

CORRELATION BETWEEN OPTICAL AND UV VARIABILITY OF A LARGE SAMPLE OF QUASARS



Selamawit Abebe Tesfahun

A Thesis Submitted to

The Department of Applied Physics

School of Applied Natural Science

Presented in Partial Fulfillment of the Requirement for the Degree of

Master's in Applied Physics (Astrophysics)

Office of Graduate Studies

Adama Science and Technology University

June, 2024

Adama, Ethiopia

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Declaration

I declare that this thesis proposal entitled “**Correlation between optical and UV variability of a large sample of quasars**” is my own work and has not been submitted to any university for similar purpose. The references used in this proposal are duly recognized by proper citations. .

Name of Student

Signature

Date

Recommendation of Advisors

we, the advisor(s) of this thesis, hereby certify that we have read the revised version of the thesis entitled “**Correlation between optical and UV variability of a large sample of quasars**” prepared under our guidance by Selamawit Abebe Tesfahun submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Applied Physics. Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Approval Page

we, the advisors of the thesis entitled “**Correlation between optical and UV variability of a large sample of quasars**” and developed by Selamawit Abebe Tesfahun, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Selamawit Abebe Tesfahun have read and evaluated the thesis entitled “**Correlation between optical and UV variability of a large sample of quasars**” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Applied Physics (Astrophysics).

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M.Sc. graduate thesis

Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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List of Acronym

AGN	Active Galactic Nuclei
BLR	Broad Line Region
CRTS	Catalin Real Time Transient
CXB	Cosmic X-ray Background
DRW	Damped Random Walk
GALEX	Galaxy Evolution Explore
HMQ	Half Million Quasars
NLR	Narrow Line Region
NUV	Near Ultraviolet
SMBH	Supermassive Blackhole
UV	Ultraviolet

Abstract

This study investigates the relationship between the optical and UV light from quasars and their redshift, revealing a strong positive linear correlation between the UV and optical band as indicated by a Pearson cross-correlation coefficient of 0.93988 and the correlation is ruled out 95% confidence level. However, this correlation is not perfect, suggesting other factors at play, such as changes in the rate of matter accumulation and echo-like phenomena in the accretion disc of a supermassive black hole. The study also explores the intricate relationship between the infrared, optical, and UV light emitted by quasars, finding that as the infrared luminosity of a quasar increases, there is a corresponding increase in UV emission and a decrease in optical emission. However, the relationship between infrared, optical, and UV light from quasars is complex and can be influenced by a variety of factors related to the black hole and its environment. The study also utilizes the structure function to analyze the variability in UV and optical measurements of quasars, rejecting the hypothesis that all quasars' inherent UV and optical fluctuations are entirely correlated. The density plot shows the distribution and concentration of optical and UV data over redshift, providing insights into the evolution of quasars over time.

Keywords: Quasar, Luminosity, Redshift, Optical/UV variability

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Quasars, brief phases of high accretion onto massive black holes at the centers of galaxies, are incredibly versatile astrophysical objects. Extensive efforts and focused searches have yielded large samples, enabling detailed exploration. They contribute significantly to understanding diverse fields such as mass clustering on various scales, molecular gas in distant galaxies, and estimates of cosmological parameters including the equation of state for dark energy. (K. B. Schmidt et al., 2011) The black hole is fed by a geometrically thin accretion disc, whose thermal emission is stratified radially, with higher energy radiation arising from the hotter inner regions.(Xin, Charisi, Haiman, & Schiminovich, 2020).

Active galactic nuclei (AGNs) exhibit varying emissions across all wavelengths explored so far. The time frames over which these emissions change range from hours to years, with shorter wavelengths displaying the quickest alterations. This behavior aligns with current models of AGN structure. According to these models, the ultraviolet (UV) and optical emissions arise from an accretion disk encircling a supermassive black hole (SMBH), while nonthermal X-ray emissions stem from a compact, inner hot plasma region (corona). The corona, being much smaller and denser compared to the accretion disk, allows for faster and more pronounced variability. Quasars exhibit noticeable changes in brightness across various wavelengths. These changes occur over time spans ranging from minutes to years and have been thoroughly investigated, particularly in optical frequencies. Surveys observing quasar behavior over time have yielded ample data on their light fluctuations. This variability follows a random pattern, resembling Gaussian fluctuations, and is well-characterized by the damped random walk (DRW) model, with its autocorrelation function.(Sánchez-Sáez et al., 2018).

We assume that (1) the optical/UV emission observed from AGN originates in an optically thick accretion disk. (2) Variations in the disk occur locally and are uncorrelated on large spatial scales. (3) Fluid in the disk is on circular Keplerian orbits. (Dexter & Agol, 2010). The



source of stochastic variability in quasars remains a puzzle, although several mechanisms are proposed. Fluctuations in accretion rate, instabilities within the accretion disk, and re-processing of X-ray emissions from a hot corona near the central supermassive black hole (SMBH) are all potential causes of variability across optical and UV wavelengths. These mechanisms often induce correlated variability between different bands, such as the well-established trend of 'bluer when brighter' in optical observations. These interband correlations offer valuable insights into physical models, especially considering that UV and optical emission regions are expected to be spatially distinct in radially stratified disks. However, recent studies suggest that variations in accretion rate alone may not entirely account for observed color changes, and localized temperature fluctuations within the disk might not be the primary driver of optical variability (Kokubo, 2015).

Previous studies investigating cross-correlations between UV and optical bands have been limited due to sparse UV data, often conducted on small datasets. For instance, (Edelson et al., 2019) utilized extensively monitored light curves from four active galactic nuclei (AGNs) captured by Swift observatory in optical, UV, and X-ray bands. Their findings revealed robust UV/optical cross-correlations, with time lags around a day, consistent with the expected scaling of $\tau \propto \lambda^{4/3}$ in a radially stratified and centrally illuminated thin disc.

This paper extends prior research by investigating UV versus optical cross-correlations across a substantial sample of quasars. Our aim is to determine if strong correlations are widespread across all quasars or if instances exist where optical and UV flux variations are either uncorrelated or only partially correlated. To achieve this, we assembled a dataset comprising over 800 quasars with sufficiently sampled and overlapping UV and optical time series, sourced from SDSS.

1.2 Statement of the Problem

Earlier researches on the correlation between optical and UV variability of quasars has made significant strides but encountered several limitations, including limited data, sparse sampling (infrequent observation might miss rapid or short lived variability events), redshift bias (research might have focused on nearby or specific redshift ranges potentially missing the impact of cosmological distance or variability). So, this research will try address these problems by extracting sample contains a broad population of quasars at various redshifts. The Sloan Digital Sky Survey (SDSS) can significantly contribute to overcoming the limita-



tions encountered in earlier research on the correlation between optical and UV variability of quasars. SDSS collects large and accurate data, obtaining high-resolution images of a quarter of the entire sky in five different colors. So the minimize the above problems the data has been collected from SDSS data release 16 having signal to noise ratio greater than 22. The study of quasar variability has been ongoing for several decades, but new studies are needed to improve our understanding of the physical processes that drive the variability. For example, recent work has shown that the intrinsic UV and optical variations of all quasars are not fully correlated, implying the existence of physical mechanisms that can generate uncorrelated optical and UV flux variations. Further studies can help us identify these mechanisms and improve our understanding of the complex physical processes that govern the behavior of quasars. To address this issue, this study aims to gain a deeper understanding of the physical phenomena underlying the distribution of optical and UV variability over the luminosity of infrared light. The goal is to uncover the mechanisms that drive these variations and how they relate to the infrared luminosity of quasars. The variability of quasars across multiple wavelengths is a useful probe of physical conditions in active galactic nuclei. In particular, variable accretion rates, instabilities, and reverberation effects in the accretion disk of a supermassive black hole (SMBH) are expected to produce correlated flux variations in UV and optical bands (Xin et al., 2020).

1.3 Objectives

1.3.1 General Objective

The general objective of this study is to investigate correlation between optical and uv variability of a large sample of quasars.

1.3.2 Specific Objectives

The specific objective of this study are:

- To investigate correlation between optical and uv variability using a structure function model
- To investigate optical and UV variability of quasars correlation with luminosity
- To investigate UV optical variability correlation with Redshift



1.4 Significance of the Study

The study of correlation between optical and UV variability of a large sample of quasars is significant because it can help us understand the physical processes that drive the variability of quasars, which are among the most luminous and energetic objects in the universe (Xin et al., 2020). Quasars are powered by accretion of gas onto supermassive black holes, and their variability is thought to reflect changes in the accretion rate, the structure and stability of the accretion disk, and the effects of reprocessing and reverberation of radiation from different regions of the disk. By comparing the variability patterns in optical and uv wavelengths, we can probe the size, temperature, and geometry of the disk, as well as the possible presence of binary black holes in some quasars. However, the nature of quasar variability is still not fully understood, and different models can make different predictions about the correlation between optical and UV variations. so this study can be important to have a scientific insight about the variability of optical and uv fluxes correlated to luminosity and Another important thing is that, this research is also serve as a reference for other researches.

CHAPTER 2

LITERATURE REVIEW

2.1 Explanation of quasars and AGNs

Active Galactic Nuclei (AGN) are among the most powerful phenomena in the Universe. Decades of observations and studies have significantly advanced our understanding of these objects. AGN are characterized by having a supermassive black hole (SMBH) at their center, with masses greater than 10^6 solar masses, that accretes matter and emits energy across the entire electromagnetic spectrum, from radio waves to gamma-rays. The process of accretion, where gravitational energy is extracted from matter falling into the black hole, is the most efficient known method of converting mass into energy (Haardt, Maraschi, & Ghisellini, 1997).

The matter being accreted orbits the black hole and, due to its angular momentum, forms a disc as energy dissipates. Magnetic viscosity within this disc transfers angular momentum outward and mass inward, creating the central engine of an AGN alongside the black hole. Regardless of whether the accretion rate is high or low, the gravitational energy released in this process is primarily emitted as thermal radiation from the disc's surface, peaking in the optical/UV bands. Many of these optical/UV photons are then reprocessed: some by dust located beyond the sublimation radius and re-emitted in the infrared (IR) band, and others by a corona of hot electrons near the accretion disc that up-scatters them via inverse Compton scattering into the soft/hard X-ray bands, where AGN emit a significant portion of their luminosity.(Harrison, 1993). In the nucleus of an Active Galactic Nucleus (AGN), the disc and corona are merely the inner components. Evidence of a complex environment surrounding this area is the significant amount of radiation that can be absorbed by nearby interstellar gas and dust, which is likely to be re-emitted at different wavelengths. The traditional AGN model includes a high-velocity gas region, known as the Broad Line Region (BLR), surrounding the accretion disc and the hot corona on a scale of 0.01–0.1 parsecs(MacDonald & Mullan, 2017). This BLR, with gas speeds ranging from 1000 – 5000 km/s, is responsible for the broad emission lines in the optical spectra and can lead to ionized absorption,



creating distinctive features in the UV and soft X-ray bands, often referred to as the warm absorbed. Regardless of whether we view the torus as dusty-compact or dusty-cloudy, it is the primary structure responsible for absorbing the primary continuum. It can be so dense that it completely obscures the primary emission up to several kiloelectronvolts (keV). Beyond distances of 100 parsecs (pc) and up to kiloparsec (kpc) scales, there is a biconical and highly structured region of slower-moving gas (< 900 km/s), known as the Narrow Line Region (NLR). Radiation passing through this region results in permitted, intercombination, and forbidden narrow lines in the optical-UV band. Lastly, the interaction between the supermassive black hole's rotating magnetic field and the accretion disc can generate powerful magnetic jets. These jets can eject material perpendicular to the disc at relativistic speeds, extending hundreds to thousands of parsecs. (Tammour, Gallagher, & Richards, 2015). Over the years, various factors have contributed to our understanding of the diverse classes of Active Galactic Nuclei (AGN) across all wavebands. This led to the proposal of the Unified Theory of AGN. In its most basic form, this theory suggests that the diversity of AGN can be largely attributed to the viewing angle, although the accretion rate and efficiency also play a significant role. A key component of this orientation-based model is the absorbing material, primarily the optically and geometrically thick torus. This torus obscures the nuclear regions of an active galaxy, which includes the accretion disc, the hot corona, and the Broad Line Region (BLR). Depending on whether our line-of-sight intercepts this obscuring material or not, we classify an AGN as either type 2 or type 1. Additionally, an AGN is classified as radio loud or radio quiet based on whether its radio frequency emission is strong or weak. Within the category of radio-loud AGN, variations in types (such as BL Lac objects, Flat Spectrum Radio Quasars, and Radio Galaxies) have been attributed to differences in orientation. This means that a specific type is referred to when the jet axis is either perfectly aligned with or increasingly misaligned from the observer's line of sight.

What becomes evident from this complex structure of AGN is the crucial role of absorption in understanding the physics of these objects. Consequently, the hard X-ray band is particularly suitable for studying the AGN population. This is because it is almost unbiased against obscuration, making it free from the constraints that impact surveys at other frequencies, ranging from optical to soft X-rays. Moreover, the hard X-ray band provides a significant opportunity for spectral studies of AGN (Tatum, Turner, Miller, & Reeves, 2013).



2.2 Quasar variability

Quasars are crucial for studying and understanding the physics of matter accretion under extreme conditions. To date, several hundred thousand quasars have been confirmed through spectroscopy, and numerous efforts have been made to identify the traits of their temporal flux variability. However, the physical mechanisms driving this variability are not well understood, partly due to the challenge of quantifying its aperiodic nature. In the optical/UV range, only the variability amplitude and its relationship with timescale have been proposed to be connected to inherent physical parameters (Sartori et al., 2019).

Several physical mechanisms have been suggested to explain the optical and UV variability in quasars. These include the superposition of supernovae microlensing, thermal fluctuations from magnetic field turbulence, and instabilities in the accretion disk. Recently, significant efforts have been made to uncover the hidden physical processes that cause extremely large flux variations in quasars. Proposed explanations for such extreme temporal variabilities include tidal disruption events, high-amplitude microlensing, significant changes in obscuration or accretion rate, and supernovae. However, it's still uncertain how or if these factors relate to the more typical optical variability observed in quasars (Ross et al., 2018). To characterize the variability of quasar optics, a continuous time first-order autoregressive model was proposed. This model is also known as the Ornstein Uhlenbeck process or damped random walk (DRW) process.

Several researchers have demonstrated that the DRW process offers a superior statistical model for most quasar variability compared to a variety of other stochastic deterministic models. However, it has been pointed out that the best fit DRW processes are biased in τ due to an insufficient temporal baseline in existing surveys for probing the white noise portion of the power spectral density (PSD).

Therefore, any correlations reported between these model parameters and physical parameters, such as black hole mass or Eddington ratio, could potentially be analysis artifacts. Moreover, deviations from a DRW process in quasar variability have started to be acknowledged. For instance, Kepler light curves with approximately 30 minute sampling have revealed a steeper power-law index of about 3 at very high frequency (Kozłowski, 2017). To check the characteristics of the quasars, we calculated the variance of the light curves and the optical luminosities, where the intrinsic variance is referred to as the variance in this paper,



and is described by

$$\sigma_{\text{mag}}^2 = \frac{1}{N-1} \sum_{i=1}^N (\text{mag}_i - \overline{\text{mag}})^2 - \frac{1}{N^2} \sum_{i=1}^N e_i^2 \quad (2.1)$$

where N is the number of data points, mag and e is the observed magnitude and its uncertainty, respectively.

The optical luminosity (L_{opt}) can be approximately calculated by

$$L_{\text{opt}} = 4\pi D^2 F_{\text{opt}} \times 10^{(m_{\text{std}} - m_{\text{obs}})/2.5} \text{ erg s}^{-1}, \quad (2.2)$$

L_{opt} : Optical luminosity

F_{opt} : Observed optical flux

m_{std} : Standard optical magnitude

m_{obs} : Observed optical magnitude

where D_L is the luminosity distance calculated with $\Omega_\Lambda = 0.728$, $\Omega_M = 0.272$, and $H = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $F_0 = 3.968 \times 10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ is the zero-point flux density, and $\lambda_{\text{eff}} = 5237.44 \text{ \AA}$ is the effective wavelength (Tachibana et al., 2020).

$$D_L = \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

D_L : Luminosity distance

C : Speed of light ($3 \times 10^8 \text{ m/s}$)

H_0 : Hubble constant (current expansion rate)

z : Redshift (cosmic expansion)

Ω_m : Density parameter for dark matter

Ω_Λ : Density parameter for dark energy

2.3 Techniques for Finding Quasars and AGNs

Quasars were originally detected through their optical emissions of radio waves, a technique that was both practical and successful due to the relatively faint radio emissions from ordinary stars and galaxies. However, it was soon found out that most quasars did not emit radio waves and could be distinguished by their surplus ultraviolet (UVX) radiation compared



to regular stars. The UVX method is recognized as an effective way to identify quasars with redshifts up to about 2.2. Beyond this limit, the *Lyalph* emission moves into the observed B band, causing quasars to lose their unique UV excess. It's also now known that only about 10% of the quasars and AGNs in the early samples were potent radio emitters, also referred to as radio-loud objects (Sandage, Véron, & Wyndham, 1965). For detecting quasars at higher redshifts, alternative methods are required. This task becomes challenging due to two reasons: (1) around redshifts of 3, the optical/UV SEDs of quasars become difficult to differentiate from stars, and (2) the spatial density of quasars at z greater than 3 decreases swiftly with an increase in redshift. The slitless-spectrum technique, which was pioneered and developed, offered a color-independent approach to detect high-redshift quasars by directly identifying their strong, broad emission lines, especially *Lyalph*, on low-dispersion objective-prism photographs. This technique was later implemented on large telescopes using a transmission grating prism combination (grism) as the dispersion device. However, it was also acknowledged that the slitless-spectrum technique had a significant selection bias as it favored the detection of quasars with strong emission lines. An important breakthrough in this issue was made by using a digital detector with a grism at the Hale 5-m telescope and by creating and implementing a numerical selection algorithm to identify emission-line objects. The properties and efficiencies of these objects could be quantified, and the effectiveness of this approach is well demonstrated by the grism spectra for a variety of high-redshift quasars from their survey.

The introduction of fast plate-scanning machines like COSMOS and APM allowed the extension of color-based techniques for discovering quasars to higher redshifts. The first quasar with $z = 4$ was found using this method. These machines and multi-color techniques enabled the use of more complex color combinations to distinguish quasars from stars and to provide quantitative estimates of the selection efficiency as a function of redshift and apparent magnitude, which were essential for determining the luminosity function.

Later, the Sloan Digital Sky Survey combined the multicolor technique with a dedicated survey telescope and the largest digital camera built until that time to pioneer a new frontier in extragalactic research by conducting a digital survey of 10,000 square degrees in five filters (York et al., 2000).



2.3.1 Radio and X-Ray Techniques

Quasars and Active Galactic Nuclei (AGNs) are most easily discovered and identified using radio and X-ray techniques. This is because typical stars and galaxies emit weakly at these wavelengths. To detect these compact sources, one needs high sensitivity and positional accuracy of approximately one arcsecond in the sky. Radio and/or X-ray catalogued objects are matched with optical catalogs for identification. Follow-up optical spectra from a large telescope are used to confirm the identification and determine the object's redshift. Radio and hard X-ray sources have the significant advantage of being unaffected by dust obscuration that may be present along the AGN line of sight. If spectral data is available at the 1 keV range, it can be used to estimate the column density of any absorbing gas along the line of sight. In the past, radio surveys were limited because only about 10% of AGNs are radio loud, meaning radio surveys only included a small portion of the total population. However, the introduction of deep, wide-area surveys like FIRST (Baker, Hunstead, & Brinkmann, 1995) has opened up new possibilities. FIRST, with its milli-Jansky flux limits, has the sensitivity to detect radio-quiet quasars.

The use of multi-color imaging data from the SDSS has led to the discovery of new AGN classes, such as reddened broad absorption-line quasars that are radio sources, and has shed new light on the issue of dust obscuration. The combination of data from FIRST and SDSS has solved a problem that plagued earlier radio surveys: the challenge of effectively pre-selecting redshift for candidate objects. Previously, extensive follow-up spectroscopy was required to find high-redshift or rare quasars and AGNs. Now, multicolor SDSS data can be used to pre-sort candidates into the desired groups for follow-up. X-ray data has been crucial in quasar and AGN studies since the first X-ray detections, as it was understood that the emission likely came from near the central black hole. Indeed, X-ray emission could be considered the defining characteristic of AGNs (e.g., Elvis et al. 1978). However, this was somewhat irrelevant at the time due to the low sensitivity of the original X-ray observatories. Now, following work with ROSAT and initial results from Chandra and XMM-Newton, the situation has changed: the deepest X-ray surveys are identifying objects not previously noted in optical surveys (Cooke et al., 1978).

2.3.2 Recent Large Optical Surveys

The study of quasar evolution was a significant driving force behind two large-scale surveys, the 2dF survey (Boyle et al., 2000) and the SDSS (York et al., 2000). The 2dF aimed to cover 750 square degrees of sky to a brightness of $B < 21$ mag and discover more than 25,000 quasars with a redshift of $z < 2.3$ using the UVX technique. The SDSS aimed to survey 10,000 square degrees of sky in five colors (u' , g' , r' , i' , z') to find 100,000 quasars covering all redshifts up to 5.8 (Boyle et al., 2000) estimated the luminosity function from the first 6,684 quasars in the 2dF quasar survey, which was primarily based on the UVX technique using u , bJ , r UK Schmidt plates. They estimated the survey to be 90% complete for $z < 2$. Their final sample included 5,057 objects from 196 square degrees of sky with $MB < -23$ mag, $18.25 < bJ < 20.85$, and $0.35 < z < 2.3$. They combined their sample with 867 objects from the LBQS (Hewett, Foltz, & Chaffee 1995) and fitted a two-power law form to the luminosity function data.

They found that a polynomial evolution of $B(z)$ fits the data well. Their main conclusion is that for 2dF+LBQS, $-26 < MB < -23$ mag ($q_0 = 0.5$) and $0.35 < z < 2.3$, pure luminosity evolution works well, with the characteristic luminosity of quasars increasing by a factor of 40 at the peak of activity. However, the EQS (Edinburgh Quasar Survey, Miller et al., unpublished) and HEQS (Hamburg/ESO Quasar Survey, (Wisotzki et al., 2000)) do not fit as well, particularly for $z < 0.5$, where the LBQS has few or no data. On the left, the space

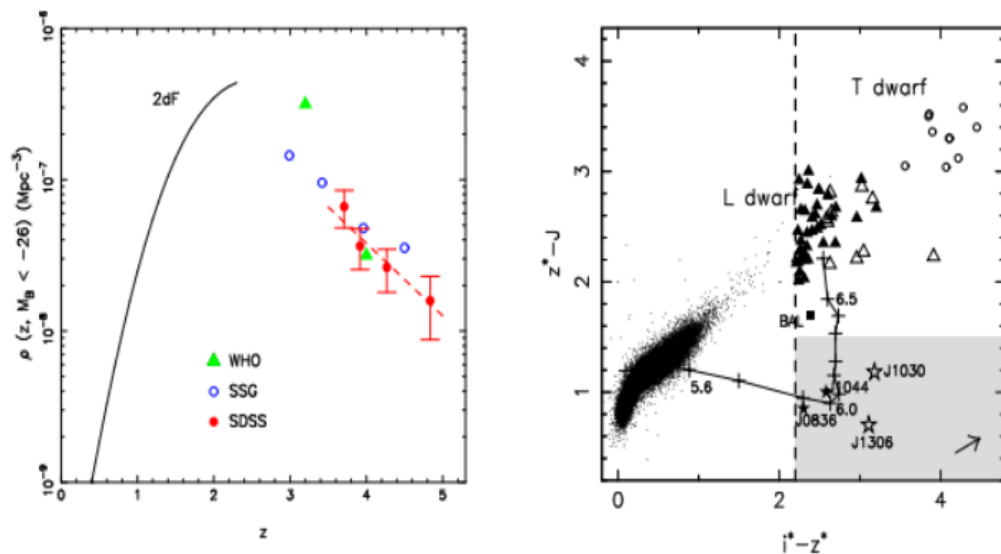


Figure 2.1: Space density of quasars as a function of redshift



density of quasars with a magnitude less than -26 as a function of redshift is shown for the 2dF, SDSS, SSG, and WHO surveys (Fan et al. 2001b). On the right, the z -J versus z diagram for the SDSS demonstrates how the infrared J band allows for the differentiation of quasars with $z > 5.8$ from the abundant L and T dwarfs. The SDSS has been instrumental in the search for high-redshift quasars due to its extensive sky coverage and the use of the z filter with an effective wavelength of approximately $9100\text{\AA}$, which expanded the discovery space in redshift to $z = 5$ and beyond.

Fan et al. (1999) showed how the r , i , z filters were utilized to discover the first quasars with $z \approx 5$ by their distinct separation from the stellar locus. Fan et al. (2001a, b) subsequently used this technique to compile a well-defined, color-selected sample of 39 quasars with $3.6 < z < 5.0$ and $i \leq 20$ mag in 182 square degrees of sky. They estimated the luminosity function for objects with $27.5 < M_{1450} < -25.5$ and its evolution with redshift.

Their results, which agree within the errors at $z \approx 4$ with the previous results of WHO, SSG, and KDC, indicate a decline in space density of a factor of 3 per unit redshift for $z > 3.6$. They find a flatter slope for the luminosity function at $z \approx 4$ compared to earlier surveys for $z < 3$. These results confirm that pure luminosity evolution does not match the data between redshifts 2 and 5.

Fan et al. (2001c) then extended their work to discover four quasars with $z > 5.8$ by using observations in the infrared J band to help eliminate nearby and numerous L and T dwarf stars. They showed that the space density at $z = 6$ is about a factor of 2 below that at $z = 5$ and follows the decline with redshift just described. These objects provide the strongest evidence yet for a detection of the Gunn-Peterson absorption and thus evidence for reionization at redshifts in the vicinity of $z \approx 6$.

In summary, the 2dF and SDSS results now cover the range $0.3 < z < 6.3$ for high luminosity, optically selected quasars and reach close to the epoch of reionization. They provide the most comprehensive data on the evolution of such quasars that exist to date (Fan et al., 2001).

CHAPTER 3

METHODOLOGY OF THE STUDY

3.1 SAMPLE SELECTION

In order to study the observed-frame correlation between UV and optical variability in a large sample of quasars, UV and optical light curves are extracted from SDSS.

The Sloan Digital Sky Survey (SDSS) has a long history of creating and releasing catalogs of quasars for use in cosmology and studies of quasar physics. The 16th data release of the SDSS Quasar Catalogue (SDSS DR16Q) was released in 2020, and for quasar candidates it provides their information containing right ascension (RA), declination (Dec.) and spec-z. Because of the rigorous visual inspection with the advanced classification and redshift. determination pipeline, data from SDSS DR16Q contain fewer errors compared with the original Data Release 16 of SDSS. The catalogue of SDSS DR16Q contains 750 414 quasars, including 225 082 newly added ones. (Yao et al., 2023) As DR16Q represents the final SDSS-IV quasar catalog, it contains all quasars observed as part of eBOSS, TDSS, and SPIDERS. Additionally, like the catalog of (Pâris et al., 2018) , henceforth DR14Q), quasars observed in SDSS-I/II, and SDSS-III/BOSS have been included. Quasars presented in (Schneider et al., 2010), henceforth DR7Q) and (Pâris et al., 2017), henceforth DR12Q) that did not have an eBOSS observation were added via coordinate matching. Due to quasar identification errors, quasars in DR14Q without a match in DR16Q were not included in DR16Q. The python code for generating DR16Q is available publicly.

In this study optical and uv light curves in "r" band and "u" band respectively are extracted from SDSS data release 16 quasar catalogue using SQL query. The query is designed to select and filter data about quasars (QSOs) that meet certain criteria, such as a specific range of redshift (between 0.4 and 0.8) due to the scarcity of high-redshift samples in SDSS DR16Q. (Yao et al., 2023)At redshifts between 0.4 and 0.8, quasars are typically bright enough in the optical and UV bands to be observed with good signal quality. This ensures that their light curves are well-sampled and reliable for analysis. And consider high

Superset Numbers	
Observations from SDSS-I/II	73,325
Observations from SDSS-III/IV	1,367,290
Total observations in Superset	1,440,615
Quasar observations in Superset	920,110
Duplicate quasar observations in DR16Q	199,904
Quasar-only Numbers	
Quasars with automated redshift only	341,622
Quasars with a visual inspection redshift	408,792
Total DR16Q quasars	750,414

Figure 3.1: The number of observations and objects appearing in both the DR16Q superset and the DR16Q quasar-only catalog (Lyke et al., 2020).

signal-to-noise ratio(greater than 22. high SNR reduces the relative uncertainty in each measurement. This means that the data points on light curves are more reliable, enabling better modeling of quasar behavior over time.(Osłowski, van Straten, Hobbs, Bailes, & Demorest, 2011) By joining multiple tables, it consolidates various types of related information about each quasar, including their positions, photometric measurements, spectral fluxes, and classifications out each quasar, including their positions, photometric measurements, spectral fluxes, and classifications.

3.2 Data analysis

3.2.1 Observed data

In order to characterize the correlations between optical and UV variability in the sample as a whole, first quantify the pearson cross correlation coefficient for the 860 sources. Pearson's, also known as the Pearson Product-Moment Correlation Coefficient (PPMCC) or bivariate correlation, is a measure of the linear correlation between two variables X and Y.(Weisstein, 2006).

The Pearson's correlation coefficient ($r_{u,v}$) between two variables uv and optical respectively are calculated using the following formula:



$$r_{u,r} = \frac{\sum_{i=1}^n (u_i - \bar{u})(r_i - \bar{r})}{\sqrt{\sum_{i=1}^n (u_i - \bar{u})^2 \sum_{i=1}^n (r_i - \bar{r})^2}} \quad (3.1)$$

Since the simple hypothesis is that the intrinsic UV and optical variations of all quasars are fully correlated, 95% confidence is ruled out.

- Calculate the sample mean (flux) ($\bar{x}$): Add up all the numbers and then divide by the number of samples (860).
- Calculate the standard deviation (s): The standard deviation is a measure of how spread out the numbers in the data are.
- Find the standard error (SE): The standard error of the mean is the standard deviation divided by the square root of the sample size (n). It's the standard deviation of the sampling distribution of the mean.

$$SE = \frac{s}{\sqrt{n}} \quad (3.2)$$

- Find the margin of error (E): The margin of error for a confidence interval is the amount that you add and subtract from the sample mean to obtain the confidence interval. For a 95% confidence interval, the z-score is approximately 1.96.

$$E = z \times SE = 1.96 \times SE \quad (3.3)$$

- Calculate the confidence interval: The confidence interval is the range in which you expect the population mean to fall based on your sample mean. It's calculated as:

$$CI = \bar{x} \pm E \quad (3.4)$$

3.2.2 Calculation and Software used

Software used

In the field of astrophysics, studying the correlation between optical and UV variability in celestial objects such as quasars using a software is common. This study involves the use of



several Python libraries, each with its unique role. Pandas and NumPy are used for data manipulation and numerical computations respectively (W. Schmidt & Völschow, 2021). They allow efficient handling of large datasets and perform complex mathematical operations. Matplotlib.pyplot and Seaborn are visualization libraries used to plot the data, enabling a graphical understanding of the variability and correlations. The Astropy library, specifically designed for astronomy, is used for its powerful tools for astronomical data analysis (Greenfield et al., 2013). Scipy.stats provides statistical functions to perform tests, fit data, and more, which is crucial in studying correlations. The sklearn.mixture and Gaussian Mixture models are used for clustering data and fitting multiple Gaussian distributions, which can be useful in identifying different groups or patterns in the variability data. These libraries collectively provide a comprehensive toolkit for analyzing and understanding the intricate patterns of optical and UV variability in quasars

Calculations done by listed software's

The structure function is a statistical tool used in time series analysis, particularly in astronomy, to study the variability and correlations in data . A structure function evaluates how power is distributed across timescales where variations are correlated, and it is theoretically equivalent to power-spectrum analysis. The structure function method has a key advantage of analyzing time series data in the time domain. This approach helps reduce windowing and aliasing issues, which are exacerbated by irregularly sampled astronomical data and commonly affect Fourier-based power-spectrum analysis. (Collier & Peterson, 2001)

The structure function for time series is defined and calculated as:-

$$V(\tau) = \frac{1}{N(\tau)} \sum_{i=1}^{N(\tau)} [y(t_i + \tau) - y(t_i)]^2 \quad (3.5)$$

- $V(\tau)$ This is the structure function at a given time. It's a measure of the variability in a time series.
- τ This is the time lag, which is the amount of time between two measurements in the time series.
- $N(\tau)$ This is the number of pairs of points $y(t_i)$ and $y(t_i + \tau)$ in the time series. The pairs are chosen such that the time difference between the two points in each pair is approximately equal to τ .



- $y(t_i)$ and $y(t_i + \tau)$ These are the measurements in the time series.

In order to study optical and uv variability of quasars correlated with luminosity, luminosity of infrared light curves are calculated. Observations have shown that the UV/optical variation amplitude of quasars depends on several physical parameters including luminosity (Kang et al., 2018). The luminosity of quasars is calculated from its flux and luminosity distance by following (Tachibana et al., 2020) steps as mentioned in section two:-

$$L = 4\pi D_L^2 F \quad (3.6)$$

- L represents the **luminosity** of the astronomical object. Luminosity is the total amount of energy emitted by an object per unit time. It is measured in erg/s.
- $|D_L|$ represents the luminosity distance to the object. Luminosity distance is a measure of distance to astronomical objects which takes into account the expansion of the universe. It is measured in centimeters (cm).
- $|F|$ represents the **flux** of the object. Flux is the amount of energy that passes through a unit area per unit time. It is measured in erg/s/cm².

The luminosity distance (DL) is calculated from the redshift (z) of the quasars. In a cosmological context, the luminosity distance is related to the redshift (z) of the light from the object. In a universe with a cosmological constant (Λ) and matter density (Ω_M), the luminosity distance can be calculated from the redshift using the following relation

$$D_L = (1+z) \int_0^z \frac{dz'}{H(z')} \quad (3.7)$$

- $H(z)$ is the Hubble parameter as a function of redshift which depends on (Ω_M) , (Ω_Λ) .
- z is the Redshift.

In order to study variability between optical and uv variability correlated with redshift Variability is calculated as the standard deviation of the magnitudes. And the distribution of optical and uv variability along with redshift is plotted using a python library. Model the variability in the optical and UV flux as a function of redshift. This is where the infinite Gaussian model comes in. In this context, an infinite Gaussian model might refer to a Gaussian process, which is a powerful tool for modeling variability in time series data (Guo &



Gu, 2014). A Gaussian process is a collection of random variables, any finite number of which have a joint Gaussian distribution. It's defined by a mean function and a covariance function. In Python, you can use the GPy or sklearn.gaussian_process libraries to create a Gaussian process model (Xin et al., 2020).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Cross Correlation Coefficient

In this study Pearson cross correlation coefficient is calculated, which is equal to 0.93988. The Pearson cross-correlation coefficient is a measure of the linear correlation between two variables. In the studying of variability of quasars in the UV and optical bands, it used to quantify the relationship between the variability in these two bands.

A Pearson cross-correlation coefficient (0.93988) which is found in this study is very close to 1, which indicates a strong positive linear correlation between magnitude light curves of the UV and optical bands. When the flux in the UV band increases, the flux in the optical band also tends to increase, and vice versa. But not a perfect one. There is some variability in the data that is not explained by the linear relationship. Specifically, changes in the rate of matter accumulation, fluctuations, and echo-like phenomena in the accretion disc of a supermassive black hole are anticipated to cause linked changes in the intensity of ultraviolet (UV) and optical bands (Xin et al., 2020). Figure 4.1 shows the scatter plot which shows the relationship between psfMag_u and psfMag_r which are presumably magnitudes measured in different filters (u and r) for QSOs.

From the plot, it's clear that there's a strong positive correlation between psfMag_u and psfMag_r. This is indicated by the upward trend from the bottom left to the top right. In other words, as the value of psfMag_u increases, so does the value of psfMag_r. The regression line in the plot also supports this observation. The line is an estimate of the relationship between the two variables, and it's clear from the plot that the line is ascending and the density of points is higher along the line, showing a strong positive correlation between these two variables. That means measurements are closely related for most of the quasars.

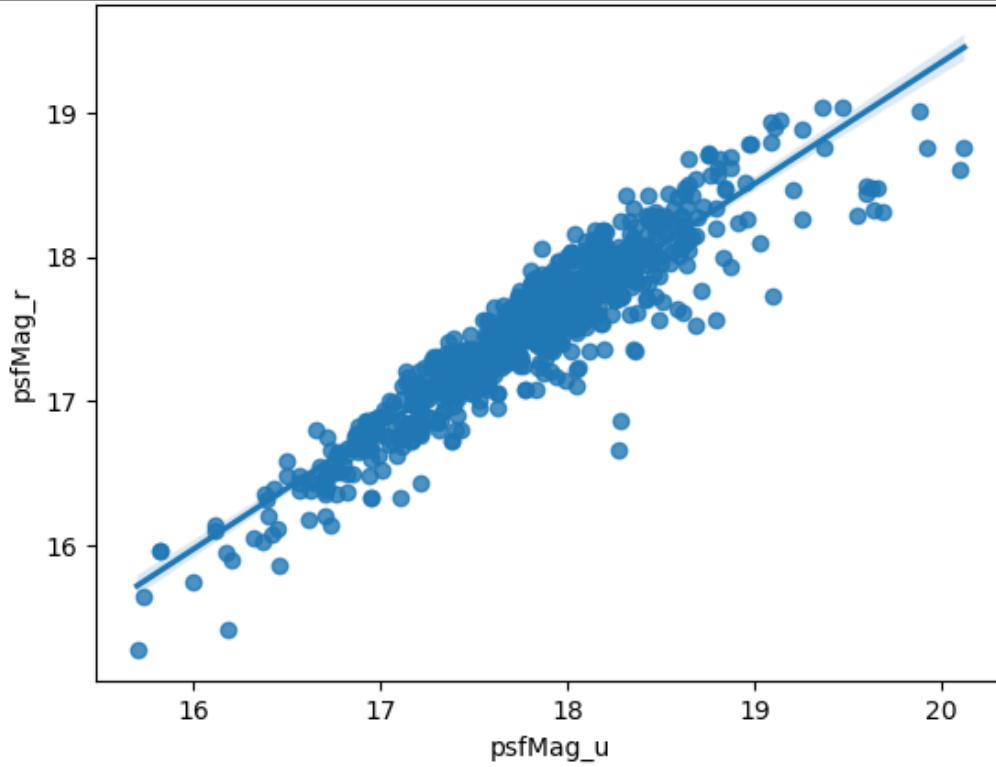


Figure 4.1: Scatter plot of uv and optical magnitudes (psfmag in in erg/s/cm^2).

4.2 Estimation of correlation between optical and uv variability using structure function

The structure function is a measure of variability as mentioned in section three. The structure function is a valuable tool for studying the correlation between UV and optical variability in quasars, helping to probe physical conditions, understand accretion disc dynamics, identify correlated variations, test hypotheses about variability (Kang et al., 2018). Figure 4.2 shows the distribution of structure function values for the optical and UV measurements. The peaks of the distributions represent the most common structure function values for UV and optical variability. The peak of the optical distribution appears to be at a lower structure function value than the UV distribution. This suggests that the most common structure function values are lower for optical variability compared to UV variability, which means UV measurements might be more variable than the optical measurements. The spread of the distributions (i.e., their width) gives you an idea of the variability in structure function values. The optical distribution appears to have a wider spread than the UV distribution, suggesting more variability in optical measurements compared to UV measurements among quasars.

The area where the two distributions (histograms) overlap represents structure function values that are common to both UV and optical variability. This indicates the optical and UV variability's are correlated. In our expanded sample, we observe significant correlations.

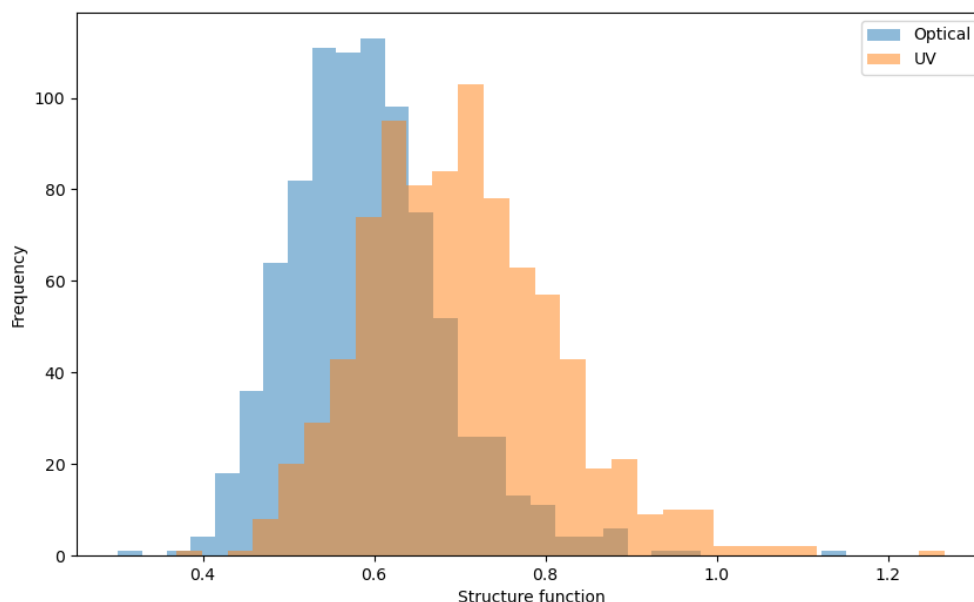


Figure 4.2: Distribution of structure function values for the optical and UV measurements

However, with about 95% confidence, we dismiss the straightforward assumption that all quasars' inherent UV and optical fluctuations are entirely linked.

4.3 Investigation of optical and uv variability correlated with luminosity

Fluctuations in the accretion rates, instabilities, luminosity and echo effects within the accretion disc of a supermassive black hole are anticipated to result in linked changes in flux in the ultra-violet and optical bands (Xin et al., 2020). In this study the luminosity is calculated from infrared flux, because the infrared radiation is associated with dust that is heated by the quasar's radiation and this heat is responsible for the emission of radiation across a broad spectrum, including the infrared range (Yu. Sazonov, Ostriker, & Sunyaev, 2004). The temperature of an object determines the amount of infrared radiation it emits. The concept that the temperature of an object determines the amount of infrared radiation it emits is rooted in the principles of thermal radiation and blackbody radiation. The inner and outer parts of an accretion disk emit radiation in different parts of the electromagnetic spectrum due to their varying temperatures and physical conditions. The outer, cooler parts of the

disk emit more in the optical and infrared (IR) wavelengths, while the inner, hotter parts emit primarily in the UV and X-ray wavelengths (Narzilloev & Ahmedov, 2022). Studying the infrared (IR) light emitted by quasars can provide valuable insights into the physical conditions and processes occurring in the outer parts of the accretion disk. In this paper, luminosity is calculated from infrared flux (psfFlux_i). And luminosity distance is calculated from redshift and Hubble constant. From luminosity distance, luminosity is calculated.

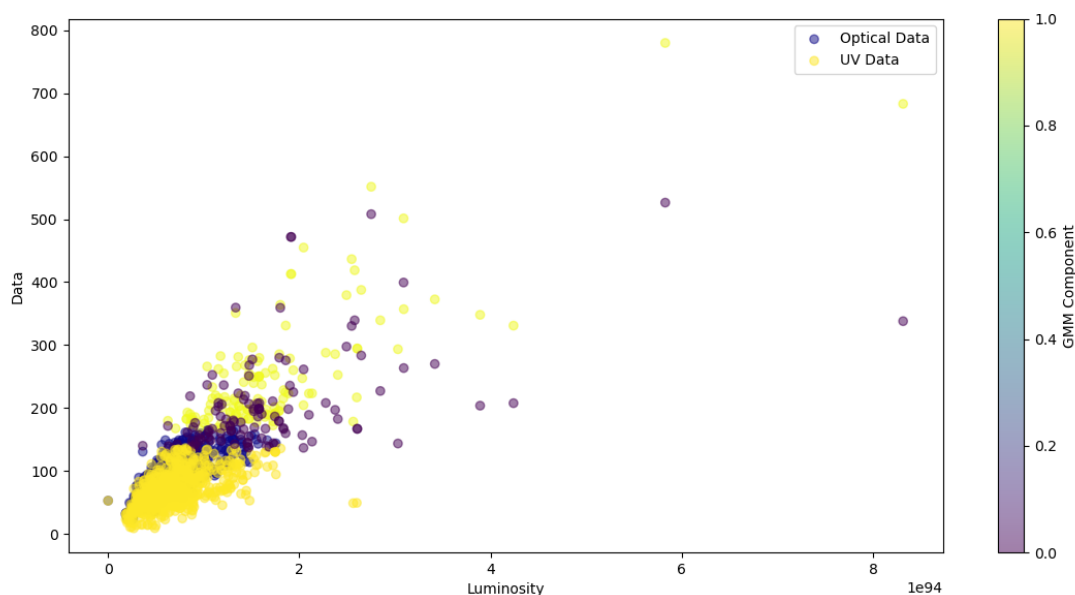


Figure 4.3: Distribution of optical and uv observations over infrared luminosity (luminosity in in erg/s)

Figure 4.3 shows a scatter plot of the distribution of optical and uv observation over infrared luminosity. The color bar on the right indicates the correlation coefficient, with purple representing lower correlation and yellow representing higher correlation. From the plot, it appears that most data points are concentrated in a small area where the values on the y-axis (which represents the optical and UV data) range approximately from 0 to 100, and the luminosity values on the x-axis range from around 0 to 1.5×10^{34} . This is indicated by the blue to yellow colors suggesting a higher correlation in that region. This suggests that for most quasars in the dataset, both the optical and UV observations tend to have lower values at lower luminosities. As the luminosity increases, the correlation between optical and UV observations decreases, as indicated by the purple color.

To show most data points are concentrated in a small area a 2D histogram is used. In Figure 4.4 the color bar on the right indicates the count of occurrences, with purple representing lower counts and yellow representing higher counts. The green to yellow colors suggesting a

higher count in that region. This suggests that for most quasars in your dataset, both the optical and UV observations tend to have lower values at lower luminosities. As the luminosity increases, the frequency of quasars with higher optical and UV observations decreases, as indicated by the purple color.

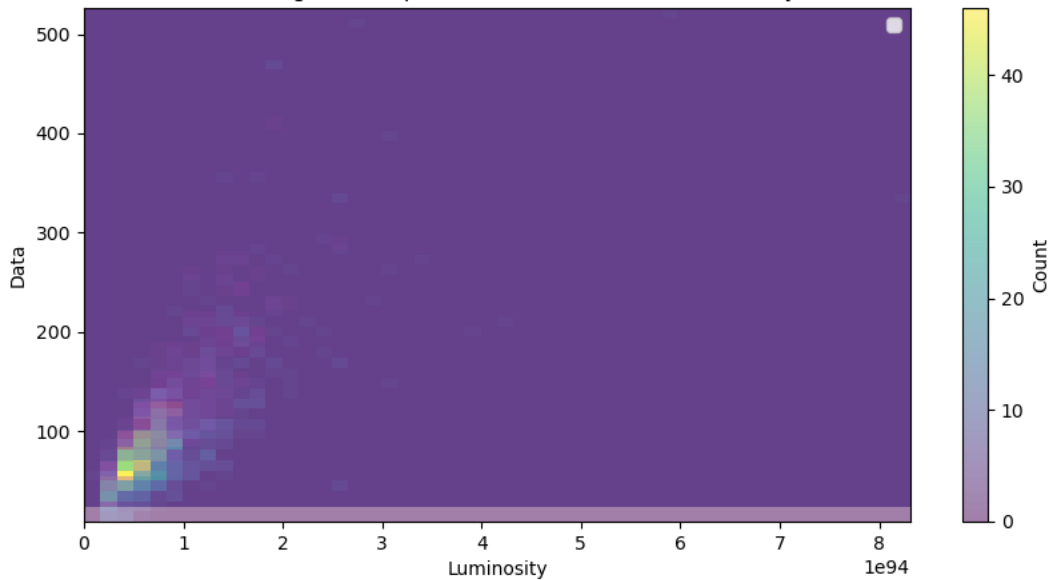


Figure 4.4: The 2D histogram distribution of optical and UV data over luminosity (luminosity in 10^{34} erg/s)

The optical and UV light from quasars mainly comes from the hot, gaseous accretion disk around the black hole. According to the blackbody radiation principle, the temperature of the accretion disk determines the peak wavelength of the emitted light: higher temperatures result in shorter wavelengths (UV), while lower temperatures result in longer wavelengths (optical). In contrast, infrared light is usually emitted by cooler, dustier regions of the galaxy. For quasars, infrared emission often comes from dust heated by the active galactic nucleus (AGN). This dust can be found in the torus surrounding the AGN or in the quasar's host galaxy.(Chen et al., 2017). The temperature of the disc determines the peak wavelength of the emitted light due to the blackbody radiation principle. Higher temperatures correspond to shorter wavelengths (UV), while lower temperatures correspond to longer wavelengths (optical). When a quasar's infrared luminosity increases, it typically means there is more heated dust present. This increased dust heating is often due to a higher amount of material falling into the black hole. As more material is accreted, the accretion disk heats up, causing the peak of its emission to shift towards the UV part of the spectrum. Therefore, quasars



with higher infrared luminosity are expected to show stronger UV emission and weaker optical emission. This relationship aligns with observations that higher infrared luminosity in quasars corresponds to increased UV light and decreased optical light (Jin, Lusso, Ward, Done, & Middei, 2024).

As the intensity of infrared light (or infrared luminosity) from quasars continues to rise, there is a noticeable drop in the number of quasars that have high levels of optical and ultraviolet (UV) observations. (Jin et al., 2024) This trend could be influenced by a variety of factors:-

- **Availability of Material:-** The amount of matter available to be pulled into the black hole can affect the light we observe. More material can lead to more energy release and thus more light.
- **Orientation of the Quasar:-** The direction in which the quasar is facing in relation to us can also impact what we observe. For instance, if the quasar is oriented such that the accretion disk (the disk of material falling into the black hole) is visible to us, we might observe more light.
- **Accretion Disk and Black Hole Physics:** There are also more intricate processes at play related to the physics of accretion disks and black holes themselves. These processes can affect the emission of light in various ways, leading to variability in the observed optical and UV light. In essence, the statement is saying that the relationship between infrared, optical, and UV light from quasars is complex and can be influenced by a variety of factors related to black holes and their environments.

4.4 Optical and UV Variability Correlated With Redshift

The relationship between changes in the optical and UV light from quasars and their redshift is currently a subject of active study. This relationship can offer a deeper understanding of the conditions and mechanisms at work in active galactic nuclei (AGN). These include fluctuating rates of matter accumulation, instabilities, and echo-like effects within the accretion disk surrounding a supermassive black hole.

Figure 4.5 showed that the “Distribution of Optical and UV Data over Redshift”. It’s a scatter plot with the x-axis representing the “Mean Redshift” and the y-axis representing the “Mean Flux”. The plot includes data from two different bands: the Optical Band (represented in blue) and the UV (Ultraviolet) Band (represented in red). Optical Band he blue points are

densely clustered and spread across the entire range of the x-axis (redshift), but they are mostly concentrated towards the lower end of the y-axis (flux). This indicates that most optical flux measurements are low to moderate in value, regardless of the redshift. UV Band the red points are less densely packed and spread across all values on the x-axis (redshift). However, they show more variation in flux values on the y-axis, including some higher flux measurements. This suggests that the UV flux can vary more widely than the optical flux at any given redshift.

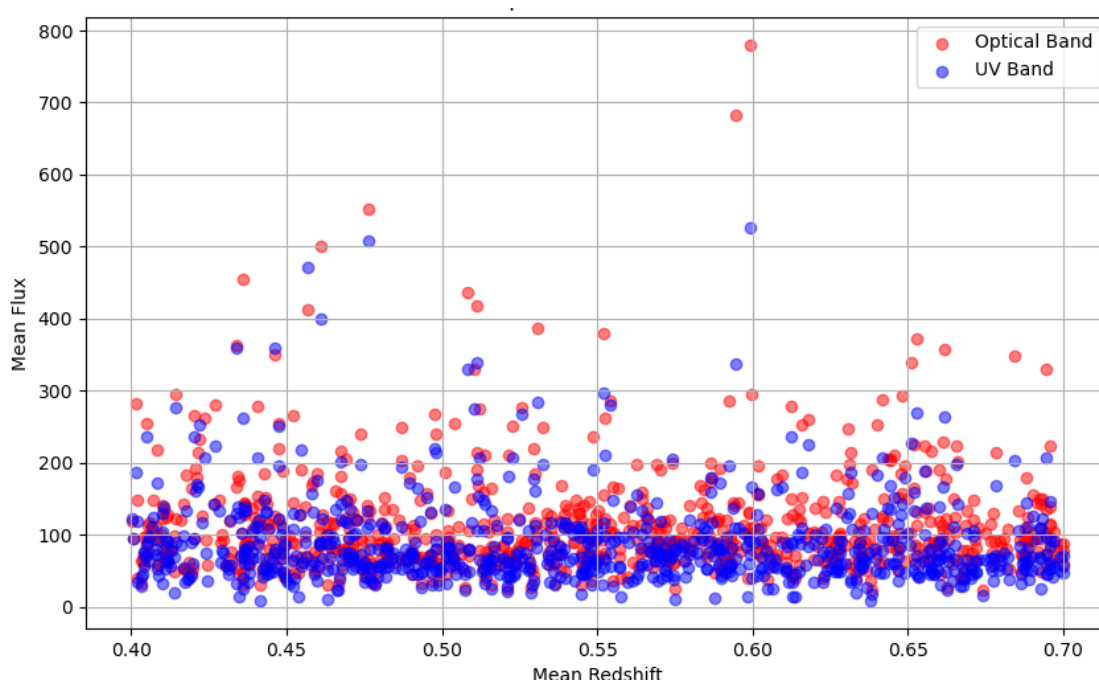


Figure 4.5: The distribution of optical and UV variability correlated with redshift (flux in in erg/s/cm^2)

There seems to be a general trend for both bands to have lower flux at higher redshifts. This could be due to the fact that objects at higher redshifts are further away, and their light is more likely to be absorbed and scattered during its journey to us, resulting in lower observed flux. There's considerable variability, especially in the ultraviolet band. This could be due to various factors, including the inherent properties of the quasars, the effect of interstellar medium on the light from the quasars.

let's relate the result with reverberation effect which is a phenomenon that can influence the observed relationship between the variability in optical and UV light from quasars and their redshift. Redshift is a concept in astronomy that describes how much the wavelength of light has been stretched or "shifted" towards the red end of the spectrum due to the expansion of the universe. The greater the redshift, the further away the light source (in this case, a quasar)



is from us, and the longer ago the light was emitted as mentioned in section two. Now, let's talk about the reverberation effect. This effect is essentially an “echo” or “reflection” of variability that occurred in the past. In the context of quasars, variability refers to changes in the intensity of the light they emit. This variability can be caused by various physical processes occurring in the vicinity of the supermassive black hole at the center of the quasar, such as changes in the accretion rate of matter into the black hole.

So, if a quasar is further away (and thus has a higher redshift), the light we are seeing from it was actually emitted a long time ago. This means we might be observing the “reverberations” or “echoes” from variability that occurred in the past. In other words, the changes in light intensity we see now are a reflection of what was happening in and around the quasar's supermassive black hole when the light was originally emitted.

This is why the reverberation effect can contribute to the observed correlation between optical and UV variability with redshift in quasars. It's like looking at a delayed recording of events, with the delay being due to the time it takes for the light to reach us. (Stone & Shen, 2023) Figure 4.6 shows a density plot, which is a type of data visualization that shows

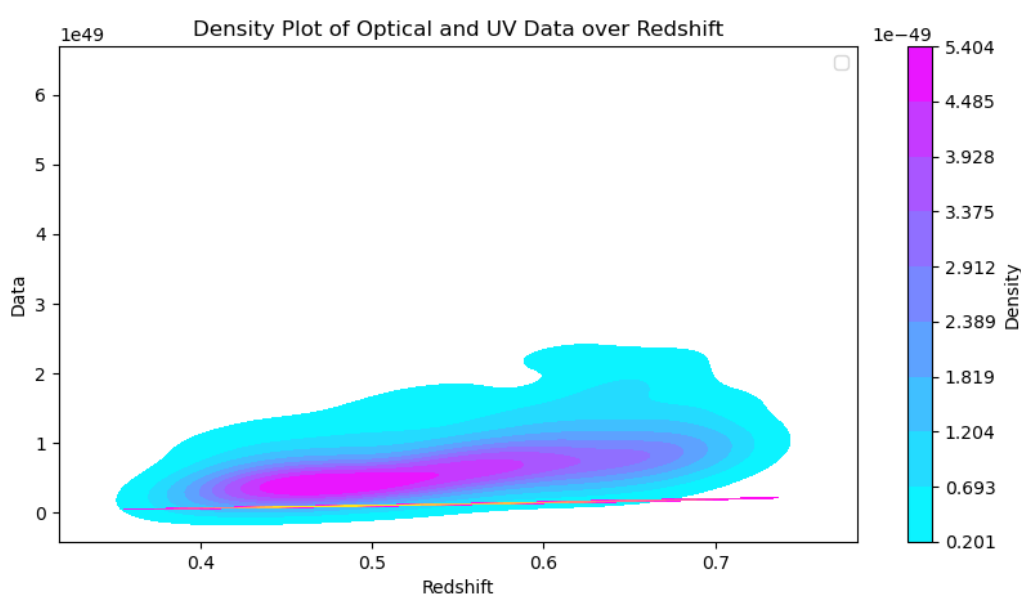


Figure 4.6: Density of optical and uv fluxes over redshift

the distribution of data over a continuous interval or time period. The plot helps to get clear understanding about the density of UV and optical flux. This plot has a color gradient to represent the density of data points, with darker colors indicating higher densities.

In this specific plot, the horizontal axis represents “Redshift”. Redshift is a measure of how much the wavelength of light has been stretched due to the expansion of the universe.



The vertical axis is labeled “Data” represents scientific data measurement related to the optical and UV (ultraviolet) data of quasars, which ranges from 0 to approximately $1e+49$.

The color bar on the right side of the plot indicates the density level, with values ranging from 0 to approximately 4.5. The densest area appears around a redshift value between approximately 0.4 and 0.5, indicating a higher concentration of data points in that range.

This plot is particularly interesting because it shows the distribution and concentration of optical and UV data over redshift. In the context of astrophysics, this can be used to understand the evolution of quasars over time as they move away from us, causing their light to shift towards the red end of the spectrum (redshift).

CHAPTER 5

CONCLUSION

The study reveals a strong positive linear correlation between the UV and optical band variability in quasars, as indicated by a Pearson cross-correlation coefficient of 0.93988. This suggests that an increase in the UV band flux is typically accompanied by an increase in the optical band flux, and vice versa. However, this correlation is not perfect, indicating that there are other factors at play that contribute to the variability in the data. These factors could include changes in the rate of matter accumulation, fluctuations, and echo-like phenomena in the accretion disc of a supermassive black hole. The scatter plot further supports this observation, showing a clear upward trend and a high density of points along the regression line, which indicates a strong positive correlation between the measurements in the UV and optical bands for most quasars. Therefore, the study provides valuable insights into the linked changes in the intensity of UV and optical bands in quasars, although some variability remains unexplained by the linear relationship.

The study utilizes the structure function to analyze the variability in UV and optical measurements of quasars. The findings suggest a strong correlation between UV and optical variability, with UV measurements showing more variability than optical ones. However, despite the observed correlations in the expanded sample, the study rejects the hypothesis that all quasars' inherent UV and optical fluctuations are entirely correlated with about 95% confidence. This indicates the presence of other factors influencing the variability in these measurements.

The study explores the intricate relationship between the infrared, optical, and UV light emitted by quasars. The research suggests that the variability in the optical and UV light from quasars is influenced by several factors, including the availability of material being accreted by the black hole, the orientation of the quasar, and the complex physics of the accretion disk and the black hole itself.

The study finds that as the infrared luminosity of a quasar increases, indicating more heated dust present due to higher accretion rates, there is a corresponding increase in UV emission and a decrease in optical emission. This aligns with the principle of blackbody



radiation, where higher temperatures result in shorter wavelength (UV) emissions and lower temperatures result in longer wavelength (optical) emissions.

However, as the infrared luminosity continues to rise, there is a noticeable decrease in the number of quasars with high levels of optical and UV observations. This suggests that the relationship between infrared, optical, and UV light from quasars is complex and can be influenced by a variety of factors related to the black hole and its environment.

There is a relationship between the optical and UV light from quasars and their redshift. This relationship is being actively studied to gain a deeper understanding of the conditions and mechanisms at work in active galactic nuclei (AGN), including fluctuating rates of matter accumulation, instabilities, and echo-like effects within the accretion disk surrounding a supermassive black hole. The optical and UV flux measurements show different distributions. The optical flux measurements are mostly low to moderate in value, regardless of the redshift, while the UV flux measurements show more variation, including some higher flux measurements. The reverberation effect can influence the observed relationship between the variability in optical and UV light from quasars and their redshift. The density plot shows the distribution and concentration of optical and UV data over redshift. This can be used to understand the evolution of quasars over time as they move away from us, causing their light to shift towards the red end of the spectrum (redshift).

Recommendation

Based on the findings of this study, it is recommended to further investigate the factors contributing to the variability in UV and optical flux measurements in quasars. While a strong positive correlation has been observed, the presence of unexplained variability suggests that other factors, potentially related to the physics of the accretion disk and the black hole itself, are at play. Future research could focus on these aspects, possibly incorporating more detailed models of black hole accretion and disk instabilities. Additionally, the study's findings regarding the relationship between infrared, optical, and UV light from quasars indicate a complex interplay of factors related to the black hole and its environment. Further observational and theoretical work is recommended to better understand this relationship. Finally, given the observed relationship between the optical and UV light from quasars and their redshift, it would be beneficial to continue studying this relationship to gain deeper insights into the evolution of quasars over time. This could involve long-term monitoring of quasars across a range of redshifts and the development of more sophisticated models to predict flux measurements based on redshift. In addition to the above recommendations, it is important to note that there is currently no specific model that can accurately predict the variability in UV and optical flux measurements in quasars. This highlights the complexity of the problem and the need for innovative approaches. It is recommended to explore the development of new predictive models, possibly leveraging advanced techniques such as machine learning or deep learning, which have shown promise in handling complex prediction tasks in various fields.

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