions in AGNs (Fabian et al., 2015; Tortosa et al., 2018). The excellent timing capabilities allows us to conduct variability and lag analyses to probe the coronal size and geometry.

2.3 XMM-Newton

The X-ray Multi-Mirror Mission (XMM-Newton), launched in 1999 December by ESA, is one of the most successful and long standing X-ray observatories (Jansen et al., 2001). It is designed to provide high throughput and moderate spectral resolution over a wide range, 0.2 - 12 keV. It carries three co-aligned telescopes, having 58 mirrors each, with Wolter-I optics. The incoming X-rays are focused onto the detectors of the European Photon Imaging Camera (EPIC) system (Strüder et al., 2001). In addition to epic, *XMM-Newton* also carries the Reflection Grating Spectrometers (RGS) for high resolution spectroscopy. RGS is mounted behind two of the three telescopes and disperse the X-ray into high resolution spectra in 0.3 - 2.5 keV band. An Optical Monitor (OM) is also onboard to facilitate simultaneous optical observations.

EPIC consists of two types of detectors - one p-n junction (pn) camera and two metal oxide semiconductor (MOS1 and MOS2) detectors - each at the focal plane of the three telescopes. These cameras operate over the 0.2 - 12 keV band with an energy resolution of about 70 - 150 eV at 1 keV. The angular resolution is about 6'' FWHM. These cameras can be operated in different modes such as Full Frame, Small Window and Timing, depending upon the source brightness and variability.

EPIC-PN

Among the three cameras, epic-pn has the best sensitivity and fastest readout time and hence is the most widely used in observing bright AGNs. It has an

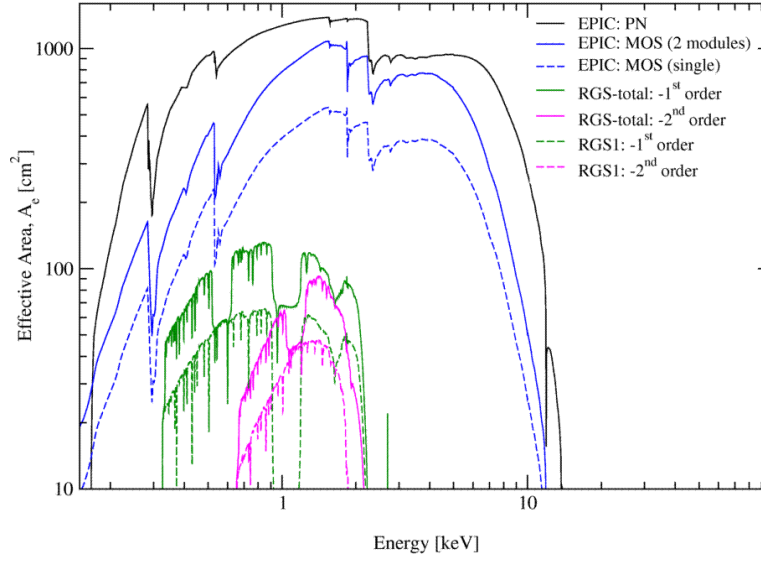


Figure 2.6: Effective areas of all detectors from the *XMM-Newton* mission. Image Credit: XMM-Newton/Handbook.

effective area of $\sim 1200 \text{ cm}^2$ at 1 keV, significantly larger than MOS detectors. The different modes of operation provides much flexibility: small window has a time resolution of 5.7 ms, suitable for moderate brightness sources while timing mode provides a $30 \mu\text{s}$ resolution for high time-resolution studies of bright and rapidly varying objects.

XMM-Newton observations are analysed using the Science Analysis Software (SAS) along with the recent calibration files. Major steps involved are:

1. **Event File Preparation:** The observation data files (ODF) are processed using the sas task EPCHAIN to produce calibrated event files with applied gain and bad pixel corrections.
2. **Filtering Flaring Background:** High energy lightcurves are generated to identify soft proton flares and the periods with high count rates are excluded to create cleaned event files.
3. **Source and Background Extraction:** Source photons are extracted from circular regions, typically of $35''$ - $40''$ in size, centered around the source. Background events are selected from nearby source free regions on the same CCD. Events are selected with appropriate choices for single and double pixel events and filtered for bad or problematic events, as per the science requirement.
4. **Generate Detector Response:** Response matrices and ancillary files are

generated using the RMFGEN and ARFGEN tools.

5. **Lightcurves** for timing analysis can be extracted with required bin sizes over the energy ranges necessitated by the undertaken study.

The unique combination of large effective area, moderate spectral resolution and excellent timing capability makes *XMM-Newton* observations vital for AGN studies. Simultaneous coverage of the soft (0.3–2 keV) and hard (2–10 keV) X-ray bands allow us to model multiple spectral components such as the soft excess, warm absorber and reflection features originating in different physical regions around the supermassive black hole. Moreover, the spacecraft has a highly elliptical 48-hour orbit, giving long uninterrupted observations for studying spectral and temporal variability on timescales from minutes to days.

2.4 Considerations in Multi-Mission Analysis

Each of the above discussed missions provide unique and complementary capabilities: *AstroSat* offers simultaneous broadband coverage with multiple instruments, *NuSTAR* extends the sensitivity to hard X-rays and *XMM-Newton* provides exceptional throughput and spectral resolution in the soft to medium energy band. Together they enable us to investigate the broadband X-ray spectral and temporal behaviour of AGNs, as is undertaken for this thesis work. Such broadband coverage significantly reduces uncertainties associated with fitting only a limited energy range and provides stronger constraints on the physical properties of the accretion disk–corona system.

Nevertheless, combining observations from different instruments also introduces several potential sources of systematic uncertainty. Unlike statistical uncertainties, which arise from the finite number of detected photons, systematic biases originate from assumptions made during the analysis or from differences between the observations themselves. For example, AGNs are intrinsically variable sources and observations obtained at different epochs may correspond to different flux or spectral states. If these datasets are analysed using a single spectral model without accounting for intrinsic variability, the inferred physical parameters may not accurately represent any individual state of the source. In addition, different instruments possess different calibration characteristics, energy responses and background properties, which can introduce small discrepancies between the measured spectra.

To minimise these effects, simultaneous observations are preferred whenever available. When observations from different epochs are combined, care must be taken to account for possible source variability through independent cross-normalisation constants, variability analyses or multi-epoch spectral modelling. Cross-calibration constants are often included during spectral fitting to account for instrumental differences, while consistency checks between individual datasets help distinguish genuine spectral evolution from calibration effects. These considerations ensure that the physical interpretation is based on intrinsic source behaviour rather than observational systematics.

Chapter 3

Broadband Spectral Variations of Mrk 279

This chapter presents a long term broadband X-ray spectral analysis of the Seyfert 1 galaxy, Mrk 279; the analysis and results has derived from our published work, Akhila et al. (2024). As discussed in Chapter 1, Seyfert-1 galaxies are the low luminosity subclass of active galaxies. Their spectrum is a power law continuum with several features such as broad and narrow emission lines and a smooth excess emission component at soft energies (E.g., Schmidt & Green, 1983; Osterbrock & Pogge, 1985; Arnaud et al., 1985; Boller et al., 1995; Fabian et al., 2000; Netzer, 2015; Rani et al., 2019; Ezhikode et al., 2021; Mochizuki et al., 2023). These features are thought to arise from regions of different environmental conditions such as temperatures and densities, around the central supermassive black hole. Another important characteristic of AGNs is the variations in their X-ray fluxes that occur over a wide range of timescales and amplitudes. In AGNs, X-ray radiation has been observed to exhibit variations of over a few ~ 1000 s upto years. These variations have amplitude differences upto an order of magnitude (E.g., Turner et al., 1999). Earlier studies show that majority of NLS1 galaxies soften as they become brighter. It is observed that the variability is stronger in softer energies (Markowitz et al., 2003; Markowitz & Edelson, 2004).

In this work, we study the spectral variations in a Seyfert galaxy Mrk 279. Data from multiple missions – *AstroSat*, *NuSTAR* and *XMM-Newton*, are used for the purpose. The X-ray spectrum is modelled as a double Comptonization along with the presence of neutral Fe $K\alpha$ line emission, enabling the evolution of the individual spectral components to be investigated across multiple epochs. The source’s X-ray flux and luminosity at all epochs are determined. Variations

in the source’s flux state and spectral components during the observation period are studied and any correlations between fluxes of different bands and their photon indices are investigated.

The primary objective of this study is to investigate the long-term evolution of the X-ray emission in Mrk 279 and understand the physical processes responsible for its spectral variability. In particular, we try to determine whether the observed changes in flux are accompanied by corresponding changes in the spectral shape and to identify which spectral components drive the variability. By constraining the continuum and reflection components through broadband spectral modelling, this study aims to provide insights into the physical conditions of the accretion disk–corona system and the mechanisms governing X-ray emission.

Mrk 279 is particularly well suited for such an investigation because it is a bright and nearby Seyfert 1 galaxy that has exhibited significant X-ray variability over a wide range of timescales. Its extensive archival observations from XMM-Newton, NuSTAR and AstroSat, spanning different flux states over several years, provide an opportunity to study the long-term evolution of its broadband X-ray spectrum. While previous studies have mostly focused on individual observations or specific spectral features, a systematic multi-epoch broadband analysis can reveal whether the underlying spectral components evolve coherently with the source luminosity or remain relatively stable. Such studies are essential for distinguishing persistent physical changes in the accretion flow from short-term fluctuations and for improving our understanding of the evolution of AGN central engine.

3.1 Markarian 0279

Markarian 0279 (Mrk 279) is a nearby narrow line Seyfert-1 (NLS1) galaxy. Situated at a redshift of $z = 0.0305$, this active galaxy harbours a supermassive black hole of mass $M = 3.49 \times 10^7 M_{\odot}$ at its centre (Scott et al., 2009; Peterson et al., 2004). Mrk 279 has undergone extensive observational campaigns in the X-ray energies by various missions, beginning with the very early observations made by *HEAO 1* and Japan’s *ASCA* mission (Dower et al., 1980; Weaver et al., 1995, 2001). Later observations were made by advanced instruments such as the *Chandra*, *HST-STIS* and *FUSE* in May 2002 and again in 2003 (Scott et al., 2004; Kaastra et al., 2004; Gabel et al., 2005; Arav et al., 2005, 2007; Costantini et al., 2007). *Chandra* and *XMM-Newton* has also made multiple independent

observations of the source (Yaqoob & Padmanabhan, 2004; Jiang et al., 2019; Igo et al., 2020; Ursini et al., 2020a). Typical of an NLS1 galaxy, these observations have revealed significant variations in the X-ray flux of the source over time (Scott et al., 2004; Costantini et al., 2010; Ebrero et al., 2010).

Abundant variations in the continuum flux of the source was observed during the long term X-ray observations from 1979 to 1994. They revealed that the continuum flux has variabilities going upto a factor of five, with flux values ranging between $1 - 5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Weaver et al., 2001). The *ASCA* observation from 1994 was analysed by Weaver et al. (2001) using a model consisting of two power laws and a narrow Gaussian. Their analysis showed a 20 % increase in the 2-10 keV source flux over a period of only a few hours. An analysis using the *Chandra* observation, in 2002, used a continuum model consisting of two power laws modified by Galactic absorption. This study revealed a low 2-10 keV flux of $1.2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Scott et al., 2004). Similar low flux levels were previously observed in 1979 and 1991 also (Weaver et al., 2001). There was a factor two drop of flux from a previous *XMM-Newton* observation in the same year. The UV continuum flux was also reported to have decreased by a factor of ~ 7.5 during the period from 1999 to 2002 (Scott et al., 2004). In November 2005, *XMM-Newton* made further observations of the source spread over multiple orbits. Analysis of these observations found that the continuum spectrum could only be explained with models having a minimum of three components (Costantini et al., 2010). The epic-pn data was fit using a broken power law and a modified blackbody component. Their calculations estimated the 2-10 keV flux to be $\sim 2.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. The broadband flux in the 15 - 150 keV X-ray band was found to be $\sim 3.8 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ by the *Swift*-BAT survey (Cusumano et al., 2010). We analyse the source's X-ray emissions for a period of three years from early 2018 to late 2020, using multi-instrument data in order to study its flux state and its variation.

3.2 Observations

Long term observations of the source are pooled from many instruments at multiple epochs. We use the first and so far the only *AstroSat* - the first multiwavelength space observatory of India that enables simultaneous observations in the broad X-ray and UV bands - observation of the source made in 2018. For a broadband coverage, we use both SXT and LAXPC data for our analysis (Agrawal,

Table 3.1: Observation log detailing the date of observation, satellite, mission id and exposure time.

Mission	Observation Id	Date of Observation	Exposure Time (ks)
<i>AstroSat</i> <i>SXT, LAXPC</i>	9000001886	06-Feb-2018	39.94,101
	60160562002	29-Oct-2019	27.27
<i>NuSTAR</i> <i>FPMA, FPMB</i>	60601011002	03-Aug-2020	62.02
	60601011004	05-Aug-2020	200.63
	60601011006	11-Aug-2020	52.80
<i>XMM-Newton</i> <i>epic-pn</i>	0872391301	20-Dec-2020	20.02

2006; Yadav et al., 2016; Singh et al., 2017; Antia et al., 2017; Agrawal et al., 2017; Misra et al., 2017). The Nuclear Spectroscopic Telescope Array (*NuSTAR*) has observed the source twice, in the years 2019 and 2020 (Harrison et al., 2010, 2013). The 2019 observations and three orbits with enough exposure time from the 2020 observations made by the Focal Plane Modules (FPMA and FPMB) were chosen. We note that *NuSTAR*’s observation from 2020 has been studied previously for multiple purposes: Akylas & Georgantopoulos (2021); Akylas et al. (2022); Kang & Wang (2022); Pal et al. (2023). However, our aim is to analyse it for its X-ray flux state variations. Finally, we include the data from X-ray Multi-mirror Mission (*XMM-Newton*) epic-pn camera also into our datasets (Jansen et al., 2001; Strüder et al., 2001)). *XMM-Newton* has several observations of the source during the period 2002-2020. Major results from these earlier observations is discussed in the previous section. We use the latest 2020 observation which hasn’t been analysed before - having a long exposure time of 30.5 ks. Table 3.1 summarises the details of all observational data.

3.3 Data Reduction

3.3.1 AstroSat

Standard procedures of data reduction for all instruments are described in Chapter 2. Here, we discuss only the details relevant to the particular datasets under consideration. As discussed in Section 2.1, the SXT and LAXPC instruments onboard *AstroSat*, provide a wide coverage over the 0.3 - 8.0 keV and 3.0 - 80.0 keV energy bands, respectively. During this observation, SXT detector was oper-

ated in the Photon Counting (PC) mode of the telescope. *AstroSat* observed the source for over 20 orbits and Level-1 SXT data for all 20 orbits were processed using the SXTPIPELINE 1.4B software. The level-2 data thus extracted, were merged into a single cleaned event file, using the event merger tool, SXTEVT-MERGER. Filtering of the merged event file was done using the XSELECT task of HeaSoft. We selected a circular region of radius 15' centered around the source. Source spectrum was extracted from this circular region. The background spectrum was made for the blank sky background. SXT-POC team provides the detector response - response matrices and ancillary response files (RMF and ARF) for the PC mode and these standard files were used during spectral fitting.

LAXPC data is also included so as to achieve broadband range of X-ray energies. *AstroSat*'s LAXPC is a cluster of three identical proportional counters performing observations in broad X-ray band - only the data from LAXPC20 was selected for our analysis as it has more stability in its response. LAXPCSOFT was used for processing the data. It extracts the level 2 data and a fits event file was created. The GTI file containing the good time intervals was also generated. The software's tools were used for extracting the source and blank sky background spectra and the instrument's response files.

3.3.2 NuSTAR

NuSTAR gives observational data in the 3 - 79 keV energy range. Both FPMA and FPMB data was used for our analysis. Data was processed using the NuSTAR Data Analysis Software package, NUSTARDAS_v2.1.1. The pipeline software, NUIPIPELINE, was run with the latest files from CALDB. Good time interval files were created and used for generating cleaned event files. Source region, circular with radius 38", was selected. Another nearby region of same size was also selected for background extraction. Spectral files and lightcurves are generated by running the NUPRODUCTS task.

3.3.3 XMM-Newton

XMM-Newton observatory provides X-ray data in the wide 0.2 - 12 keV energy band. Only epic-pn camera data was chosen due to its high sensitivity and faster timing capabilities. Data was processed using the Science Analysis Software SAS-20.0.0. SAS task EPCHAIN was run to create the raw event file and filtered for removal of background flares. TABGTIGEN task created the good time interval

file. Single and double pixel event ($\text{PATTERN} \leq 4$) were selected after filtering out for bad or problematic ($\text{FLAG} = 0$) ones. The observation was tested for pile-up issues using EPATPLOT and it was verified that the data was free from any pile-up effect. Central circular region of radius $40''$ was selected as the source region and the spectrum was extracted. Background spectra were extracted from nearby regions of the same sizes. Detector response was accounted for, through the response matrices and ancillary response files generated by RMFGEN and ARFGEN tasks.

3.4 Spectral Analysis

Spectral fitting is performed using HeaSoft's XSPEC-12.12 package, a standard tool for modelling X-ray spectra in high energy astrophysics (Arnaud, 1996a). It includes a large library of physical and phenomenological models, including power laws, blackbody components, Comptonization models, reflection models and absorption models. It allows the user to flexibly work with these components, individually or in combinations. It uses the method of forward folding for spectral fitting. The defined model is folded using the instrument's response, which includes both the response matrix file and the ancillary response file and creates a predicted spectrum. This can then be compared directly with the observed counts.

The goodness of fit is evaluated using statistical methods, most commonly the chi-square (χ^2) statistic. In the χ^2 minimisation technique, the spectrum is first grouped to ensure that each energy bin has sufficient number of photon counts - this ensures the validity of using Gaussian statistics. The χ^2 function is defined as,

$$\chi^2 = \sum_i \left(\frac{D_i - M_i}{\sigma_i} \right)^2 \quad (3.1)$$

where, where D_i is the observed count in the i^{th} bin, M_i is the model prediction and σ_i is the corresponding statistical uncertainty. The best fitting model is obtained by minimising χ^2 with respect to the model parameters. The reduced chi-square, $\chi^2_\nu = \chi^2/\nu$, where ν is the degrees of freedom, provides a measure of goodness of fit; its values close to unity indicating an acceptable fit. Uncertainties on model parameters are determined by exploring the region of parameter space for which $\Delta\chi^2$ corresponds to the desired confidence interval: for e.g., $\Delta\chi^2 = 2.71$ for the 90 % confidence on one free parameter.

For our analysis, we grouped the spectra to have a minimum of 30 counts in each bin. As advised by the LAXPC team, the spectrum was grouped at a 5% level, resulting in three energy bins per resolution. We found that the Mrk 279 spectrum could be fit using two Comptonization components and a Gaussian component for the iron $K\alpha$ emission line. The two corona models are widely used in literature to describe several NLS1 spectra (Magdziarz et al., 1998; Czerny et al., 2003; Done et al., 2012; Petrucci et al., 2018; García et al., 2019). Such a model includes a power law model for the primary hard X-ray continuum arising from the hot corona. The soft excess component is modelled by another thermal Comptonisation component where the seed photons from the far UV end of accretion disk gets upscattered into soft X-rays. This is produced from a warm, optically thick layer of gas, distinct from the hot corona, lying above the surface of the accretion disk and hence the name ‘two-corona’ model.

The accretion disk blackbody is modelled by the *diskbb* model. XSPEC library includes *thComp*, a convolution model which can be used for any seed photon distribution and is a replacement for the older *nthComp* model (Zdziarski et al., 2020). It agrees better with the Monte Carlo results for thermal Comptonisation. We use *thComp* in convolution with *diskbb*. The second coronal component is represented by *simpl* (Steiner et al., 2009). It is a simple convolution model for Compton scattering that uses just two parameters, making it appropriate for situations where the coronal temperature is high and cannot be constrained by the data being fit. A fraction of the Comptonised seed photons are thus further upscattered by the second coronal medium. *TBabs* component is included to account for the Galactic absorption. The absorber column density is fixed to the value, $N_H = 1.78 \times 10^{20} \text{ cm}^{-2}$ (Williams et al., 2006). In order to model the intrinsic absorption by the host galaxy, *ztbabs* was also included, but we found that this does not improve the fit. Using more complicated models did not seem warranted and hence this component was excluded in further analyses. The redshift of the source is fixed at 0.0304. Normalisation of *diskbb* is defined as $N_{bb} = (R_{in}/D_{10})^2 \cos\theta$, where R_{in} is the apparent inner disk radius in km, D_{10} is the source distance in units of 10 kpc and θ is the angle of the disk. The source distance and disk angle are fixed at 124.1 Mpc and 30° , respectively (Pogge & Martini, 2002; Weaver et al., 2001). Assuming an inner disk radius of $\sim 10 R_g$, typical for an NLS1 galaxy of black hole mass $3.49 \times 10^7 M_\odot$, the normalisation is estimated to be 5.90×10^9 (Peterson et al., 2004). It is also assumed that all the seed photons from the disk undergo Compton scattering by the primary

Table 3.2: *XMM-Newton* spectral fitting parameters for the broadband 0.3 - 10.0 keV spectrum.

Model Component	Parameter Value	<i>XMM-Newton</i> 0872391301
simpl	Γ_{simpl}	$1.48^{+0.16}_{-0.21}$
	$f_{\text{Scat}} (\times 10^{-2})$	$0.72^{+0.61}_{-0.39}$
thComp	τ	$15.02^{+2.38}_{-10.66}$
	kT_e (keV)	$0.98^{+2.09}_{-0.34}$
diskbb	$T_{\text{in}} (\times 10^{-2} \text{ keV})$	$0.48^{+0.02}_{-0.03}$
zgauss	E_l (keV)	$6.41^{+0.04}_{-0.04}$
	σ (keV)	< 0.14
	$N_{\text{gauss}} (\times 10^{-5})$	$1.98^{+0.57}_{-0.53}$
χ^2/dof		158.66/159

corona, hence the covering fraction of *thComp* is fixed at unity.

The 0.3-10 keV *XMM-Newton* spectrum is fit using this model. Figure 3.1 plots the spectrum and Table 3.2 lists the best fit model parameter values.

Our aim here is to study the long term variations in the corona. For the purpose, we first fix the accretion disk as modelled by the *XMM-Newton* data. Similarly, we fix the other disk parameter, the inner temperature (T_{in}) at the obtained value of 4.8×10^{-3} keV. Also the warm corona's optical depth and Gaussian line energy are fixed at 15.02 and 6.41 keV, respectively. We then use the model to fit the data at other epochs: *AstroSat*'s combined SXT-LAXPC spectrum and the *NuSTAR* spectra. While fitting *AstroSat* spectrum, the cross normalisation between SXT and LAXPC20 is to be taken care - this was achieved by the *constant* component of XSPEC.

The model parameters obtained from fitting the *AstroSat* and *NuSTAR* data are listed in Table 3.3. Photon index of the hot corona, (Γ_{simpl}), undergoes considerable change during the period of observation. Compared to *XMM-Newton* observation, *AstroSat* yields a slightly higher value (~ 1.62). *NuSTAR* observations reveal that the index increases to ~ 1.8 for the 2019 data but then drops down to ~ 1.6 for the later observations from August 2020. Scattering fraction of the corona also follows a similar pattern. The warm coronal temperature (kT_e) could be constrained with an upper bound for all data sets. Although the *AstroSat* spectrum is not able to resolve the Gaussian line, we obtained an upper bound on its strength. Figure 3.2 plots the combined *AstroSat* spectrum, while *NuSTAR* spectra are shown in Figures 3.3 and 3.4.

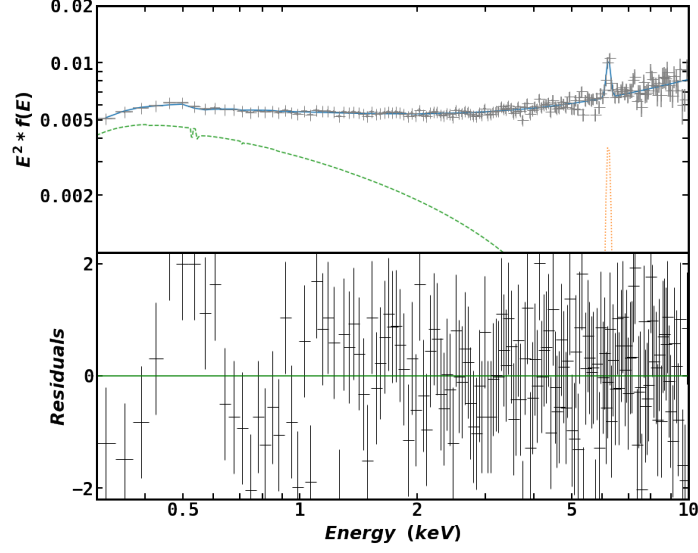


Figure 3.1: *XMM-Newton* spectrum for the energy range 0.3 - 10.0 keV fit using theoretical model. Bottom panel shows the residuals of fit.

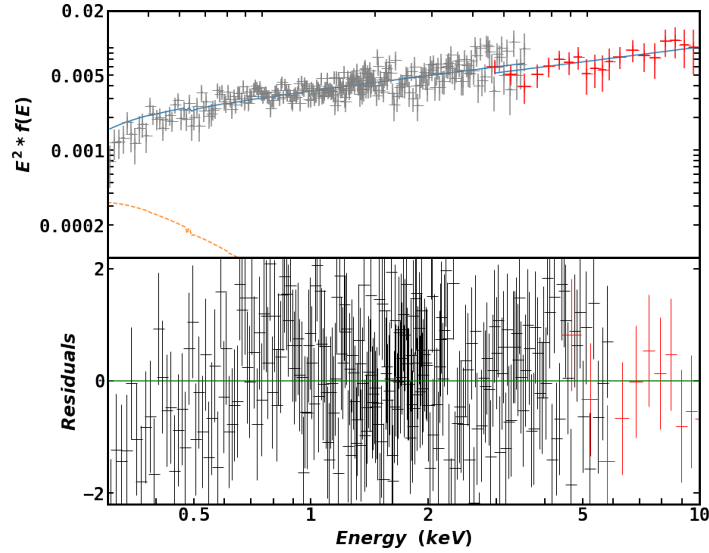
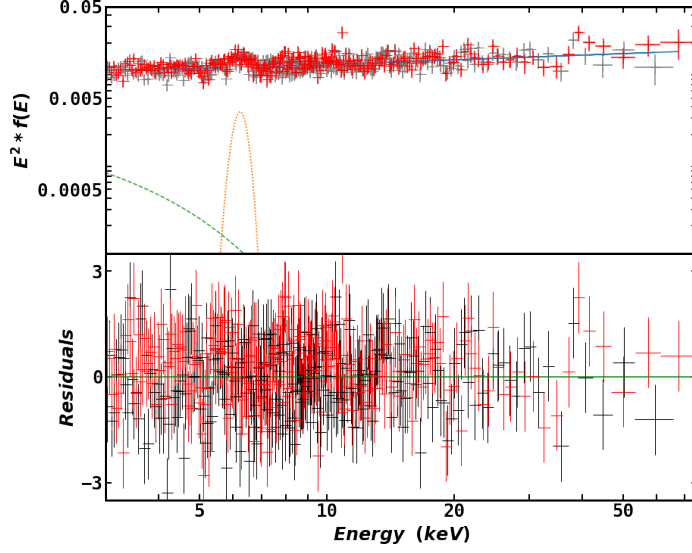
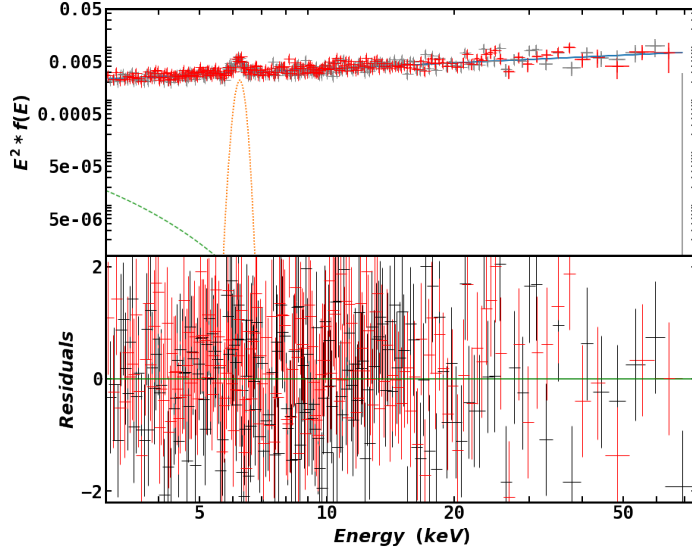


Figure 3.2: Combined SXT - LAXPC spectrum fit using theoretical model. Bottom panel shows the residuals of fit.

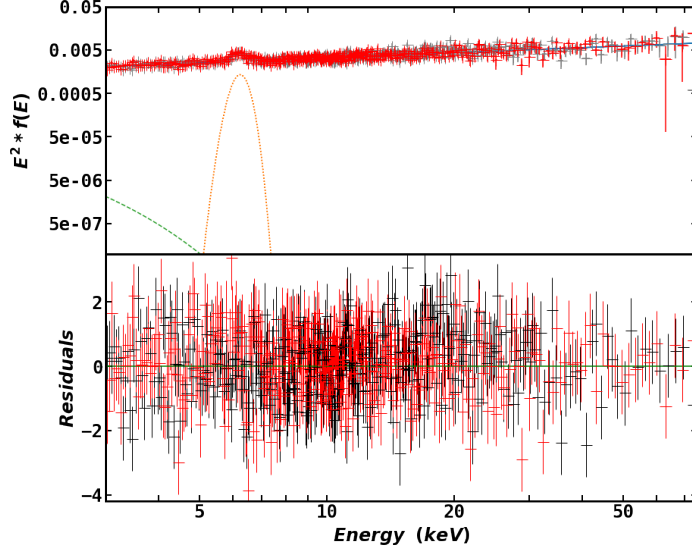


(a)

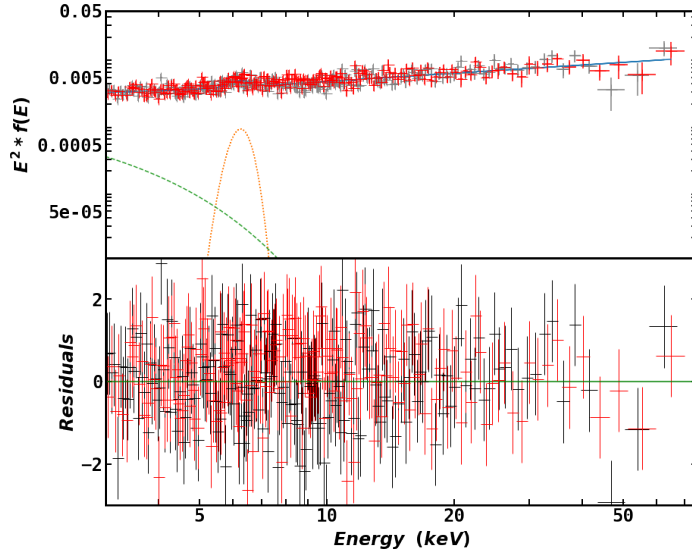


(b)

Figure 3.3: The *NuSTAR* 3.0 - 79.0 keV spectra fit using the theoretical model. Top panels show the unfolded spectrum along with the model while bottom panel plots the residuals of fit. The top and bottom plots correspond to the (a) 60160562002 and (b) 60601011002 *NuSTAR* observations, respectively.



(a)



(b)

Figure 3.4: (cont. from Figure 3.3) The *NuSTAR* 3.0 - 79.0 keV spectra fit using the theoretical model. Top panels shows the unfolded spectrum along with the model while bottom panel plots the residuals of fit. The top and bottom plots correspond to the (a) 60601011004 and (b) 60601011006 *NuSTAR* observations, respectively.

Table 3.3: Spectral parameter values for the *AstroSat* and *NuSTAR* observations. All the other parameters are kept fixed at the values obtained from the best fit model of *XMM-Newton*.

Model	Parameter	<i>AstroSat</i>	<i>NuSTAR</i>			
Component	Value	9000001886	60160562002	60601011002	60601011004	60601011006
simpl	Γ_{simpl}	$1.62^{+0.04}_{-0.04}$	$1.83^{+0.04}_{-0.04}$	$1.63^{+0.02}_{-0.04}$	$1.62^{+0.01}_{-0.01}$	$1.59^{+0.04}_{-0.05}$
	$f_{\text{Scat}} (\times 10^{-2})$	$1.46^{+0.37}_{-0.30}$	$5.83^{+3.69}_{-1.39}$	$0.76^{+0.06}_{-0.19}$	$0.70^{+0.39}_{-0.15}$	$0.70^{+0.26}_{-0.18}$
thcomp	kT_e (keV)	< 0.52	< 1.02	< 0.81	< 0.77	$0.83^{+0.07}_{-0.25}$
zgauss	σ (keV)	0.08^f	$0.24^{+0.1}_{-0.1}$	< 0.23	$0.27^{+0.07}_{-0.06}$	$0.36^{+0.39}_{-0.21}$
	$N_{\text{gauss}} (\times 10^{-5})$	< 3.20	$5.62^{+1.54}_{-1.42}$	$1.95^{+0.49}_{-0.45}$	$2.33^{+0.38}_{-0.29}$	$1.96^{+1.28}_{-0.79}$
χ^2/dof		271.96/270	502.32/509	373.98/396	762.99/740	379.15/403

3.5 Coronal X-ray Variations

The source flux and luminosity in the 0.001 - 100 keV energy range was calculated at all the epochs and is tabulated in Table 3.4. It is evident that the source undergoes large flux variations over the duration of three years. The flux increases by more than 50 % from February 2018 to October 2019, followed by which the source falls into a state of very low flux. During this epoch, the flux values drops by about 2 times. By late 2020, it return to its brighter state and the source has once again regained the flux as is revealed by the *XMM-Newton* observations. It is to be noted that despite these changes in its flux states, the source is constantly in a brighter state, with the flux values being several times higher, when compared to the earlier observations mentioned in Section 3.1. Recent reports on the cross calibration issue between *NuSTAR* and *XMM-Newton* epic suggests an empirical correction is to be added to the effective area (Fürst, 2022; Kang, Jia Lai and Wang, Jun Xian, 2023). We note that for the current observations, the epic counts being lower by about 20%, as mentioned by the *XMM-Newton* team, would not have a significant effect on the calculated flux.

We then investigate the variations in individual spectral components. XSPEC library's inbuilt *cflux* model is used for the purpose. The model, *cflux*, is first applied to the overall Comptonisation term, *simpl*thComp*diskbb* and then to *thComp*diskbb* alone. The value of fractional scattering (f_{Scat}) is kept fixed throughout. From the former term, we obtain the flux observed, as being due to both the coronal components, i.e., the net continuum flux. This includes the flux of photons that underwent scattering by both coronae along with the flux from the remaining photons which were scattered by the warm corona alone. This is termed as the net continuum flux (NCM) and does not include the line emission. Similarly, the latter application of *cflux* gives the total flux upscattered from the warm corona. Had the hot corona not been present, we would have observed this value as being the result of upscattering by the warm corona. It is indicative of the properties of the warm coronal component (WCM : *cflux*thcomp*diskbb*). Both these calculated terms include the contribution from the disk emission. To obtain the flux that is purely from the corona, the disk contribution has to be removed. Applying *cflux* to *diskbb* alone will give us the emission flux from the accretion disk and is estimated to be around $6.46 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. In order to find the line emission, *cflux* is applied to the the Gaussian component (*zgauss*),

Table 3.4: Broadband X-ray flux and luminosity of Mrk 279, calculated in the energy range 0.001 - 100 keV, over the years from 2018 to 2020.

Date of Observation	Mission	Flux ($\times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$)	Luminosity ($\times 10^{44}$ erg s $^{-1}$)
06-Feb-2018	<i>AstroSat</i>	16.61 $\pm$ 0.54	3.06 $\pm$ 0.10
29-Oct-2019	<i>NuSTAR</i>	25.00 $\pm$ 2.64	4.61 $\pm$ 0.49
03-Aug-2020	<i>NuSTAR</i>	13.19 $\pm$ 1.34	2.43 $\pm$ 0.25
05-Aug-2020	<i>NuSTAR</i>	12.05 $\pm$ 0.92	2.22 $\pm$ 0.17
11-Aug-2020	<i>NuSTAR</i>	16.44 $\pm$ 2.36	3.03 $\pm$ 0.43
20-Dec-2020	<i>XMM-Newton</i>	19.75 $\pm$ 6.45	3.64 $\pm$ 1.19

with the corresponding normalisation (N_{Gauss}) fixed. The Gaussian component corresponds to the iron $K\alpha$ line emission and contribute very little to the overall flux. Its strength is found to be roughly around ~ 2 orders less than the Comptonisation fluxes. As mentioned in the previous section, *AstroSat* data is not able to resolve this emission line properly. However we could to constrain its strength and we found that it agrees with other epochs estimations, well within the 90 % confidence interval. Figure 3.5 plots the individual spectral components. Major contribution to the source flux comes from the Comptonisation component, in accordance with the low values of the line emission. The figure shows the individual model components to closely follow the pattern of the total flux over the three years - rising, falling and then returning back to the original state. Table 3.5 tabulates all the flux values.

Akin to the strength of the emission line, *AstroSat* data was not able to constrain the Gaussian width (σ). However, a sudden change in the line width was found from the analysis using *NuSTAR* and *XMM-Newton* observations. 2019 and early 2020 *NuSTAR* observations show a broad iron line of width $\sim 0.2 - 0.3$ keV. But *XMM-Newton* showed a rapid reduction in December 2020 and we could constrain it with an upper bound of 0.14 keV.

3.6 Summary and Discussion

The long term monitoring of Mrk 279 presented in this chapter demonstrates that the source exhibits substantial variability across this period. All epochs could be successfully explained by a double Comptonisation model, consisting of a warm, optically thick component responsible for the soft excess and the hot, optically thin corona producing the primary hard power law emission, along with

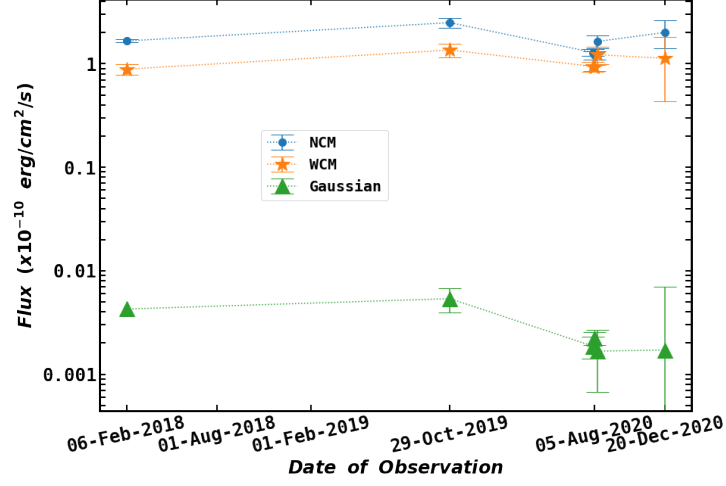


Figure 3.5: X-ray flux variations of Mrk 279 during the period from 2018-2020. The net continuum flux (NCM), warm corona flux (WCM) and emission line flux (Gaussian) are plotted in colours blue, orange and green, respectively.

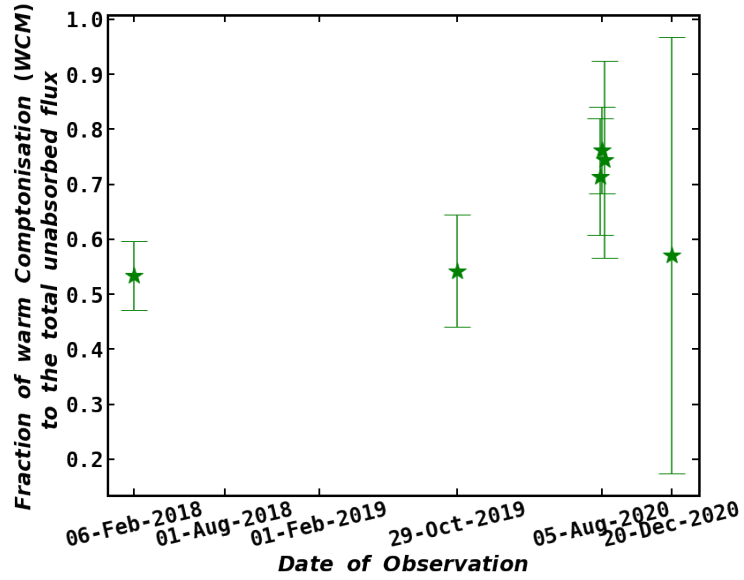


Figure 3.6: The fraction of warm Comptonised flux (WCM) to the total flux, showing its variations over the time period from 2018-2020.

Table 3.5: The net continuum flux (NCM), warm corona flux (WCM) and the emission line (Gaussian) flux for Mrk 279 through the three year timescale. All values are in units of $\text{erg cm}^{-2} \text{s}^{-1}$.

Date of Observation	Mission	NCM ($\times 10^{-11}$)	WCM ($\times 10^{-11}$)	Gaussian ($\times 10^{-13}$)
06-Feb-2018	<i>AstroSat</i>	$16.61_{\pm 0.54}$	$8.87_{\pm 0.99}$	< 4.26
29-Oct-2019	<i>NuSTAR</i>	$24.96_{\pm 2.65}$	$13.57_{\pm 2.10}$	$5.37_{\pm 1.43}$
03-Aug-2020	<i>NuSTAR</i>	$12.85_{\pm 1.01}$	$9.42_{\pm 1.01}$	$1.86_{\pm 0.45}$
05-Aug-2020	<i>NuSTAR</i>	$12.02_{\pm 1.06}$	$9.18_{\pm 0.63}$	$2.23_{\pm 0.33}$
11-Aug-2020	<i>NuSTAR</i>	$16.42_{\pm 2.36}$	$12.25_{\pm 2.35}$	$1.67_{\pm 1.00}$
20-Dec-2020	<i>XMM-Newton</i>	$20.06_{\pm 6.06}$	$11.27_{\pm 6.92}$	$1.71_{\pm 5.31}$

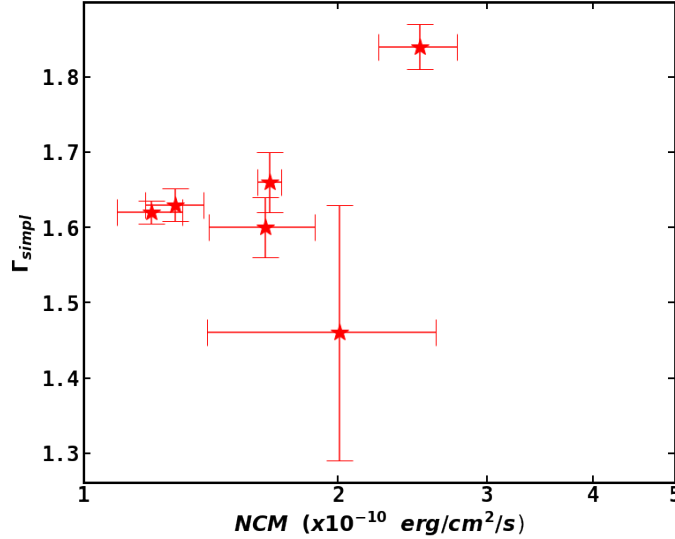


Figure 3.7: Hot photon index (Γ_{simpl}) plotted against the net continuum flux (NCM). The data do not seem to exhibit any significant correlation between the parameters; the Pearson correlation coefficient obtained was 0.41 with a two-sided p-value of 0.42.

a narrow Fe $K\alpha$ emission line. It was found that, in agreement with variations in total output, flux values of all spectral components also exhibit considerable variations during this period. This is evident from Figures 3.5 and 3.6, where the fraction of the warm Comptonised flux (WCM) to the total flux is plotted. Despite this, the shape of the spectrum, however, doesn't exhibit the short term variations. The photon index remains constant at ~ 1.6 throughout the *NuSTAR* observations of August 2020. Over longer periods of time, the index does seem to follow the trend of the continuum flux, with the exception of the December

2020 observation, where the flux regains its previous high state but the index drops down further. This behaviour suggests that the mechanisms regulating the overall radiative output of the source are not necessarily accompanied by rapid changes in the physical conditions of the X-ray emitting corona. While the luminosity varies considerably, the approximately constant spectral shape over short timescales indicates that Comptonising medium remains relatively stable during these epochs. Any evolution in the coronal properties therefore appears to occur over longer timescales, as reflected by the gradual changes in photon index across different observing epochs.

An important outcome of this study is the absence of any strong correlation between the photon index and flux. Γ_{simpl} versus flux plot is shown in Figure 3.7. The Pearson correlation coefficient was calculated to be a mere 0.41, with a corresponding two sided p-value of 0.42. Continuum flux and photon index correlations has previously been studied extensively (E.g., Singh et al., 1991; Yaqoob & Warwick, 1991; Dewangan et al., 2002; Grupe et al., 2012; Barua et al., 2020). The correlation could indicate the X-ray variability being caused by the change in the seed photon population. In such a case, the physical properties of the corona might vary with flux. Yet another possibility, valid for the two component scenario, is the super position of soft, varying power law associated with coronal emission and another harder component showing much less variability (See: Shih et al., 2002; Fabian & Vaughan, 2003; Markowitz et al., 2003).

The absence of such correlations reinforce the idea of a central engine where variations are driven by normalisation changes in the Comptonising components, rather than rapid restructuring of the emitting regions. The successful description of all epochs using the same underlying spectral model further suggests that the overall accretion disk–corona configuration remains broadly stable throughout the observation period. Although luminosity of the source changes significantly, there is no evidence for dramatic changes in the dominant emission mechanism or global geometry of the X-ray emitting regions. However, we should consider the inherent limitations in modelling sparsely sampled long term observations. Flux variability without accompanying changes in spectral shape can undermine subtle variations in the underlying physical parameters, making them difficult to constrain using broadband spectral fitting alone. The results of this chapter therefore demonstrate that broadband spectroscopy alone, while effective in constraining the average spectral properties of AGNs, is insufficient to uniquely identify the physical mechanisms driving their variability. It is hence

necessary to combine broadband spectroscopy with energy dependent variability analyses. For this reason, the next chapter move beyond spectral analysis and uses the statistical tool of fractional variability. It brings together fractional rms spectra and time variability modelling, along with joint broadband fitting to separate spectral components in another Seyfert 1 galaxy. Incorporating temporal information with spectral modelling, the following chapter tries to understand the physical origin of AGN variability. This approach builds directly on the findings of the present chapter and tries to provide a better understanding of the structure and evolution of AGN emissions.

Chapter 4

Modelling the Broadband X-ray Variability

Having studied the long term spectral behaviour of Mrk 279, we now explore the energy dependent variability patterns in AGNs - we present a novel method to model the energy dependent fractional rms variability for linearly correlated variations of a pair of spectral parameters. We demonstrate the method by applying it to an X-ray observation of the standard NLS1 galaxy, Mrk 335. The study presented has derived from our published work, Akhila et al. (2025).

4.1 AGN X-ray Variability

AGN X-ray emissions are long known, for their variability patterns. *Ariel 5* and *HEAO 1* were among the first missions to observe the long term variabilities in AGNs, spanning from a few days to years (e.g., Marshall et al., 1981). It wasn't until much later that missions such as *EXOSAT* observed short rapid variabilities, of the order of thousands of seconds, in AGN emissions (e.g., McHardy, 1985). Flux variations on timescales spanning a very wide range, from a few thousand seconds to years and having amplitude variations upto an order of magnitude have now been observed in the 0.1 - 10 keV band (McHardy, 1988; Green et al., 1993; Turner, 1994; Turner et al., 1999). AGN flux variabilities has extensively been studied (Lawrence et al., 1987; Lawrence & Papadakis, 1993; Nandra, 2001; Martin Gaskell & Kluwek, 2003; Markowitz et al., 2003; Soldi et al., 2014; Pryal et al., 2015; Komossa et al., 2016; Papadakis & Binas-Valavanis, 2024; Serafinelli et al., 2024).

As discussed in Chapter 1, typical Seyfert galaxies have X-ray spectra that

can be explained as power law emission superimposed by broad and narrow emission lines (Fabian et al., 2000; Tatum et al., 2012). A smooth emission component enhances the low energy ($< 2\text{keV}$) flux, known as the soft excess. This was first observed in 1985, in the Seyfert-1 galaxies Mrk 509 and Mkn 841, by the *HEAO* and *EXOSAT* missions, respectively (Arnaud et al., 1985; Singh et al., 1985). Since then soft excess has been observed in the X-ray spectra of several narrow line Seyfert-1 galaxies (Boller et al., 1995; Bühler et al., 1995; Middleton et al., 2007; Middei et al., 2019; Boller, 2023). Both broad and narrow line Seyfert-1 galaxies have been observed to exhibit the soft excess, but often with a stronger strength in NLS1 galaxies (Gliozzi & Williams, 2020). This additional emission in the soft X-ray energies of AGNs cannot be explained by a simple low energy extrapolation of the hard energy continuum (Done & Nayakshin, 2007; Done et al., 2012; Middei et al., 2020).

The soft excess has been explained by many different theoretical models in literature, including the obscured model, warm coronal picture and a gravitationally blurred reflection model. Though these models have crucial differences in their underlying physics, they were all quite successful in explaining the observed spectrum (Sobolewska & Done, 2005; Ding et al., 2022). In the partial covering model, soft excess is best described as a ‘leakage’ through a non-uniform absorber. The model proposes that the power law emission is obscured by the absorber and in the presence of such patchy clouds, spectral behaviour will show variations - waning a fraction from the incident radiation. The observed spectrum has contributions from both the obscured emission and the direct primary emission. In this case, any change in the spectral features maybe attributed to the changing absorber in the line of sight, without requiring intrinsic variations in the primary emitter itself (Weaver et al., 1993; Tanaka et al., 2004; Grupe et al., 2008; Reeves et al., 2008; Gallo et al., 2011, 2015; Iso et al., 2016; Tripathi et al., 2019; Parker et al., 2019; Komossa et al., 2020). Partial covering model has been used to explain the Seyfert X-ray spectrum in several studies (Weaver et al., 1993; Turner et al., 1996; Chevallier et al., 2006; Middleton et al., 2007). The warm thermal Comptonization model proposes the presence of an optically thick warm corona, distinct from the hot corona. In this model, far ultraviolet photons from the inner accretion disk undergo Compton upscattering by warm ($\sim 0.1\text{ keV}$) electrons in this second coronal component, giving rise to enhanced emissions at soft X-ray energies. The hot corona is responsible for the primary power law emission at hard energies (Dewangan et al., 2007; Middle-

ton et al., 2009; Done et al., 2012; Ezhikode et al., 2017; Petrucci et al., 2018; Kubota & Done, 2018; Ursini et al., 2020b). A study by Tripathi et al. (2019) on the Seyfert-1 galaxy Zw 229.015 suggested that the smooth and featureless spectrum favours the Comptonization picture. On the other hand, García et al. (2019) argue that thermal Comptonization picture requires parameters that are physically incompatible with the standard conditions for a corona. They propose the relativistic reflection model as a better description of this observation. The gravitationally blurred ionised reflection component is another popular candidate for explaining the soft excess (Miniutti & Fabian, 2004; Crummy et al., 2006; Liebmann et al., 2018). It refers to the X-ray illumination of the innermost regions of the accretion disk by the corona and relativistic reflection from therein. The cold material in accretion disk reflects a portion of the X-ray continuum and this component undergoes gravitational blurring due to the close proximity of the supermassive black hole. Studies on reverberation time lags also support the reflection scenario (Fabian et al., 2009; Alston et al., 2020). Additionally, the reflection model paves way to understand the accretion mechanism in NLS1 galaxies as explained in Reynolds, Christopher S. (2021). Again, Adegoke et al. (2017) showed that both the models are statistically similar in explaining the observed soft excess. A similar result was given by another recent study by Yu et al. (2023) on an *XMM-Newton* sample of six NLS1 galaxies. They conclude the presence of a warm and optically thick corona in the Comptonization model, although the reflection picture is a better explanation for the behaviour of a single source.

Here we present a technique to model the source’s energy dependent X-ray variability and identify the spectral parameters driving the variability for all the different scenarios. For this purpose, we estimate the source’s observed fractional rms (F_{var}) as a function of energy, from lightcurves extracted in multiple energy bins. The different spectral models are then used to predict the fractional rms. The X-ray variability is modelled as being caused by a pair of spectral parameters, varying in correlation, from which, F_{var} can be predicted and the parameter pair that best recreates the observed pattern maybe identified. We demonstrate the method through an investigation of the X-ray spectrum of Markarian 335 (Mrk 335).

4.2 Source Observations and Data Reduction

Mrk 335 is an extensively studied Seyfert-1 galaxy (Longinotti et al., 2007; Grupe et al., 2008; Liu & Wang, 2010; Tombesi et al., 2010; Patrick et al., 2011; De Marco et al., 2013; Longinotti et al., 2013; Kara et al., 2013; Wilkins et al., 2015; Chainakun & Young, 2015; Sarma et al., 2015; Epitropakis et al., 2016; Chainakun et al., 2016; Emmanoulopoulos et al., 2016; Choudhury et al., 2019; Ingram et al., 2019; Ezhikode et al., 2021; Liu et al., 2021b,a; Hancock et al., 2022; Yang et al., 2022). The supermassive black hole at its centre has an estimated mass of $\sim 2.6 \times 10^7 M_{\odot}$ (Grier et al., 2011). Having a typical NLS1 X-ray spectrum, it exhibits a very strong soft excess component and the presence of prominent iron lines (O’Neill et al., 2007; Larsson et al., 2008). The soft excess in this source was first observed in 1987 and has since been observed several times (Pounds et al., 1987; Turner & Pounds, 1988). Another important property of Mrk 335 is its high variability in X-ray energies and we use this variability to explore the origin of the soft excess in the source (Arévalo et al., 2008; Gallo et al., 2018).

The *XMM-Newton* observatory (Jansen et al., 2001) has made several observations of this source since 2000. In 2007, the source was observed to have fallen into a state of historically low flux (Grupe et al., 2007; Longinotti et al., 2008). It continued to remain so with occasional flaring episodes, until its re-emergence was observed by the *Swift* telescope (Komossa et al., 2020). In this study, we use a ~ 133 ks long observation made in 2006 (Obs Id 0306870101, PI : Nandra) when the source was still in its brightest flux state and showed large variability.

We consider only the epic-pn camera data for our analysis (Strüder et al., 2001). Data processing procedures for epic is described in detail in Section 2.3; here, we briefly mention the highlights relevant to the current observation alone. Science Analysis Software SAS-20.0.0. was used for processing the data. It was first filtered to remove the flaring backgrounds at high energies. Using SAS task, TABGTIGEN, a file containing the good time intervals (GTI) was created. We selected both single and double pixel events after removing flagged ones ($\text{PATTERN} \leq 4$ and $\text{FLAG} = 0$). The observation was verified to be pile-up free using EPATPLOT. Circular source region of radius $35''$ was selected and the spectrum extracted. Background was extracted from nearby source free region of similar size. Detector responses were generated using the tasks RMFGEN and ARFGEN. We extracted lightcurves having bin sizes of 100 s from the same source

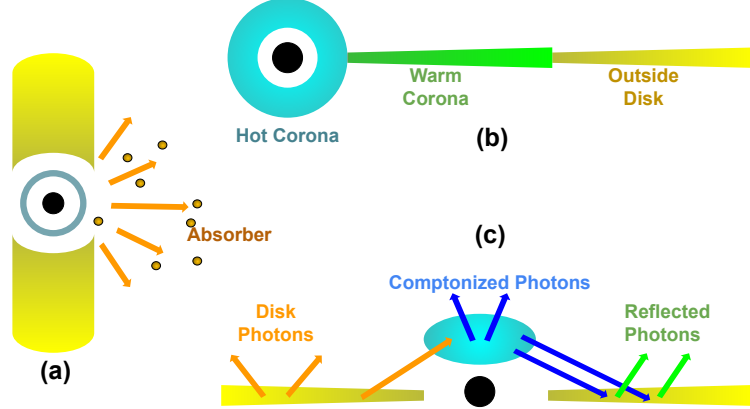


Figure 4.1: (a) : Patchy absorber partially covering the primary emission. (b) : Thermal Comptonization model geometry, where the disk (yellow) photons enter the warm Comptonization region (green) and then a fraction of these photons from warm corona enter the hot corona (blue). (c) : Blurred reflection model, wherein the corona (blue) illuminates a portion of the accretion disk (yellow). The coronal geometry may be of different flavours such as the lamppost model, spheroidal or toroidal corona or the sandwich model.

region. The lightcurves after background subtraction and accounting for dead time and exposure variations were generated using EPICLCCORR.

4.3 Spectral Analysis

Spectral fitting was done using the XSPEC-12.12.0 tool, explained in Section 3.4 (Arnaud, 1996b). XSPEC uses the χ^2 statistic to perform the fit. It also gives the uncertainties on spectral parameters, which gives their 90 % confidence interval. The 0.3 - 10 keV spectrum was grouped to have a maximum of three bins per resolution FWHM, with a minimum of 30 counts in every bin using SPECGROUP. The X-ray spectrum could be modelled as a power law continuum overlaid by emission lines. Prominent emission lines were seen in the iron band energies at 6.4 - 7.0 keV and were fit using Gaussian (*zgauss*) components. These lines correspond to the neutral Fe $K\alpha$ emission line at ~ 6.4 keV and ionised Fe xxvi line at ~ 7.0 keV (O'Neill et al., 2007). The source's cosmological redshift and galactic absorption (N_H) were fixed at $z = 0.02578$ and $3.56 \times 10^{20} \text{ cm}^{-2}$, respectively (Huchra et al., 1999; Kalberla et al., 2005). Previous observations have reported the presence of warm absorber zones in the source spectra (Gallo et al., 2013). We added two absorption edges at low energies, which significantly improved the spectral fitting. The observed soft X-ray excess of Mrk 335 has a

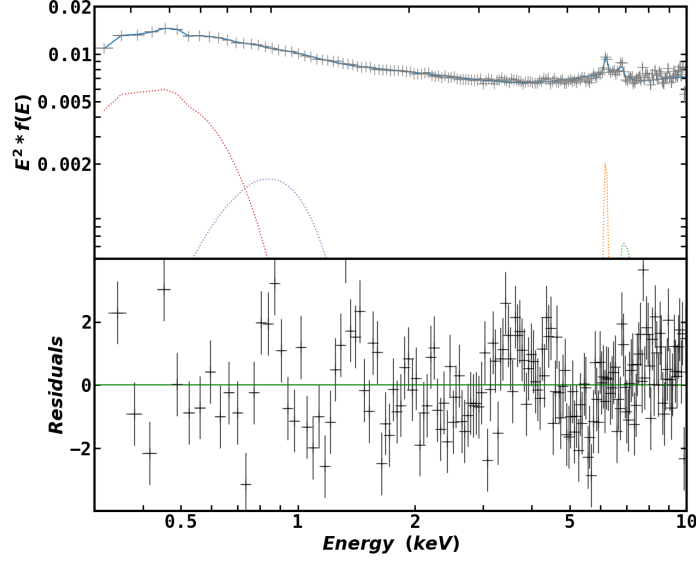
detailed analysis in literature (Grupe et al., 2008; Brightman & Nandra, 2011; Zhong & Wang, 2013; Parker et al., 2014; Wilkins, DR and Gallo, Luigi C, 2015; Gallo et al., 2015; Keek & Ballantyne, 2016; Boissay et al., 2016). These studies demonstrate that the broadband X-ray spectrum can be modelled as a partial covering model, as a Compton upscattering of the seed photons or by a relativistic reflection model. Accordingly, we fit the spectrum for all three cases.

4.3.1 Model-I : Partial Covering Model

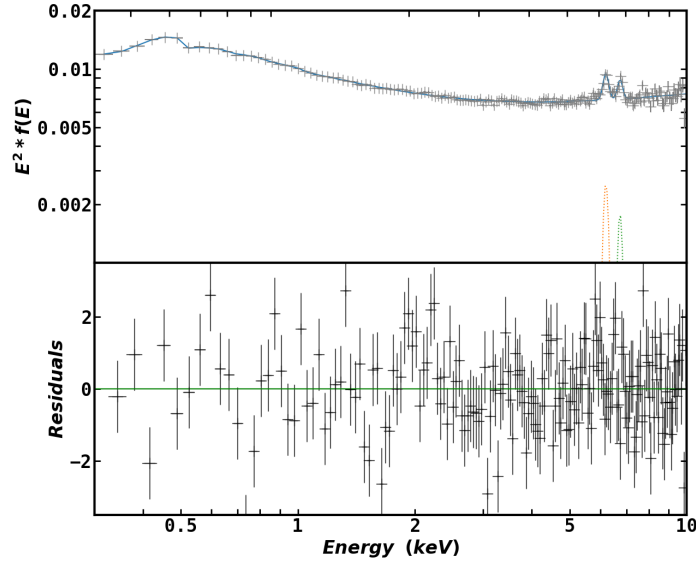
The partial covering picture describes the intrinsic continuum emission of the source to be modified by a partially covering patchy absorber. The spectrum is described as the resultant of an absorber reshaping the underlying single power law. We follow the model prescribed in Grupe et al. (2008) using the same observation. Partial covering of the primary emission is obtained by applying the *zpcfabs* component to power law emission. The model gives a better fit on adding Gaussian components of widths 0.25 keV, that mimic line emission for the soft emission lines. Additionally, an absorption edge component was added at 0.42 keV, which improved the fit. The soft energy Gaussian model components are added at energies ~ 0.1 keV and ~ 0.8 keV. We obtained the continuum emission, with a power law index of 2.31. The column density for the partially covering patchy absorber is $N_{\text{H,pc}} = 45.77 \times 10^{22} \text{ cm}^{-1}$ and having a covering fraction of 0.46. The goodness of fit is given by $\chi^2/\text{d.o.f.} = 302.3/163$. We note that, though this value is on the higher side, following the data grouping steps adopted in Grupe et al. (2008), we obtained a $\chi^2/\text{d.o.f.} = 917.4/700$, closer to the reduced χ^2 of 1.2 reported in Grupe et al. (2008). Figure 4.2a plots the spectral fitting and the best parameters of fit are listed in Table 4.1.

4.3.2 Model-II : Thermal Comptonization

In this case, the X-ray continuum was modelled as a Comptonized emission of the seed photon spectrum. The hot electrons in the corona upscatter the seed photons via Compton inverse process, resulting in an enhanced emission at low energies. The soft X-ray excess is considered to be due to the optically thick warm coronal component (Porquet et al., 2018; Middei et al., 2018; Noda & Done, 2018; Matzeu et al., 2020). The two component model prescribes a geometry where both corona components occupy physically distinct regions. As shown in Figure 4.1, the warm corona is connected to the accretion disk while



(a)



(b)

Figure 4.2: X-ray spectral fitting of epic-pn observation in the energy range 0.3 - 10.0 keV. Spectral fitting using the models namely, partial covering model (Model-I, top) and the thermal Comptonization model (Model-II, bottom), respectively are shown. In both figures, dotted lines represent the individual additive components in the model.

Table 4.1: Spectral parameters for Model-I in the energy range 0.3 - 10.0 keV.

Model	Parameter	Value
zedge	E (keV)	$0.42^{+0.006}_{-0.005}$
	τ	$0.16^{+0.02}_{-0.02}$
zpcfabs	$N_{\text{H,pc}} (\times 10^{22})$	$45.77^{+7.05}_{-6.06}$
	f_c	$0.46^{+0.03}_{-0.03}$
powerlaw	Γ_{pl}	$2.31^{+0.01}_{-0.01}$
	$N_{\text{pl}} (\times 10^{-2})$	$1.80^{+0.11}_{-0.10}$
zgauss1	$E_1(\text{keV})$	0.10^f
	N	$0.15^{+0.01}_{-0.01}$
zgauss2	$E_1(\text{keV})$	$0.76^{+0.01}_{-0.01}$
	$N (\times 10^{-3})$	$3.23^{+0.30}_{-0.26}$
zgauss3	$E_1(\text{keV})$	$6.41^{+0.03}_{-0.03}$
	$\sigma(\text{keV})$	< 0.12
zgauss4	$N (\times 10^{-5})$	$1.16^{+0.38}_{-0.34}$
	$E_1(\text{keV})$	$7.17^{+0.17}_{-0.14}$
	$\sigma(\text{keV})$	0.25^f
	$N (\times 10^{-5})$	$1.16^{+0.43}_{-0.44}$
χ^2/dof		302.3/163

Table 4.2: Spectral parameters for Model-II in the energy range 0.3 - 10 keV.

Component	Parameter	Value
zedge1	E_c (keV)	$0.38^{+0.01}_{-0.02}$
	τ	$0.17^{+0.098}_{-0.058}$
zedge2	E_c (keV)	$1.12^{+0.03}_{-0.03}$
	τ	$0.029^{+0.008}_{-0.009}$
zgauss1	E_1 (keV)	$6.41^{+0.03}_{-0.03}$
	σ	0.1^f
zgauss2	$N (\times 10^{-5})$	$1.68^{+0.220}_{-0.217}$
	E_1 (keV)	$6.96^{+0.04}_{-0.04}$
simpl	σ	0.1^f
	$N (\times 10^{-5})$	$1.00^{+0.208}_{-0.207}$
	Γ_{simpl}	$1.82^{+0.03}_{-0.15}$
	f	$0.10^{+0.02}_{-0.04}$
nthComp	UpScOnly	1.0^f
	Γ_{nthC}	$3.21^{+0.05}_{-0.05}$
	kT_e (keV)	> 0.69
	kT_{bb} (keV)	$0.0598^{+0.003}_{-0.005}$
χ^2/dof	$N_{\text{nthC}} (\times 10^{-3})$	$7.62^{+1.38}_{-0.57}$
		228.52/163

the hot corona lies beyond. We consider the particular case where the UV disk photons enter the warm Comptonizing region first and then the photons from the warm coronal medium enter the hot primary corona (Ezhikode et al., 2016; Kubota & Done, 2018; Zoghbi & Miller, 2023). Warm corona Comptonizes the disk photons, resulting in the soft excess emission and a fraction of these photons are further scattered by the hot corona, emitting in the hard X-ray energies. We use two XSPEC models, namely *simpl* and *nthComp*, to represent the hot and warm coronal components, respectively. The disk photons first enter the warm corona represented by *nthComp* emitting in the soft X-ray region, while a fraction of these photons are again upscattered by the hot corona represented by *simpl*. *simpl* is an empirical model for the Comptonization of a fraction of seed photons to a higher temperature (Steiner et al., 2009). The incoming seed photons were considered to be blackbody in shape (*inp_type*=0). Figure 4.2b shows the corresponding spectral fitting. The photon index (Γ_{simpl}) obtained has a value of ~ 1.82 . We obtained a seed photon temperature of $\sim 5.98 \times 10^{-2}$ keV. The spectral fitting returns a value of 0.98 keV for the electron temperature. Though we were unable to obtain a constraint on its upper limit, the parameter has a lower limit of 0.69 keV. The complete list of the spectral parameters of fit are given in Table 4.2.

4.3.3 Model-III : Relativistic Reflection

In this case, the X-ray spectrum was modelled as a standard relativistic reflection model. Blurred reflection features arise in the spectrum when the ‘cold’ material in the accretion disk is illuminated by the ‘hot’ corona. Since the disk radiates efficiently, it is colder than the hot coronal material. The geometry of this hot corona is still not completely understood, however, some possibilities often used in literature are the lamppost model, spheroidal or toroidal corona and the sandwich coronal model. A fraction of the X-ray photons from the corona can illuminate the disk, giving rise to the reflection spectrum (Bambi, 2024). We use *relxill* family of models for the complex relativistically blurred reflection component (Dauser et al., 2014; García et al., 2014; Dauser et al., 2016, 2020). The *relxill* code offers two variations, the lamppost geometry (*relxilllp*, *relxilllpCp*) and the coronal geometry (*relxill*, *relxillCp*). For our current analysis, we use the coronal model with a Comptonization continuum (*relxillCp*, See Figure 4.1). It accounts for the gravitationally smeared reflection of the Comptonization continuum by the accretion disk. The black hole spin parameter, *a*, was

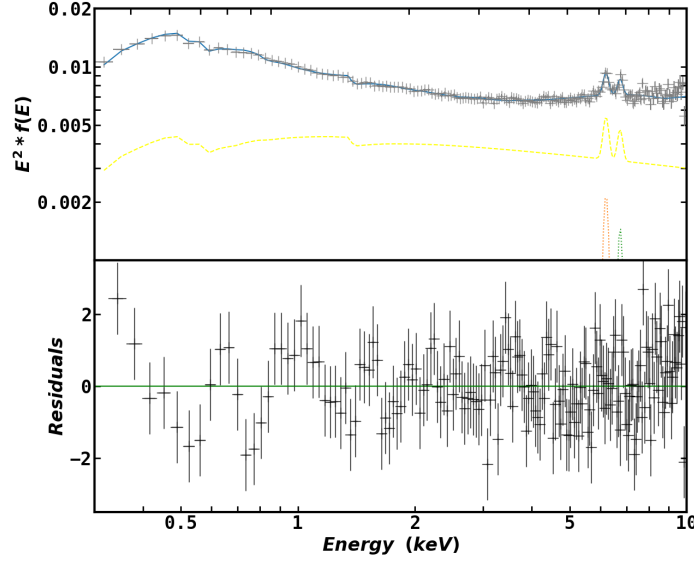


Figure 4.3: (cont. from Figure 4.2) X-ray spectral fitting of epic-pn observation in the energy range 0.3 - 10.0 keV. Spectral fitting using the blurred reflection model (Model-III) is shown. The dotted lines represent the individual additive components in the model.

Table 4.3: Spectral parameters for Model-III in the energy range 0.3 - 10 keV.

Component	Parameter	Value
zedge1	$E_c(\text{keV})$	$0.62^{+0.02}_{-0.03}$
	τ	$0.18^{+0.05}_{-0.04}$
zedge2	$E_c(\text{keV})$	$1.47^{+0.04}_{-0.04}$
	τ	$0.11^{+0.02}_{-0.02}$
relxillCp	$i(\text{deg})$	$74.11^{+1.20}_{-2.49}$
	$R_{\text{in}}(R_{\text{ISCO}})$	< 1.1
	Index1	> 8.30
	Γ_{relx}	$2.20^{+0.01}_{-0.01}$
	$\log \xi$	$2.70^{+0.06}_{-0.06}$
	A_{Fe}	$0.67^{+0.07}_{-0.07}$
	R_f	$9.495^{+3.01}_{-1.39}$
	$N_{\text{relx}}(\times 10^{-5})$	$5.597^{+0.40}_{-0.62}$
	$N_{\text{relx}}(\times 10^{-5})$	$5.597^{+0.40}_{-0.62}$
zgauss1	$E_1(\text{keV})$	$6.41^{+0.03}_{-0.03}$
	σ	0.1^f
zgauss2	$N(\times 10^{-5})$	$1.43^{+0.241}_{-0.252}$
	$E_1(\text{keV})$	$6.96^{+0.05}_{-0.04}$
	σ	0.1^f
χ^2/dof	$N(\times 10^{-6})$	$8.18^{+2.23}_{-2.45}$
		$167.6/161$

fixed at 0.998, which is its maximal allowed value. The two indices for emissivity profile were tied together while the break radius (R_{br}) and outer (R_{out}) radius were fixed at $300 R_g$ and $400 R_g$, respectively. The spectral fitting was done for a fixed accretion disk density of 10^{15} cm^{-3} and a coronal electron temperature of 60 keV, respectively. The corresponding X-ray fitting is plotted in Figure 4.3. The power law photon index for the incident spectrum (Γ_{relx}) obtained was ~ 2.20 while the reflection fraction was ~ 9.49 . Ionization parameter ($\log \xi$) returned the value ~ 2.70 . Inner disk radius (R_{in}) lies between $1 - 1.1 R_{\text{ISCO}}$. The *relxill* code defines the emissivity profile by $r^{-\text{Index1}}$ and $r^{-\text{Index2}}$ between R_{in} & R_{br} and R_{br} & R_{out} , respectively. These two parameters were tied together and we obtained a lower limit of 8.30 on Index1, the parameter has an upper limit of 10 in the model definition. This agrees with the steep emissivity profiles, with index values greater than 5, that has previously been observed for Mrk 335 (Gallo et al., 2013; Wilkins et al., 2015; Gallo et al., 2019). The parameters of fit are listed in Table 4.3.

4.4 Fractional Variability and RMS Spectra

Fractional variability is a useful and widely used tool for studying the variability properties of AGNs in different energy ranges. The source variability can be quantified through the statistical quantity, fractional root mean square variability amplitude, F_{var} . It is defined as the square root of normalised excess variance (Edelson et al., 1990; Rodriguez-Pascual et al., 1997). Excess variance is considered an indicator of the ‘intrinsic’ variability of the source, in the sense that it is calculated after removing the effect of measurement uncertainties (Edelson et al., 2002).

We follow the steps prescribed by Vaughan et al. (2003) for calculating fractional rms variability amplitude F_{var} . It is defined as given by equation 4.1 (Eqn. 10 of Vaughan et al. (2003)) :

$$F_{\text{var}} = \sqrt{\frac{S^2 - \sigma_{\text{err}}^2}{\bar{x}^2}} \quad (4.1)$$

where S is the sample variance given by equation 4.2 (Eqn. 6 of Vaughan et al. (2003)) :

$$S^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2 \quad (4.2)$$

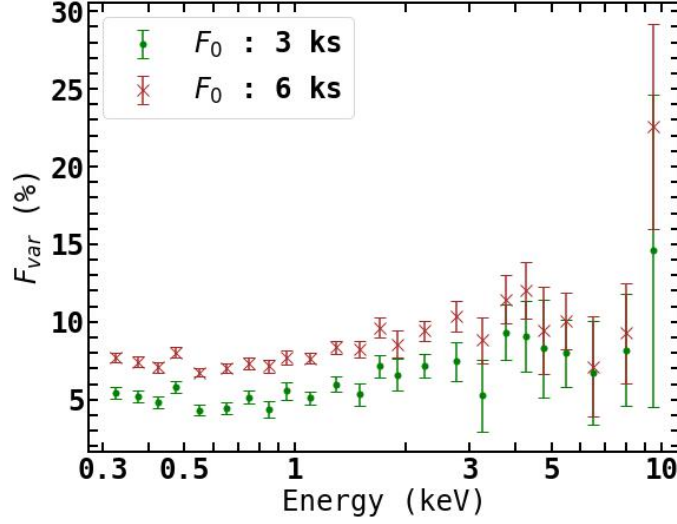


Figure 4.4: RMS spectra plotting the observed F_{var} as a function of energy. Source lightcurves were extracted at different energy bands. From each of those lightcurves, F_{var} were determined and plotted against energy. This was repeated for lightcurves with different segment sizes, 3 and 6 ks.

and $\overline{\sigma_{\text{err}}^2}$ is the mean square error as given by equation 4.3 (Eqn. 9 of Vaughan et al. (2003)) :

$$\overline{\sigma_{\text{err}}^2} = \frac{1}{N} \sum_{i=1}^N \sigma_{\text{err},i}^2 \quad (4.3)$$

The error on F_{var} is given by equation 4.4 (Eqn. B2 of Vaughan et al. (2003)):

$$\text{err}(F_{\text{var}}) = \sqrt{\left(\frac{1}{2N} \frac{\overline{\sigma_{\text{err}}^2}}{\bar{x}^2 F_{\text{var}}} \right)^2 + \left(\sqrt{\frac{\overline{\sigma_{\text{err}}^2}}{N}} \frac{1}{\bar{x}} \right)^2} \quad (4.4)$$

Lightcurves were extracted in multiple energy bins. Corresponding to each lightcurve, we consider segments of varying lengths, giving us segments of sizes, 500 s, 700 s, 1 ks, 1.5 ks, 3 ks and 6 ks. For each of these cases average count, variance and excess variance were calculated at all energy bins, from which F_{var} and its errors were determined using the above given equations. The F_{var} values thus estimated from the observation, are denoted by F_0 . The rms spectra for this observation can then be created by plotting F_0 as a function of energies. We find that, for segment sizes lower than 3 ks, for some of the energy bins, the excess variances could not be detected. Hence we limit the future analyses to segments of sizes 3 and 6 ks only. RMS Spectra for the 3 and 6 ks segments are plotted in

Figure 4.4.

4.5 Fractional Variability Prediction

4.5.1 Method

We attribute the variation of the count rate in a given energy band, R_i (where the subscript i denotes the energy band) as being caused by variations in two spectral parameters say, X and Y . In the linear approximation this means that the variation of the count rate, ΔR_i can be written as :

$$\Delta R_i(X, Y) = \left(\frac{\partial R_i}{\partial X} \right)_{X_0} \Delta X + \left(\frac{\partial R_i}{\partial Y} \right)_{Y_0} \Delta Y \quad (4.5)$$

where X_0 and Y_0 are the steady state values of X and Y and ΔX and ΔY are their variation. Noting that the predicted normalised F_{var} at the energy band denoted by i is F_{P_i} , given by, $F_{P_i}^2 = (\Delta R/R_i)^2$, this gives us :

$$F_{P_i}^2 = A_i^2 \delta X^2 + B_i^2 \delta Y^2 + 2A_i B_i C_{XY} |\delta X| |\delta Y| \quad (4.6)$$

where $\delta X = \Delta X/X_0$, $\delta Y = \Delta Y/Y_0$, $A_i = \frac{X_0}{R_i} \left(\frac{\partial R_i}{\partial X} \right)_{X_0}$ and $B_i = \frac{Y_0}{R_i} \left(\frac{\partial R_i}{\partial Y} \right)_{Y_0}$. C_{XY} gives both the strength and the sign of the cross term, such that $C_{XY} = 1, 0, -1$ represent the cases when the δX and δY are correlated, un-correlated and anti-correlated, respectively. Fractional values of C_{XY} can be interpreted as when δX and δY are either partially correlated or that there is a phase lag between them such that $C_{XY} = \cos \phi$.

We estimate the partial derivatives, $\left(\frac{\partial R_i}{\partial X} \right)_{X_0}$ and $\left(\frac{\partial R_i}{\partial Y} \right)_{Y_0}$, numerically using the XSPEC software. We consider the best fit model spectra and then the change in the model count rate at a given energy band are determined by introducing a 10 % variation in the value of the spectral parameter. The ratio of this change in the count rate to that of the parameter value was taken as the corresponding partial derivative. Note that this exercise was undertaken in the model count rates (and not the photon rate) and hence the response of the instrument is being taken into account. The best fit spectral values were then used to estimate the values of A_i and B_i .

We then compare the predicted F_p with the observed ones (F_0) to obtain the

best fit values for $|\delta X|$, $|\delta Y|$ and C_{XY} by minimising the χ^2 function :

$$\chi^2 = \sum_{i=0}^n \left(\frac{F_{0i}^2 - F_{Pi}^2}{\sigma_i} \right)^2 \quad (4.7)$$

Here, F_{0i}^2 refers to the squared observed fractional rms variability amplitude (F_{var}) and σ_i is the error on F_{0i}^2 . The minimisation of χ^2 can be done analytically and one can then obtain expressions for the best fit values. This is explained in Appendix A. However, sometimes these analytical expressions gave unphysical best fit values, such as $|\delta X|$ or $|\delta Y| < 0$ or $|C_{XY}| > 1$. Thus, in our analysis, we use the python library LMFIT to minimise the χ^2 while allowing the parameter values to be restricted within a specified range (Newville et al., 2016).

4.5.2 Model-I : Partial Covering Model

In order to model the source's intrinsic variability, we consider the different spectral parameters. For a given segment length, spectral parameters were varied in combinations of one and two and all possible combinations were considered. For each combination, the parameter values were varied slightly and the corresponding values of R_{0i} , R_{1i} and R_{2i} were determined for all the energy bins. From these values, A_i and B_i can be calculated as explained above. These values were then input into the LMFIT package, along with corresponding frms (F_{0i}^2) and its uncertainties (σ_i). The fit parameters δX^2 , δY^2 , C_{XY} and the resultant predicted F_P were obtained as output. From all possible parameter combinations, the combination that gives the best χ^2 fit was determined, under the conditions that neither δX^2 nor δY^2 could be negative and that C_{XY} lies between -1 and +1. The predicted rms spectra for a given segment size and combination of model spectral parameters can be created by plotting F_P as a function of energies.

For each of the three considered scenarios, the model parameters were varied individually and in pairs. For the partial covering model, the best fit was given by a combination of the covering fraction (f_c) and the power law photon index (Γ_{pl}) for both segment sizes (3 ks and 6 ks). For a segment length of 3 ks, the combination is obtained for the values of δf_c and $\delta \Gamma_{\text{pl}}$ being 5.93 % and ~ 2.14 %, respectively. Similarly, for the 6 ks case, the lowest χ^2 is again given by the same combination with δf_c and $\delta \Gamma_{\text{pl}}$ values of 8.86 % and 2.43 %, respectively. In both the cases, the two parameters are slightly correlated, represented by C_{XY} values of ~ 0.3 . Table 4.4 tabulates the parameter combinations with lowest χ^2 for

Table 4.4: Fit statistics for different parameter combinations of Model-I.

Segment Size	X	δX (%)	Y	δY (%)	C_{XY}	χ^2/dof
3 ks	f_c	$5.93^{+0.20}_{-0.22}$	Γ_{pl}	$2.14^{+0.23}_{-0.25}$	$0.29^{+0.06}_{-0.06}$	17.89/21
	f_c	13.14	N_{pl}	14.39	0.91	22.15/21
	Γ_{pl}	1.97	N_{pl}	6.30	0.35	25.47/21
6 ks	f_c	$8.86^{+0.18}_{-0.16}$	Γ_{pl}	$2.43^{+0.22}_{-0.26}$	$0.28^{+0.05}_{-0.04}$	18.95/21
	f_c	15.47	N_{pl}	16.24	0.84	24.82/21
	Γ_{pl}	2.50	N_{pl}	9.37	0.45	39.83/21

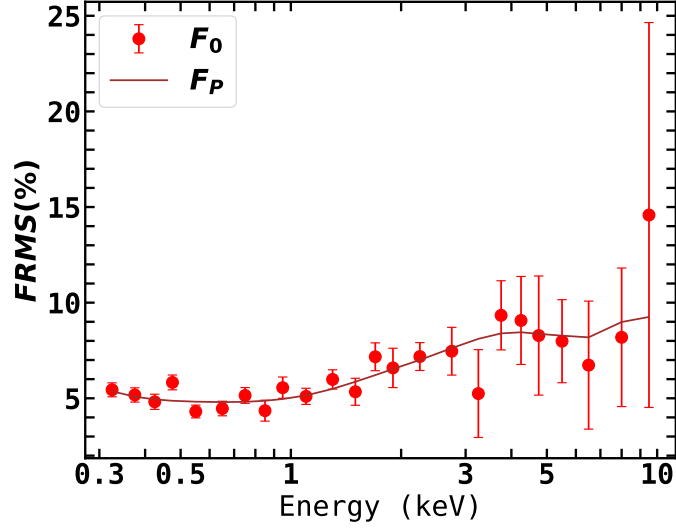
Table 4.5: Fit statistics for different parameter combinations of Model-II.

Segment Size	X	δX (%)	Y	δY (%)	C_{XY}	χ^2/dof
3 ks	Γ_{nthC}	$2.49^{+0.26}_{-0.29}$	N_{nthC}	$5.66^{+0.19}_{-0.19}$	$-0.59^{+0.04}_{-0.04}$	16.93/21
	f	10.40	N_{nthC}	4.91	0.04	21.88/21
	Γ_{simpl}	2.29	N_{nthC}	5.37	-1.00	36.85/21
6 ks	Γ_{nthC}	$2.87^{+0.23}_{-0.30}$	N_{nthC}	$8.15^{+0.16}_{-0.16}$	$-0.51^{+0.03}_{-0.03}$	16.98/21
	f	10.21	N_{nthC}	7.34	0.17	24.70/21
	Γ_{simpl}	2.25	N_{nthC}	7.72	-0.81	53.34/21

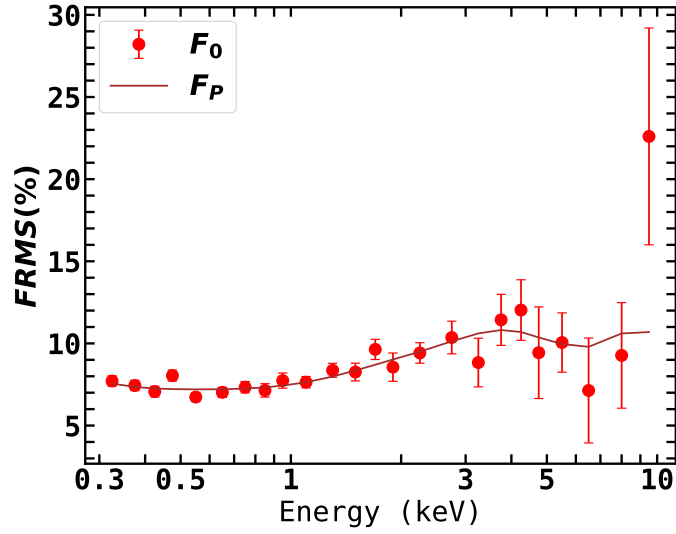
three cases, all other combinations give higher values of χ^2 . For both segment sizes, we plot a continuous curve by calculating F_P values at very small energy bins (0.1 keV) using the obtained fit parameter values. The resultant spectra is plotted in Figure 4.5.

4.5.3 Model-II : Thermal Comptonization

For the thermal Comptonization case, we consider all possible model parameters that determine the X-ray spectrum in the full energy range. As with the partial covering model, the parameters are again varied individually and in combinations of two. Our analysis showed that varying the electron temperature (kT_e) does not bring about a significant change in the count rates and hence kT_e was not considered during the current analysis. The whole procedure was repeated for all combinations of the spectral parameters for both segment sizes. For the 3 ks case, the best fit was obtained by varying the parameters, photon index (Γ_{nthC}) and normalisation (N_{nthC}) of the warm thermal corona. The values of $\delta\Gamma_{\text{nthC}}$ and δN_{nthC} obtained are $\sim 2.49\%$ and $\sim 5.66\%$, respectively, with a correlation C_{XY}

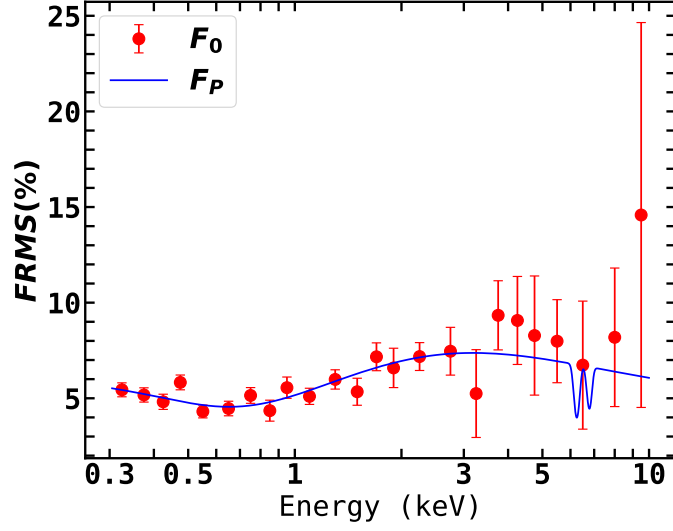


(a)

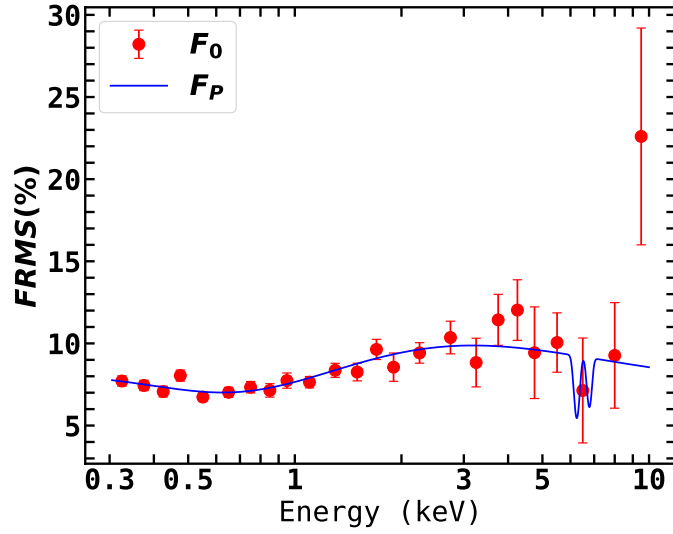


(b)

Figure 4.5: The observed F_{var} values (F_0) are plotted along with a continuous curve corresponding to the predicted F_{var} (F_P) using the partial covering model (brown curve) model. Top and bottom panels show the plots for segment sizes 3 ks and 6 ks, respectively.



(a)



(b)

Figure 4.6: The observed F_{var} values (F_0) are plotted along with a continuous curve corresponding to the predicted F_{var} (F_P) using the warm Comptonization (blue curve) model. Top and bottom panels show the plots for segment sizes 3 ks and 6 ks, respectively.

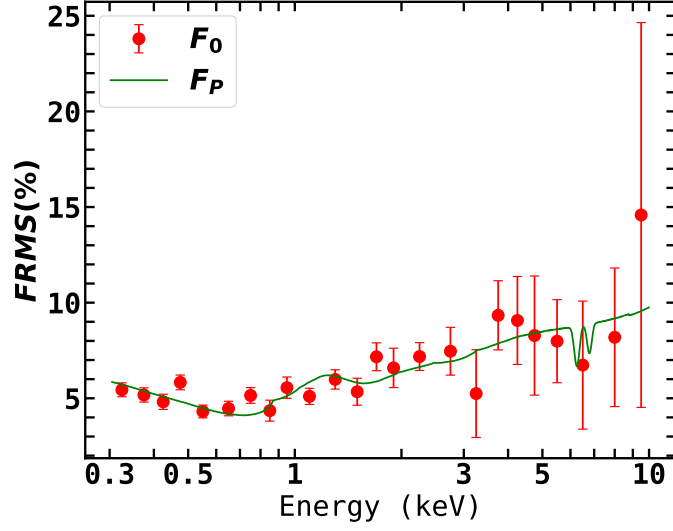
Table 4.6: Fit statistics for different parameter combinations of Model-III.

Segment Size	X	δX (%)	Y	δY (%)	C_{XY}	χ^2/dof
3 ks	Γ_{relx}	$1.91^{+0.12}_{-0.17}$	$\log\xi$	$2.64^{+0.10}_{-0.14}$	$-0.49^{+0.10}_{-0.08}$	22.81/21
	Γ	1.58	N_{relx}	6.50	-0.65	23.91/21
	R_f	6.57	N_{relx}	8.89	-0.92	30.93/21
6 ks	Γ_{relx}	$1.53^{+0.23}_{-0.33}$	N_{relx}	$8.90^{+0.21}_{-0.24}$	< -0.53	29.86/21
	$\log\xi$	15.82	N_{relx}	24.44	-0.95	44.57/21
	R_f	7.44	N_{relx}	12.74	-1.00	46.76/21

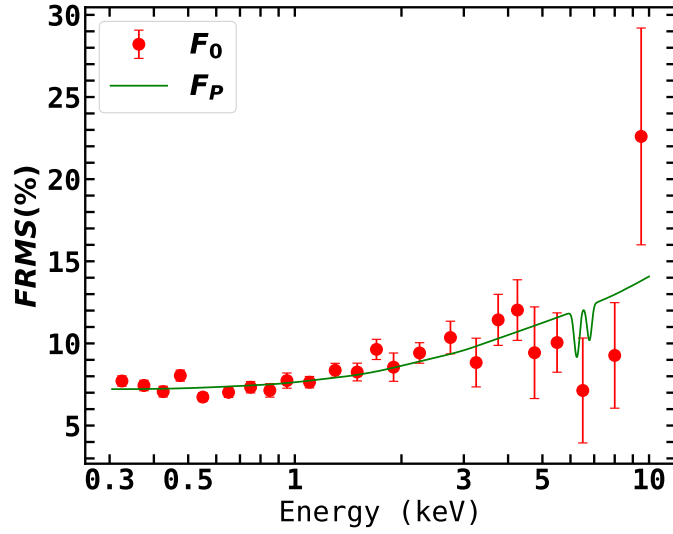
~ -0.59 , indicating significant anti-correlation between the two parameters. For the case with the larger segment of 6 ks length, the best fit is again given by the same combination of photon index (Γ_{nthC}) and normalisation (N_{nthC}). The values of $\delta\Gamma_{\text{nthC}}$ and δN_{nthC} are then $\sim 2.87\%$ and $\sim 8.15\%$. In this case also, we see a slight anti-correlation between the two parameters, $C_{XY} \sim -0.51$. Parameter combinations with the least values of χ^2 are given in Table 4.5. The continuous curve is plotted for small energy bins of size 0.1 keV, as depicted in Figure 4.6.

4.5.4 Model-III : Relativistic Reflection

As with the previous models, here we consider all model parameters that determine the spectrum, except the iron abundance. We find that the model count rates are not sensitive to changes in the inner disk radius (R_{in}) and hence it was not considered for the analysis. The procedure as described earlier was followed and the rms spectrum was created. For the reflection model, the power law photon index (Γ_{relx}) and the accretion disk's ionisation parameter ($\log\xi$) of *relxillCp* gives the best fit for the case of 3 ks long segment. Here, the values of $\delta\Gamma_{\text{relx}}$ and $\delta\log\xi$ obtained are given by $\sim 1.91\%$ and $\sim 2.64\%$, respectively and the two have a C_{XY} value of ~ -0.49 . However for the 6 ks case, the best fit is given by a different parameter combination of the power law index (Γ_{relx}) and normalisation (N_{relx}) parameters of *relxillCp*. We found that, in this case, the two parameters are anti-correlated with the values of $\delta\Gamma_{\text{relx}}$ and δN_{relx} being $\sim 1.53\%$ and $\sim 8.90\%$ and $C_{XY} < -0.53$. As before, parameter combinations giving the best χ^2 values are tabulated in Table 4.6. A continuous curve was also plotted by choosing very small energy bins of 0.1 keV size. The resultant rms spectra are shown in Figure 4.7.



(a)



(b)

Figure 4.7: The observed F_{var} values (F_0) are plotted along with a continuous curve corresponding to the predicted F_{var} (F_P) using the blurred reflection (green curve) model. Top and bottom panels show the plots for segment sizes 3 ks and 6 ks, respectively.

4.6 Results and Discussion

Mrk 335 has an X-ray spectrum characteristic of a typical Seyfert-1 galaxy with a strong soft excess component and significant flux variations in the X-ray band. The broadband X-ray spectrum of the source could be interpreted as a partial covering absorber modifying the power law, a warm thermal Comptonization component or as the gravitationally smeared reflection from the accretion disk. We fit spectral models representing these three interpretations to the *XMM-Newton* observation of Mrk 335 in its high flux state and find that the spectrum could very well be represented by all the aforementioned pictures. The photon indices obtained for all three cases fall well within the range of 1.8 - 2.5, typically observed for similar galaxies (Nandra & Pounds, 1994; Page et al., 2005).

Previous studies on the *XMM-Newton* observation considered in this work has been reported to show high variability in its X-ray emission (Wilkins, DR and Gallo, Luigi C, 2015; Mastroserio et al., 2020). We estimated the fractional rms amplitude, F_{var} , as a function of energy, E , for two different segments sizes 3 ks and 6 ks. We developed a scheme which, for a given spectral model fitting, would predict $F_{\text{var}}(E)$ as being caused by the coherent variations in two of the spectral parameters. This enables us to identify the spectral parameters responsible for the observed variability pattern. As can be seen from Figure 4.4, F_{var} has a non-monotonous behaviour with energy. There is evidence that F_{var} decreases from 0.3 keV to about 0.7 keV and then rises up at higher energies. Our analysis shows that none of the three spectral models can explain the observed profile using a single parameter variation; which always results in a reduced χ^2 being greater than 45/21.

In the partial covering interpretation of the X-ray spectrum, there exists a single power law emission along with a neutral patchy absorber that partially covers the source emission. In order to explain the observed variation of fractional rms with energy, the analysis undertaken here shows that a variation in the primary emission itself is required. This is manifested in the best fit requiring a variation in the power law index (Γ_{pl}). Previous study on the galaxy on IRAS 3224- 3809 by Yamasaki et al. (2016) shows that, rms variability over a timescale of ~ 1 day can be explained by changing the partial covering fraction. From our analysis of Mrk 335 using the partial covering scenario, we see that variations on smaller timescale could be explained by variations in the covering fraction (f_c) along with the photon index. The results are the same for both segment

sizes, of 3 ks and 6 ks, with similar values of χ^2 . In both the cases, the varying parameters are slightly correlated with a C_{XY} of ~ 0.3 .

In the warm Comptonization interpretation, a hot corona Comptonizes X-ray photons from the warm corona, with the latter giving rise to the soft excess. Thus variations of the normalization of the warm Comptonization component (with other parameters staying static) will cause an overall normalization change in the overall spectrum, leading to an F_{var} which is constant with energy. In this case, the rms analysis shows that there needs to be a variation in the photon index of the warm thermal Comptonization (Γ_{nthC}). Moreover, the variations in the normalization and Γ_{nthC} are anti-correlated with each other, since the cross-correlation C_{XY} value turns out to be negative. Note that Γ_{nthC} depends on the optical depth and temperature of the warm corona. A decrease in Γ_{nthC} implies an increase in either the warm coronal temperature or its optical depth. Thus, the analysis suggests that energy dependent F_{var} for both the timescales can be explained in terms of variations of the normalization and temperature (or optical depth) of the thermal corona. It is interesting to note that although significant variability is present at high energies, the energy dependent F_{var} can be explained solely due to variations of the warm coronal parameters, which in turn changes the seed photon spectrum of the hot Comptonization component.

For the case when the soft excess is explained by the relativistic reflection model, we note the exceptionally high values of emissivity index and reflection fraction parameters. For this model, a variation in the normalization of the reflection component will give rise to constant energy independent fractional rms, F_{var} . The rms analysis shows that when combined with a change in the photon index Γ_{relx} , this leads to an increase in F_{var} with energy. Such a scenario can broadly explain the data as shown in Figure 4.7b, for a segment size of 6 ks. However, this does not produce the dip in F_{var} at ~ 0.7 keV, leading to higher value of $\chi^2/\text{dof} = 30/21$ (See Table 4.6). It is interesting to note that a combination of variations in the photon index Γ_{relx} and ionization parameter $\log \xi$ can produce this a dip as is evidenced by Figure 4.7a, for the fitting for segment size of 3 ks. The same combination, however, does not provide a good fit when the segment size is 6 ks, resulting in a higher $\chi^2/\text{dof} = 47.92/21$. This suggests that perhaps more than two parameter variation are required to explain the data for the reflection model. The steep emissivity profile and an extreme value of the reflection parameter for a non point-like X-ray source, along with the requirement for variations in more than two parameters, indicates that the

blurred reflection model might not be a suitable description of the current Mrk 335 spectrum.

We also note that the fit statistics are somewhat low for a few of these combinations, especially in the cases of partial covering and the Comptonization models. Such low values of χ^2 could suggest an over estimation of the uncertainties. This situation could possibly arise when there is an intrinsic correlation between the variabilities in different energy bands, as discussed in Ingram (2019). They proposed revised expressions for estimating the uncertainties under such circumstances, assuming that the variability power spectrum is known. However, for the current analysis, the available observation is not sufficiently long to reliably determine the power spectrum required for such a treatment. Furthermore it is not clear how this formalism can be directly applied when the fractional variability, F_{var} , is being computed directly from the lightcurves, rather than a power spectrum analysis.

Nevertheless, all three competing spectral models were analysed using the same methodology and statistical assumptions. Consequently, while a more rigorous treatment of the correlated uncertainties may alter the absolute values of the goodness-of-fit statistics, it is not expected to qualitatively affect the relative comparison between the models. The principal conclusion - that variability modelling of the considered observation favours the relativistic reflection scenario over alternative spectral interpretations - therefore remains unchanged.

Finally, we point out that the variability analysis presented in this chapter is restricted to segment lengths of 3 ks and 6 ks, as statistically significant excess variance could not be measured for shorter timescales with the available data. Consequently, the present study primarily probes variability occurring on kilosecond timescales and longer. Variability arising from faster physical processes in the immediate vicinity of the black hole, such as rapid changes in coronal heating, magnetic reconnection events or other small-scale fluctuations, may therefore not be fully captured. If present, such rapid variations would be averaged over within the adopted segment lengths and hence would contribute less prominently to the measured fractional rms spectra. Nevertheless, the selected timescales represent the shortest intervals over which reliable energy-dependent variability measurements could be obtained for this observation. The objective of this work is to distinguish between competing spectral models using variability information and the adopted timescales provide sufficient signal-to-noise to achieve this. Future observations with longer uninterrupted exposures or higher

count rates will enable this methodology to be extended to shorter timescales, allowing the investigation of faster variability processes in the innermost regions of AGNs.

The method presented in this chapter attributes the AGN X-ray variability to be caused by two spectral parameters varying in combination. The technique has the potential to differentiate between spectrally degenerate models, proposed for AGN physics. By identifying the drivers of observed variability, this technique can aid in advancing our understanding of the inner mechanism of the central engine in AGNs. Moreover, the study demonstrated the potential of the developed method to be applied to other datasets of different AGNs, providing us with a new approach to understand the energy dependent X-ray variations and the underlying physical processes.

Chapter 5

Summary and Discussion

The comprehensive goal of this thesis has been to advance our understanding of physical processes governing the accretion mechanism in active galactic nuclei by combining long term spectral evolution studies with detailed broadband spectral modelling and energy dependent variability analysis. Using *AstroSat*, *NuSTAR* and *XMM-Newton* observations, the work examines both long term changes in X-ray spectra over multi-year data and short period variations to probe the geometry and energy dynamics of AGN central engine. Incorporating these complementary approaches, the thesis tries to create an interpretation of how variations in accretion disk, corona and their ambient environment together determine the observed X-ray spectra and variability patterns of AGNs.

The long term data of Mrk 279 was examined with the goal of understanding how the X-ray spectrum of the source evolve over multi-year timescale and the physical changes accompanying these variations. Studying data from multiple epochs provide a way of separating the intrinsic changes in continuum emission from other factors such as reflection and obscuration and to study accretion flow and the black hole environment over longer periods. This gives us a clear view of underlying physics of AGN dynamics, beyond the short term fluctuations that are typically analysed during single observation studies.

The analysis showed that individual spectral components follow the variations in total flux state and luminosity. Over the different epochs, the source underwent flux state transitions, accompanied by changes in its spectral shape. Each epoch showed its own spectral shape, with variations in photon index and hence the overall curvature, appearing independent of the source's instantaneous

brightness. No significant correlation was observed between the continuum flux and photon index. Some observations showed a relatively steeper spectrum, while others had a more flat one. These trends did not follow a monotonic or flux-induced pattern. Overall, the continuum behaved in a way that indicates intrinsic spectral variability without having a one-to-one correspondence with brightness/luminosity.

However, changes in spectral shape, determined by variations in the photon index, are tied to long term variations in continuum rather than rapid fluctuations. While Mrk 279 exhibit short timescale variability in flux, these rapid variations do not show clear changes in spectral form. But when spectra taken years apart are compared to one another, subtle changes in spectral shape do show up. This behaviour suggests that the physical conditions driving the spectral evolution, such as variations in accretion rate or coronal geometry, operate over longer timescales. Short term variability is possibly dominated by fluctuations in emission normalisation without changing the fundamental spectral components.

Together these findings suggests a physical picture where the important driver of spectral evolution in Mrk 279 is the slow variation in accretion flow rather than sudden changes in geometry of emission region. The absence of Γ -flux correlations indicate that coronal heating processes remains stable while long term variations of continuum indicate gradual changes in accretion rate or the disk-coronal coupling over multi-year timescale. Since the short term variabilities do not have a corresponding index variation, they might be caused by changes in normalisation in emission that doesn't alter its physical properties. Such a variability pattern is consistent with AGN models where structural variations are slow but there are rapid variations arising from purely flux driven processes.

These results add to our understanding of AGN variability stating that long term spectral stability in photon index accompanied by multi-year changes in continuum is not uncommon in Seyfert galaxies. Mrk 279 belongs to the class of AGNs where corona maintains a roughly constant shape while flux variations are caused by slow changes in accretion flow. The differences in long term spectral variability and short term normalisation driven fluctuations indicates that AGN variability involves multiple processes having its own timescales and possibly associated with different regions of disk-corona system.

Building on the insight that long term spectral analysis alone cannot completely reveal the observed characteristics, we extend our study to a combined spectral–timing approach to understand the processes governing the AGN X-ray emission. Although time-averaged spectra provides valuable information on the underlying emission components, it alone cannot distinguish between the multiple physical processes that can produce similar spectral shapes. In order to overcome such degeneracies, in this work we incorporate variability-based techniques to identify the spectral features driving the observed variability. Analysing spectral and temporal patterns together, this method aims to recognise the most physically plausible model for the X-ray characteristics such as geometry, soft-excess origin and coronal variability mechanisms.

We first aim to understand how does the variability depend on energy and what we can infer from this, about the origin of different spectral components. For this purpose, we carried out a detailed analysis of the fractional rms variability amplitude spectrum across different X-ray energy bands. Unlike time-averaged spectroscopy, which explains only the mean spectral shape, this combined approach can isolate the varying components and giving us a more direct understanding of the physical processes shaping the X-ray emission. Since it combines spectral modelling with variability diagnostics, we can test which combinations of spectral components are required to reproduce the observed energy dependent variability. The methodology thus extends beyond a simple variability measurements and instead uses variability as a discriminant between competing physical models.

Several physically distinct models were equally capable of fitting the selected spectrum of Mrk 335. The considered models included a partially covering patchy absorber, a warm thermal Comptonisation and gravitationally blurred reflection. These models have very distinct and unique underlying physical explanations. Despite this, they all provided statistically acceptable fitting of the *XMM-Newton* observation. This degeneracy where different physical processes generating very similar spectral shapes is a well-known limitation in AGN studies. As a consequence, the time-averaged spectrum by itself cannot determine which component was primarily responsible for the observed emission, motivating the usage of energy dependent variability as an additional factor.

The rms spectrum created for the source has a distinct, non-monotonous variability vs energy pattern. The variability amplitude decreases with energy at very soft X-ray range upto 0.7 keV and then increases towards higher energies.

Soft energies exhibited comparatively lower fractional variability, indicating that soft X-ray emission contains a relatively stable component. This stable component does not vary along with the rapidly changing hard continuum. At higher energies, the spectrum is most sensitive to intrinsic fluctuations of the coronal power law emission, resulting in relatively higher values for rms amplitudes. Another distinct feature is the noticeable dip in the 6–7 keV region which is coincident with the iron K complex emission lines. Such a dip can arise naturally when a narrow spectral feature is over imposed on the more variable continuum. This behaviour is common in AGNs, where the continuum dominates broadband variability and relatively steady emission or absorption components will dilute this variability creating reduced amplitudes at particular energies. The overall shape of the rms spectrum can provide key constraints for identifying the physical components that must be varied in order to recreate observed variability pattern.

This rms spectrum effectively distinguishes between competing physical models by identifying the parameters varying on the sampled timescale. Comparing the predicted rms spectrum of each model with observed pattern, we can obtain a more definite conclusion on the ability of each spectral model in representing the observed emission. For each spectral configuration, the fractional variability expected at each energy is computed as F_P , which gives a quantitative measure on how a small change in a chosen variable parameter (such as coronal normalization or temperature) can manifest as change in model flux across the spectrum. This predicted rms is then compared with the observed rms spectrum. Our analysis showed that none of the three spectral models could explain the observed pattern by variability of a single spectral parameter. Variation in at least two parameters is warranted in all cases. Both partial covering and warm Comptonisation models could explain the observation using the same set of parameters for variabilities at both the timescales, 3 ks & 6 ks. In the case of gravitationally blurred reflection model, the best fit was given by different parameter pair for the two cases, indicating that maybe more than two parameters are required for explaining the observed pattern. This, combined with the very steep emissivity profile and extreme values of the reflection parameter, allow us to disregard reflection model as a plausible explanation for the current observation of the source.

The analysis demonstrates the effectiveness of combining time-averaged spectroscopy with energy dependent variability modelling to probe the physical ori-

gin of AGN X-ray emission. Spectral fitting techniques alone will allow multiple models to reproduce the observed spectral shapes equally well. With the well-known degeneracy between partial covering, warm Comptonisation and blurred reflection scenarios, such methodology cannot uniquely identify the underlying geometry or physical processes. By incorporating the fractional rms spectrum into the modelling, this analysis uses variability as an additional tool that is directly sensitive to how different spectral components respond to changes in the primary continuum.

Through this combined analysis, the modelling of frms variability identify scenarios that can reproduce features of both spectral and temporal domains. The models that recreates spectral shape alone and not the energy dependent variability maybe then be disregarded. The methodology thus tells us that variability is not simply an observational feature but can be utilised as a powerful tool for model discrimination. In a broader sense, the study gives us a systematic methodology for breaking degeneracies in AGN X-ray spectral modelling. A strategy that can be applied to a wide range of similar sources where spectroscopic techniques alone remains insufficient.

Together, the studies presented in this thesis consider the different complementary aspects of AGN behaviour. The long term spectral investigation establishes that broadband X-ray continuum can evolve significantly across epochs without exhibiting simple correlations between slope and luminosity. It also tells us that the spectral shape often follows the continuum only on longer timescales rather than rapid flux changes. The variability-based modelling study demonstrates that different physical models, though degenerate in spectral domain, predict distinct energy dependent variability signatures. These findings show that AGN emission cannot be fully characterised either by long term trends or instantaneous features, alone. Rather a comprehensive physical picture requires both spectral and temporal information to be analysed jointly. The results obtained reinforce the idea that the AGN disk-corona system undergo geometrical and energetic variations on both gradual and rapid timescales and that separating these effects requires methodological frameworks that bring together multi-epoch and variability-based constrains.

The results obtained contribute towards a clearer picture of how AGNs vary across different timescales and why the X-ray spectra appears so complex. The

long term study shows that gradual changes in the continuum could possibly indicate evolving physical conditions of the corona or accretion flow, even in cases where there is no direct correlation with flux. The second study adds that different spectral models can reproduce similar time-averaged spectral shape, but their variability predictions can differ strongly. This demonstrates that using variability as an additional diagnostic is essential for identifying dominating the physical processes in different energy bands. Overall, the findings highlight that AGN studies require a joint spectral–timing approach to reveal how the disk-corona system and their surroundings interact to produce the observed high energy emission.

We also note some limitations of the current study. The long term analysis utilises data that was irregularly sampled across the years. This restricts its sensitivity to variations on intermediate timescales and can limit our ability to find finer correlations between the continuum and spectral shape. In the variability modelling analysis, the ability to discriminate between the multiple models depends on the accuracy of the rms spectrum and the parameter relations obtained from time-averaged spectral fitting. Moreover physical models considered are idealised - components such as scattering in complex absorbers or contributions from distant reflection can introduce additional variability not captured in our simplified methodology. Finally, both works focus on individual sources and though these methods can be generalised for similar AGN sources, the physical inferences must be tested on larger sample sets to evaluate their universality.

Overall, this thesis demonstrates that a multi-domain approach that combines long term spectral evolution along with variability-informed modelling, provides us with a powerful pathway towards understanding AGN X-ray emission. The results emphasise that no single dataset or technique is sufficient on its own. By establishing and applying such integrated methodologies, the thesis contributes towards a better physical understanding of the AGN disk-corona system and lays the foundation for future studies that utilises the advanced spectral resolutions and timing capabilities of current and upcoming X-ray observatories.

Chapter 6

Recommendations

The present studies have provided us with constraints on long term spectral evolution and short term variability of AGN emission. A future research will likely follow this up with a systematic spectral-timing methodology applied to multiple sources. Such studies on large source sample will allow us to have a general understanding of the geometry, size and physical conditions of the corona. Spectroscopic and temporal studies from upcoming missions such as *XRISM* and *New Athena*, will enable detailed studies of the physics of accretion disk and corona with resolution and sensitivity capabilities not yet achieved. These high resolution missions can reveal structural features, ionisation states and reflection signatures with unprecedented precision. Combining these spectral capabilities with variability resolved analyses such as flux-resolved, time-resolved and fractional rms studies can provide further constrain on how the disk and corona interact and identify components that are responsible for observed changes in emission across energy bands.

An important task for future research is to break degeneracies inherent in spectral modelling. Applying physically motivated models of coronal geometry, such as lamppost, patchy and radially extended configurations and fitting these models simultaneously to time-averaged and variability informed spectra, we can isolate the contributions from the primary continuum and reflection components. Extending this approach to larger samples of Seyfert galaxies and other accretion-powered systems will allow us to identify the trends and correlations between coronal and disk properties and fundamental parameters such as black hole mass, spin and Eddington ratio.

Simulation studies of future observations using *New Athena* and associated tools such as SIXTE represent another possibility. By generating realistic spectra,

lightcurves, rms spectra and lag-energy distributions, these simulations will allow us to assess how upcoming high sensitivity missions can resolve current modelling degeneracies. Such techniques will ensure that models developed using current data can directly be applied to future instruments, giving us predictive models of disk-corona physics having sensitivity and resolutions that was previously inaccessible. Collectively, these approaches can bridge the gap between present observational constraints and detailed physical understanding of the X-ray emission of AGNs, providing a strong framework for future studies in the field.

Appendix A

Analytical solution for fit parameters of predicted fractional variability

As mentioned in Section 4.5, the parameters δX^2 , δY^2 and C_{XY} in Eqn. 4.6 may also be determined analytically. For this we define the function χ^2 given by Eqn. 4.7. For the cases,

$$\frac{d\chi^2}{d\delta X^2} = 0 \quad \frac{d\chi^2}{d\delta Y^2} = 0 \quad \frac{d\chi^2}{dC_{XY}} = 0 \quad (\text{A.1a-c})$$

The set of equations given below will follow directly:

$$\begin{bmatrix} \sum_i \frac{A_i^4}{\sigma^2} & \sum_i \frac{A_i^2 B_i^2}{\sigma^2} & \sum_i \frac{A_i^3 B_i^2}{\sigma^2} \\ \sum_i \frac{A_i^2 B_i^2}{\sigma^2} & \sum_i \frac{B_i^4}{\sigma^2} & \sum_i \frac{A_i B_i^3}{\sigma^2} \\ \sum_i \frac{A_i^3 B_i}{\sigma^2} & \sum_i \frac{A_i B_i^3}{\sigma^2} & \sum_i \frac{A_i^2 B_i^2}{\sigma^2} \end{bmatrix} \begin{bmatrix} \delta X^2 \\ \delta Y^2 \\ C_{XY} \end{bmatrix} = \begin{bmatrix} \sum_i \frac{F_{0i}^2 A_i^2}{\sigma^2} \\ \sum_i \frac{F_{0i}^2 B_i^2}{\sigma^2} \\ \sum_i \frac{F_{0i}^2 A_i B_i}{\sigma^2} \end{bmatrix} \quad (\text{A.2a-c})$$

The equations A.2a-c may then be solved for δX , δY and C_{XY} respectively. If the term $\sum_{i=0}^n \frac{1}{\sigma^2} A_i^2 B_i^2$ was denoted as $A_i^2 B_i^2$ and so on, then these equations become:

$$\delta X^2 = \frac{[(F_{0i}^2 A_i^2)(B_i^4)(A_i^2 B_i^2) + (F_{0i}^2 A_i B_i)(A_i^2 B_i^2)(A_i B_i^3) + (F_{0i}^2 B_i^2)(A_i^3 B_i)(A_i B_i^3)] - [(F_{0i}^2 A_i^2)(A_i B_i^3)(A_i B_i^3) + (F_{0i}^2 B_i^2)(A_i^2 B_i^2)(A_i^2 B_i^2) + (F_{0i}^2 A_i B_i)(B_i^4)(A_i^3 B_i)]}{[(A_i^4)(B_i^4)(A_i^2 B_i^2) + (A_i^2 B_i^2)(A_i^3 B_i)(A_i B_i^3) + (A_i^3 B_i)(A_i^2 B_i^2)(A_i B_i^3)] - [(A_i^4)(A_i B_i^3)(A_i B_i^3) + (A_i^2 B_i^2)(A_i^2 B_i^2)(A_i^2 B_i^2) + (B_i^4)(A_i^3 B_i)(A_i^3 B_i)]} \quad (\text{A.3})$$

$$\delta Y^2 = \frac{[(F_{0i}^2 B_i^2)(A_i^4)(A_i^2 B_i^2) + (F_{0i}^2 A_i^2)(A_i B_i^3)(A_i^3 B_i) + (F_{0i}^2 A_i B_i)(A_i^3 B_i)(A_i^2 B_i^2)] - [(F_{0i}^2 A_i B_i)(A_i^4)(A_i B_i^3) + (F_{0i}^2 A_i^2)(A_i^2 B_i^2)(A_i^2 B_i^2) + (F_{0i}^2 B_i^2)(A_i^3 B_i)(A_i^3 B_i)]}{[(A_i^4)(B_i^4)(A_i^2 B_i^2) + (A_i^2 B_i^2)(A_i^3 B_i)(A_i B_i^3) + (A_i^3 B_i)(A_i^2 B_i^2)(A_i B_i^3)] - [(A_i^4)(A_i B_i^3)(A_i B_i^3) + (A_i^2 B_i^2)(A_i^2 B_i^2)(A_i^2 B_i^2) + (B_i^4)(A_i^3 B_i)(A_i^3 B_i)]} \quad (\text{A.4})$$

$$C_{XY} = \frac{[(F_{0i}^2 A_i B_i)(A_i^4 B_i^4) + (F_{0i}^2 B_i^2)(A_i^2 B_i^2)(A_i^3 B_i) + (F_{0i}^2 A_i^2)(A_i^2 B_i^2)(A_i^3 B_i)] - [(F_{0i}^2 B_i^2)(A_i^4)(A_i B_i^3) + (F_{0i}^2 A_i B_i)(A_i^2 B_i^2)(A_i^2 B_i^2) + (F_{0i}^2 A_i^2)(B_i^4)(A_i^3 B_i)]}{[(A_i^4)(B_i^4)(A_i^2 B_i^2) + (A_i^2 B_i^2)(A_i^3 B_i)(A_i B_i^3) + (A_i^3 B_i)(A_i^2 B_i^2)(A_i B_i^3)] - [(A_i^4)(A_i B_i^3)(A_i B_i^3) + (A_i^2 B_i^2)(A_i^2 B_i^2)(A_i^2 B_i^2) + (B_i^4)(A_i^3 B_i)(A_i^3 B_i)]} \quad (\text{A.5})$$

For the special case where only one spectral parameter was varied ($\Delta Y = 0$), the equations will reduce to:

$$\delta X^2 = \frac{F_{0i}^2 A_i^2}{A_i^4} \quad \delta Y^2 = 0 \quad C_{XY} = 0 \quad (\text{A.6a-c})$$

Substituting these values of δX^2 , δY^2 and C_{XY} in equation 4.6 will give the value for the predicted F_P .

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