



# REVERBERATION MAPPING OF ACTIVE GALACTIC NUCLEI

Michael Hlabathe

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Supervisors: Dr. Encarni Romero-Colmenero (SAAO/SALT), Dr. Steve Crawford (NASA)  
and Prof. Patricia Whitelock (SAAO/UCT)

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# Abstract

Recent times have seen an increase in observational campaigns aimed at contributing to the overall sample of active galactic nuclei (AGNs) with central super-massive black hole (SMBH) mass estimates using reverberation mapping (RM) technique. RM makes use of the time variability of the broad emission lines from the nearby broad-line region (BLR) to measure their time response or delay ( $\tau$ ) relative to the incident ionizing continuum from the accretion disc. This delay is a consequence of light-travel time effects and directly enables the size of the BLR to be determined as  $R_{\text{BLR}} = c\tau$  ( $c$  is speed of light). Assuming virialized motions of the gas clouds in the BLR, and combining the velocity width ( $\Delta V$ ) of a Doppler broadened emission line with  $R_{\text{BLR}}$  leads to the estimation of the black hole mass  $M$ . RM can also be used to measure the accretion-disc size in which the X-ray variability source is assumed to drive UV/optical variations in the accretion disc leading to wavelength-dependent delays that scale as  $\tau \propto \lambda^{4/3}$ .

Here, both aspects of RM are explored using photometric and spectroscopic observations of 3C 120, PG 2304+043 and SDSS J132447.65+032432.6, with observations emanating from the Southern African Large Telescope (SALT) and Las Cumbres Observatory (LCO) robotic telescopes. The broad emission-line and inter-band continuum delays in these AGNs are measured using the Interpolated Cross-Correlation Function (ICCF) and **RE**verberation **AGN** Markov Chain Monte Carlo (CREAM).

For 3C 120, the multi-line lag measurements are reported as  $\tau_{\text{ICCF}} = 18.8_{-1.0}^{+1.3}, 2.7_{-0.8}^{+0.7}, 21.2_{-1.0}^{+1.6}$  and  $16.9_{-1.1}^{+0.9}$  days relative to the V-band continuum, for the broad emission lines  $\text{H}\gamma$ ,  $\text{He II } \lambda 4686$ ,  $\text{H}\beta$  and  $\text{He I } \lambda 5876$ , respectively. Combining the  $\text{H}\beta$  delay with its rms velocity width, led to the determined SMBH mass for 3C 120 as  $M = (6.3_{-0.3}^{+0.5}) \times 10^7 (f/5.5) \text{ M}_{\odot}$ . This determined mass is consistent with previous estimates of the SMBH mass in 3C 120, but with smaller  $1\sigma$  uncertainties on the mass. Investigations into the continuum inter-band delays reveal they are consistent with expectations from a geometrically-thin, optically-thick accretion disc, but the size of the observed disc at  $\lambda_0 = 5477\text{\AA}$  is  $1.6\times$  larger than predicted by CREAM standard thin-disc model with  $L/L_{\text{Edd}} = 0.4$ . This larger than predicted size is consistent with similar previous studies. Lastly, the velocity-resolved measurements indicate a kinematic structure of the BLR gas clouds that is consistent with Keplerian motion.

For PG 2304+043, the CREAM model with face-on inclination  $i = 0$  and an adopted SMBH

mass  $M = (3.98 \pm 0.92) \times 10^8 \text{ M}_\odot$  yield the temperature  $T_1 = (1.12 \pm 0.14) \times 10^4$  at one light day from the black hole and the standard blackbody accretion disc with  $L/L_{\text{Edd}} = 0.003$ .

For SDSS J132447.65+032432.6, the measured  $\text{H}\beta$  delay  $\tau_{\text{CCF}} = 22.97^{+10.99}_{-12.93}$  days led to a central SMBH mass of  $M = (5.18^{+2.48}_{-2.91}) \times 10^7 (f/3.85) \text{ M}_\odot$  when combined with the velocity width from the mean spectrum. This result makes this AGN one of the few with an estimate of the SMBH mass beyond the local universe ( $z > 0.3$ ).

These results have a direct consequence on the RM of AGNs as a whole.

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# Plagiarism Declaration

*I, Michael Hlabathe, know the meaning of plagiarism and declare that all of the work in the document, save for that which is properly acknowledged, is my own.*

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Date: 16 May 2023



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# Chapter 1

## Introduction

### 1.1 Galaxies

Our own Milky Way galaxy is one of the several billions of galaxies existing in the observable Universe today, using today's technology. A galaxy is an astronomical object composed of dark matter, stars (millions to trillions young and/or old), interstellar dust, and gas, interacting gravitationally. It is not yet fully understood how galaxies are formed and evolve into various morphological states (from simple to complex ones). Additionally, galaxies exhibit an array of sizes, from dwarfs to giants. [Hubble \(1926\)](#) used a sample of galaxies (recorded on photographic plates) to devise a galaxy classification scheme known as the *tuning fork diagram*, used to classify galaxies based on their visual appearance or morphology. The standard diagrammatical model of Hubble's tuning fork is illustrated in Figure 1.1.

The tuning fork diagram features three main groups in the form of spirals, ellipticals, and lenticulars. On the left are ellipticals, designated E0 to E7. The E0 elliptical galaxies appear nearly circular, with E7 appearing highly elongated (e.g., [Robson 1996](#)). Spiral galaxies have arms extending outward from the center in a spiral pattern. Spiral galaxies can be further subdivided into barred (SBa, SBb, SBc) and non-barred (Sa, Sb, Sc) types, depending on the degree of the opening (or tightness) of the spiral arms (e.g., [Robson 1996](#)). Lenticulars are an intermediate class of galaxies (denoted by the symbol S0) lying at the center of the tuning fork. A fourth group of galaxies, not featuring in Hubble's original classification scheme, are irregular galaxies, which do not have a definite shape (are neither elliptical nor spiral in morphology). Increased observational evidence indicates that Hubble's simple classification scheme does not account for all morphological shapes, and thus modifications were proposed (e.g., [de Vaucouleurs 1959](#), [Kormendy & Bender 1996](#), [Graham 2019](#)). Nevertheless, Hubble's classification scheme still remains widely used to this day.

In terms of components, spiral galaxies (like the Milky Way) contain the bulge, disc and halo as the main three components (Figure 1.2). The bulge is located at the center of the

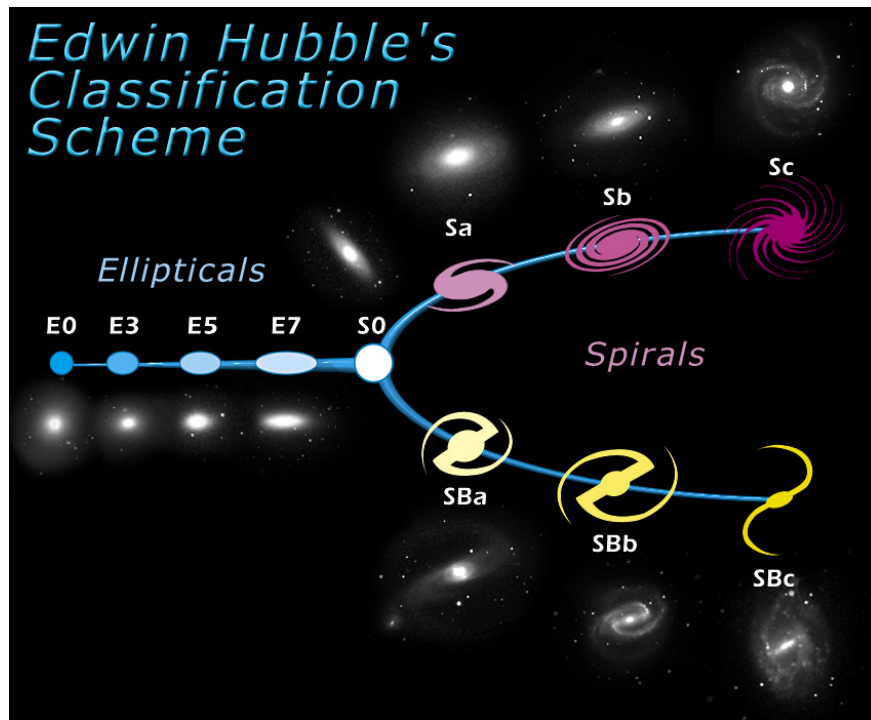


Figure 1.1: The tuning fork diagram showing galaxy morphological classification. Image credit: NASA & ESA.

galaxy. It contains a mixture of both young and old stars, with the majority of the stars being old and red. Young and bright stars reside in the dense spiral arms in the disc. Stars like our Sun (yellow stars), for example, reside in the disc. The disc also marks the location of open clusters. A halo is a region further out from the center which contains a generation of older stars, with little dust and gas. It is also the location of globular clusters. Elliptical galaxies, on the other hand, have a bulge as the only component. They contain almost no interstellar dust or gas, and are known to harbor mostly old stars. Lenticular galaxies have a disc structural component and contain a significant amount of dust, older stars and overall appear faint. Regardless of the type of galaxy, a massive black hole lies at the center of every giant galaxy. A black hole is a compact region at the center of a galaxy whose gravitational pull is so strong not even electromagnetic radiation can escape it.

With that, it is important to note that the difference between these different galaxies does not only lie in their morphology, range of sizes and constituents. The difference also lies in their power output (i.e., luminosity or brightness), a distinguishing characteristic between normal and active galaxies. The latter galaxies are the primary focus of this study and henceforth, the emphasis is placed on them.

<sup>1</sup><https://sci.esa.int/web/gaia/-/58206-anatomy-of-the-milky-way>

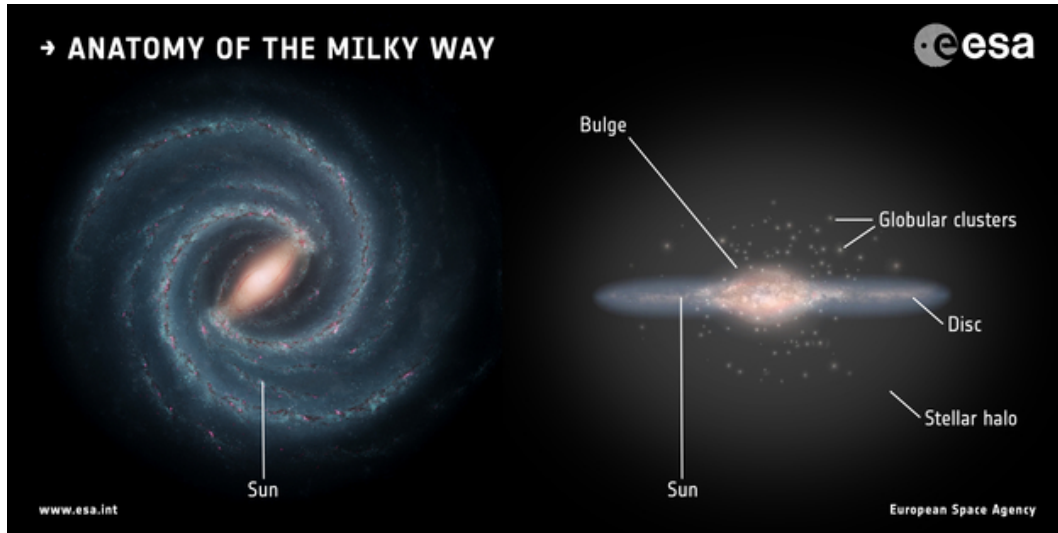


Figure 1.2: A cartoon of the Milky Way (a spiral) galaxy with its main components shown<sup>1</sup>.

## 1.2 Active Galaxies

An active galaxy is one that bears an active galactic nucleus (AGN) at its center, it is otherwise a normal or quiescent galaxy. One of the earlier properties of AGNs was their strong emission lines, first observed by [Fath \(1909\)](#) in the case of NGC 1068. Almost a decade later, [Campbell & Paddock \(1918\)](#) made observations of NGC 4151 and noted similarities with NGC 1068. But it was the discovery of 3C 273 (see [Hazard et al. 2015; 2018](#), on the history) that revolutionized how AGNs are perceived today. At the time of its discovery, 3C 273 was considered to have the largest redshift of  $z = 0.158$  ([Schmidt 1963](#)), corresponding to a distance of 2.5 billion light years from Earth. With an absolute magnitude  $-26.7$  ([Greenstein & Schmidt 1964](#)), 3C 273 was the farthest and most luminous known object in the sky at the time. Its luminosity ( $L = 0.5 \times 10^{13} L_{\odot}$ ) was estimated to be at least 100 times more than normal galaxies at similar distances ([Ulrich 1981](#)). Its observed emission lines were significantly redshifted from their rest wavelengths, a phenomenon unfamiliar at the time. Through photographic plate observations, [Smith & Hoffleit \(1963\)](#) found 3C 273 to be variable on relatively short timescales of months, indicating that it was small. Residing in the constellation Virgo, 3C 273 is today recognised as a quasi-stellar object (Section 1.3).

Subsequently, more discoveries of AGNs took place, and what caught the eye of many astronomers was the diversity of their observed characteristics. Such characteristics include a broad range of luminosities ([Steffen et al. 2006, Maoz 2007](#)), strong and broad UV/optical emission lines ([Vanden Berk et al. 2001](#)), a big blue bump UV/optical component ([Shields 1978](#)), blueshifted absorption lines ([Arav et al. 2001](#)), and multi-wavelength variability ([Türler et al. 1999](#)). These eventually led to the formulation of the AGN unified model (Section 1.2.1).

### 1.2.1 Unified Model

[Antonucci \(1993\)](#), [Urry & Padovani \(1995\)](#) tried to explain all of the AGN characteristics based on line-of-sight orientation. This led to the schematic view in [Figure 1.3](#), which defines an AGN as consisting of several components including ([Netzer 2015](#), for a review):

- a central super-massive black hole (SMBH) with a lower mass limit  $\sim 10^6 M_{\odot}$ ;
- an optically-thick, geometrically-thin (or thick or slim) accretion disc immediately surrounding the SMBH;
- the high-density region consisting of fast-moving gas clouds called the broad-line region (BLR) at 0.01 - 1 pc from the disc;
- a dusty torus that obscures both the BLR and the disc from some viewing angles;
- the lower-density region consisting of slow-moving gas clouds called the narrow-line region (NLR) at 3 - 30 pc from the disc;
- a sub-pc to kpc relativistic scale jet on either side of the SMBH in radio-loud AGNs.

One of the strongest pieces of evidence of the unified model came from the spectropolarimetric observations of NGC 1068 ([Antonucci & Miller 1985](#)), a Seyfert 2 AGN ([Section 1.3](#)). The BLR in Seyfert 2 cannot be seen directly because is hidden to our line of sight by the dusty torus, but whose scattered (polarized) light is reflected into the line of sight leading to the presence of broad lines in the polarized spectrum. This brought about the deduction that, under the unified model, both Type 1 and Type 2 AGNs are intrinsically the same, the difference is due to line-of-sight orientation.

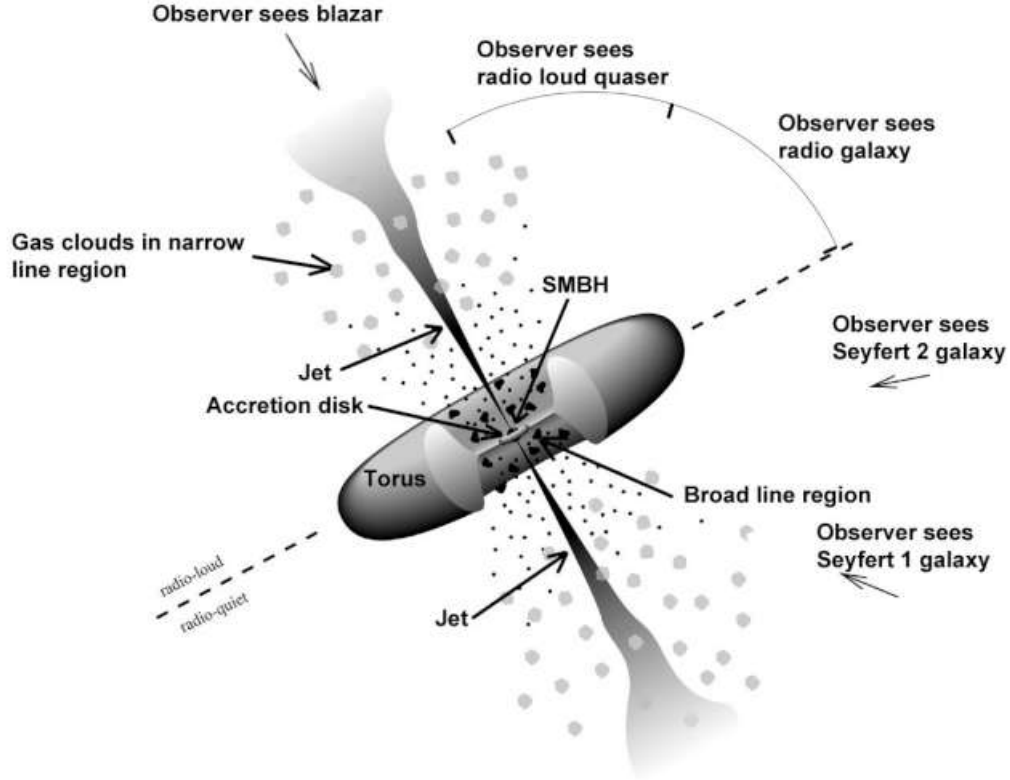


Figure 1.3: Unified view (not to scale) of the AGN (Urry & Padovani 1995). The different components making up an AGN are shown, these include, the central SMBH, accretion disk, the dusty torus, and the broad and narrow-line regions. The different subclasses of AGNs are also shown.

### 1.3 Classification of AGNs

The unified model in Figure 1.3 is an attempt to explain the different subclasses of AGNs observed based on orientation (Antonucci 1993, Urry & Padovani 1995, Urry 2003, Padovani et al. 2017). That is, different subclasses of AGNs will show different spectral features depending on the observing angle or inclination.

The different subclasses of AGNs include Seyferts, Quasars, Radio Galaxies and BL Lactertae (BL Lac) objects. Seyfert galaxies, as they are now known, were named after Carl Seyfert based on his work on nuclear emission in spiral galaxies (Seyfert 1943). They lie in the intermediate luminosity range and are categorized as Seyfert 1 (Sy1) and Seyfert 2 (Sy2). The difference between these two classes lies in the observational properties explainable by the AGN unification scheme in Figure 1.3. In Sy2 galaxies (viewed edge-on), the dusty molecular torus obscures the broad-line emitting clouds leading to narrow lines being present in the spectra. The narrow lines have widths (up to velocities of  $\sim 1000 \text{ km s}^{-1}$ ) (Robson 1996, Netzer 2015). Sy1 (viewed pole-on), on the other hand, exhibit both broad and narrow lines in their spectra. The majority of these broad lines have gas velocities in

the range 1000 - 15000 km s<sup>-1</sup> (Robson 1996, Sulentic et al. 2000, Netzer 2015). Another subclass of Seyferts is the narrow-line Seyfert 1 galaxies (NLSy1), which also exhibit both broad and narrow lines. The defining criteria for NLSy1 is the width of the broad H $\beta$  < 2000 km s<sup>-1</sup>, the relative weakness of [O III] emission line ([O III]/H $\beta$  < 3) and typically strong Fe II multiplets (Osterbrock & Pogge 1985, Goodrich 1989). Based on the relative strengths of the broad and narrow components, Seyfert galaxies can be further subclassed into intermediate types, such as Seyfert 1.5 and Seyfert 1.9 (Osterbrock & Koski 1976, Osterbrock 1981).

Quasars (QSOs) are the most luminous objects in the category of AGNs, with luminosities extending up to 10<sup>13</sup> L<sub>⊙</sub>. Observationally, they exhibit very broad emission lines in their spectra. The broad emission-line widths characterizing quasars can also characterize the most powerful Seyfert 1s, making the distinction between these two classes not that obvious from spectroscopy. The difference lies in their redshifts, quasars are high redshift objects (e.g., Wang et al. 2021, the current record holder as of 9 December 2022) and more luminous, while Seyferts are low redshift objects (e.g., Bentz et al. 2013, sample). The quasar optical emission lines tend to be shifted with respect to the systemic quasar velocity. This phenomenon was first observed or highlighted by Gaskell (1982) through noticing that high ionization lines (HILs), most notable C IV, are blueshifted from the quasar redshift determined from low ionization lines (LILs). This tendency was later evidenced by several studies (e.g., Wilkes 1986, Espey et al. 1989, Tytler & Fan 1992, McIntosh et al. 1999, Vanden Berk et al. 2001, Shen et al. 2016a). The LILs, such as Mg II, have average velocity comparable to systemic velocity (Hewett & Wild 2010). As shall be seen later, the FWHM measurements (Peterson et al. 2004) indicate that HILs are broader than LILs due to BLR stratification (Kollatschny 2003).

Radio Galaxies can be also subdivided into radio-loud (where the jet is present) and radio-quiet (where the jet is not present) galaxies. The RQ AGNs (Sy1 and Quasars) are defined as above, while RL AGNs are defined as having the ratio ( $R$ ) of the radio flux to the optical flux of  $R > 10$  (Kellermann et al. 1989; 2016). The jet in radio-loud (RL) is said to be responsible for a significant fraction of the total bolometric luminosity, while radio-quiet (RQ) are energetically weak (Wilson & Colbert 1995). The RL AGNs are hosted in ellipticals and RQ tend to be hosted in spiral galaxies. The majority of the optically found QSOs are RQ AGNs and relatively few are RL AGNs.

BL Lac objects when compared to other subclasses of AGN, exhibit an almost featureless continuum in their spectra (Falomo et al. 2014). They are highly variable, extremely luminous and highly polarized (Padovani & Giommi 1995). In the unified model, a BL Lac is seen when the relativistic jet is along the line of sight of the observer.

## 1.4 Observational Properties of AGNs

The telltale signs of AGNs are the observed properties previously mentioned, which makes them intriguing objects to pursue. Below, each individual property or characteristic is expanded upon or explained.

### 1.4.1 Energy Generation in AGN

AGNs are said to dominate the total energy output from the parent (or host) galaxy. Their brightness or luminosity is due to the accretion of matter onto the central SMBH (Salpeter 1964, Lynden-Bell 1969, Rees 1984). That is, matter (i.e., surrounding gas) does not directly fall into the SMBH. Instead, the strong gravitational field from the SMBH drags the matter along the accretion disc at high speeds creating viscous friction in the disc (as it swirls into SMBH), leading to the powerful luminosities ( $10^8 - 10^{13} L_{\odot}$ ) observed in the cores of AGNs. The total energy output emitted by a normal galaxy, on the other hand, is a result of the combined emission from all of its stars.

The scenario of the observed luminosities being driven or fueled by accretion of matter onto SMBH involves the conversion of accreted material to observed photons. Bearing Figure 1.3 in mind, in order for a central radiating object (i.e., SMBH) of mass  $M$  to accrete ionized hydrogen gas distributed spherically at a radius  $r$ , its gravitational attraction must be greater or balance the outward radiation pressure

$$\frac{\sigma_e L}{4\pi r^2 c} \leq \frac{GMm_p}{r^2}, \quad (1.1)$$

where  $\sigma_e$  is the Thomson scattering cross-section for the electron,  $m_p$  is the mass of the proton,  $G$  is the gravitational constant and  $c$  is speed of light. Therefore

$$L \leq \frac{4\pi GMcm_p}{\sigma_e}. \quad (1.2)$$

The right-hand side of Eqn. 1.2 is known as the Eddington limit (named in honour of Sir Arthur Stanley Eddington). It sets the limit for maintaining spherical accretion by a central object. When an object exceeds this limit, its gas is radiated outward or away (i.e., shutting down accretion). The parameters in Eqn. 1.2 are all constants, except for  $M$ , implying the Eddington limit depends only on the mass of the central object. The maximum luminosity for a given mass

$$L_{\text{Edd}} = 1.26 \times 10^{38} \frac{M}{M_{\odot}} \text{ ergs s}^{-1} \quad (1.3)$$

is known as the Eddington luminosity (Rybicki & Lightman 1979). The larger the mass  $M$ , the higher the value of  $L_{\text{Edd}}$ . It's worth noting that some AGNs may exceed the Eddington limit above, although rarely, during the process called super-Eddington accretion if their geometry is non-spherical (e.g., Lanzuisi et al. 2016, Tsai et al. 2018). If the gas is accreted

onto a SMBH at a rate  $\dot{M}$ , the radiative efficiency is

$$\eta = \frac{L_{\text{bol}}}{\dot{M}c^2} \quad (1.4)$$

where  $\dot{M}$  is the mass accretion rate ( $M_{\odot} \text{ yr}^{-1}$ ) and  $L_{\text{bol}}$  is the AGN bolometric luminosity (Bian & Zhao 2003), defined as the total luminosity emitted by the accretion disc. The quantity  $\eta$ , measures the fraction of mass inflow  $\dot{M}$  that is converted to radiation (also called conversion efficiency). It also relates the bolometric  $L_{\text{bol}}$  and Eddington luminosity  $L_{\text{Edd}}$  according to

$$L_{\text{bol}}/L_{\text{Edd}} = \eta \mathcal{M}, \quad (1.5)$$

where  $L_{\text{bol}}/L_{\text{Edd}}$  is the Eddington ratio and  $\mathcal{M} = \dot{M}/L_{\text{Edd}}c^{-2}$  is the dimensionless accretion rate (see, Du et al. 2015; 2016b; 2018b, for details). Eqn. 1.5 implies the Eddington ratio is directly linked with the measure of the dimensionless accretion rate. The Eddington accretion rate (i.e., the maximum rate at which the central object can accrete gas) is determined by setting the bolometric luminosity equal to the Eddington luminosity

$$\eta \dot{M} c^2 = \frac{4\pi G M c m_p}{\sigma_e} \quad (1.6)$$

resulting in

$$\dot{M}_{\text{Edd}} = \frac{4\pi G M m_p}{\eta c \sigma_e}. \quad (1.7)$$

Estimating the value of the radiative efficiency  $\eta$  is not easy and its estimation is often accompanied by assumptions on the details of the accretion process. For instance, the efficiency of disc accretion onto non-rotating (Schwarzschild) black holes is estimated to be  $\eta = 0.06$ , or  $\eta = 0.32$  for a maximally rotating (Kerr) black hole (Thorne 1974). Generally, the efficiency is adopted as  $\eta = 0.1$  through assuming the black hole is surrounded by a geometrically-thin and optically-thick accretion disc (Shakura & Sunyaev 1973).

### 1.4.2 AGN Big Blue Bump

The AGN continuum emission or spectral energy distribution (SED) reveals a characteristic feature called the “Big Blue Bump” (BBB), thought to be due to thermal emission from the accretion disc (Sanders et al. 1989). This feature is shown in Figure 1.4, and appears to descend all the way to  $\sim 5000 \text{ \AA}$ . Generally, this BBB feature extends from the ultraviolet (UV) to the optical and descends sharply all the way to the X-ray side (in log-space), with a cutoff below 0.6 keV (Zhou et al. 1997, and references therein). Disc models aimed at reproducing the observed SED of AGNs have been proposed, in order to constrain the physics of the ionizing flux. These includes models that consider the role of optically-thick thermal emission from the accretion disc in giving rise to the observed BBB (Shields 1978, Malkan & Sargent 1982) and those that consider the role of optically-thin thermal free-free emission from the disc (Antonucci & Barvainis 1988, Barvainis 1993). However,

due to observational constraints, emission-line spectra covering UV/optical side and X-rays simultaneously are seldom obtained. One way to deal with this is to create a composite spectrum, combining several spectra (e.g., [Zheng et al. 1997](#)). This means the accuracy of the proposed disc models is often limited to the visible part of the bump. Alternatively, the SED of AGNs can be studied through multi-wavelength variability observations. The SED from the multi-wavelength continuum observations (e.g., [Cackett et al. 2020](#)) are well reproduced by the disc model of [Shakura & Sunyaev \(1973\)](#). In this model, the thermal emission induced in the disc as a result of X-ray irradiation (due to a hot corona) above the disc ([Haardt & Maraschi 1991](#)). In this model, the underlying SED is approximated by a power-law spectrum of  $f_\nu \propto \lambda^{-1/3}$  after correcting for reddening. This disc model will be explored some more in the later chapters in the form of **C**ontinuum **R**Everberation **A**GN **M**arkov Chain Monte Carlo ([Starkey et al. 2016; 2017](#)).

### 1.4.3 AGN Emission Lines

The optical spectra of Type 1 Seyferts or Quasars typically features some of the broad and narrow emission lines (Figure 1.4). It is an established fact that the broad lines originate or are produced in the nearby BLR, at a distance of  $\sim 1$  pc from the central source. The BLR consist of high-density gas clouds ( $n_e \geq 10^9 \text{ cm}^{-3}$ , [Osterbrock \(1989\)](#)) that are photoionized by the incident continuum radiation from the accretion disc. This incident continuum radiation is reprocessed into broadened emission lines due to typically high Doppler velocities ( $10^3 - 10^4 \text{ km s}^{-1}$ , [Peterson \(1993\)](#)). The broad lines are typically from  $\text{H}\gamma$ ,  $\text{H}\beta$ ,  $\text{H}\alpha$  and species such as  $\text{HeI}$ ,  $\text{HeII}$  and  $\text{FeII}$ . The formation of narrow lines in the BLR is suppressed due to high electron density and collisional de-excitation. In this process, an excited atom will experience energy loss in the form of kinetic energy due to rapid collisions and cascade down to lower energy levels.

The far-extended NLR ( $\sim 1$  kpc) gives rise to narrow lines such as  $[\text{O II}]$ ,  $[\text{O III}]$ ,  $[\text{Ne III}]$ ,  $[\text{N I}]$ ,  $[\text{N II}]$ ,  $[\text{Fe VII}]$  and  $[\text{S II}]$ . The low electron density ( $n_e \approx 10^3 \text{ cm}^{-3}$ , [Peterson \(1993\)](#)) means collisional de-excitation is not likely (i.e., forbidden transitions happen before collisional de-excitation). These narrow lines typically have Doppler velocities of  $10^2 - 10^3 \text{ km s}^{-1}$ .

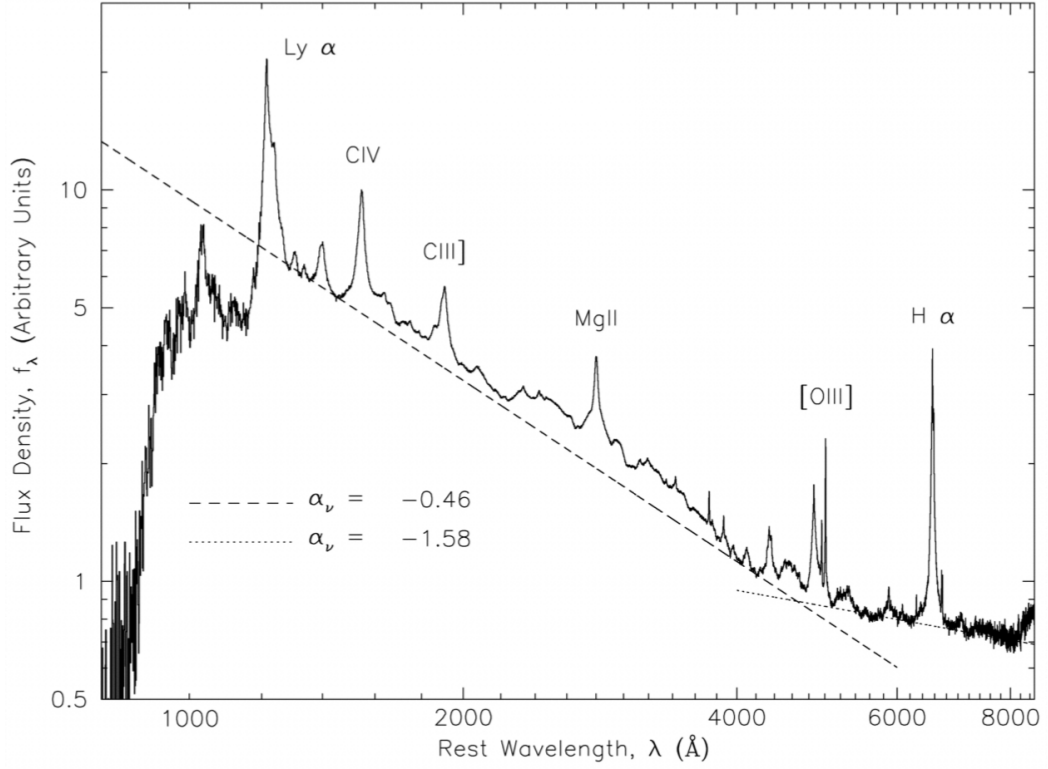


Figure 1.4: The composite QSO spectrum from SDSS with some of the broad and narrow emission lines typical of AGNs. The dotted lines are the power-law fits to the continuum or SED, with the best-fit indices as indicated. Image is adapted from [Vanden Berk et al. \(2001\)](#).

#### 1.4.4 AGN Absorption Lines

AGNs can also exhibit broad absorption lines (BALs) in their spectra. The BALs are believed to be caused by intervening outflow of gas from the nucleus ([Liu et al. 2015](#), and references therein). In terms of the unified model (Figure 1.3), the outflow is viewed along the line of sight of the observer resulting in blueshifted BALs with outflow velocities in the range  $0.1c - 0.2c$  ([Hamann et al. 2013](#)). Most of the observed BALs are from the high ionization species, such as C IV  $\lambda 1549$ , Si V  $\lambda 1397$ , N V  $\lambda 1240$  ([Arav et al. 2001](#), [Hall et al. 2013](#), [Liu et al. 2015](#)). The rarely observed BALs, are the low ionization species such as Mg II  $\lambda 2798$  and Al III  $\lambda 1857$ .

#### 1.4.5 Variability

Most AGNs exhibit variations at various wavelengths or bands (Figure 1.5). These variations are typically characterized by aperiodic and stochastic variations ([Ishibashi, W. & Courvoisier, T. J.-L. 2009](#)), suggesting random physical processes. The source of these observed variations still remains unclear and may be due to:

- variable X-ray source irradiating the accretion disc (Morgan et al. 2012);
- instabilities in the accretion disc caused by an inward accretion flow (Arévalo & Uttley 2006);
- fueling of AGN by multiple supernova explosions or starbursts resulting in stochastic variations (Aretxaga & Terlevich 1994);
- gravitational microlensing by stars in the host galaxy along the line of sight (Hawkins 1993);
- magnetic activity in the disc (e.g., Lesch & Pohl 1992).

To test the just-mentioned phenomena for plausibility, one has to consider an accretion-disc model that is able to reproduce the observed variability of the light curves, the underlying SED, including producing expected variability timescales and light travel-time delays. In saying that, several multi-wavelength monitoring campaigns reveal light-curve variations in different bands to be correlated with each other (e.g., Edelson et al. 1996, Wanders et al. 1997, Kriss et al. 2000, Fausnaugh et al. 2016). This is provided as an example in Figure 1.5 in which the variations at UV/optical wavebands are correlated with X-ray variability on short timescales (days to a few tens of days) (see also Breed et al. 2009; 2010). The observed rapid variability implies an emitting region that is spatially small (on the order of days); if it were not, the variations would appear smoothed. In such a case as Figure 1.5, the X-ray variability is expected to lead the variations at UV/optical wavelengths. Although, at other times, it has been observed to follow (e.g., Gaskell 2006). In the former scenario, the UV/optical variations can be explained in terms of X-ray reprocessing. This X-ray is believed to be related to a hot corona situated just above the central SMBH which irradiates the disc causing continuum-continuum variability in the disc, called the “lamp-post” model (Cackett et al. 2007). Thus, the variability induced in the disc provides a direct way to resolve the smallest accessible regions of the central engine (Edelson & Nandra 1999), via a technique known as Reverberation Mapping (RM, Blandford & McKee 1982). Using RM, there is some evidence in support of the reprocessing model above in which shorter variations respond faster than longer variations taking into account light-travel times (e.g., Sergeev et al. 2005, Cackett et al. 2007). However, in recent times the model has been called into question following lack of reconciliation with predictions from the model. That is, the disc sizes predicted are much smaller than observed (e.g., Fian et al. 2022, and references therein). Not only that, in studies where there are X-ray observations (e.g., Edelson et al. 2015, Fausnaugh et al. 2016), the delay between X-ray and UV is longer than expected. The X-ray/UV correlation is weaker compared to UV/optical. Overall, there is comprehensive evidence indicating that the above model description is incomplete or not adequate and must be revisited.

The temporal variability features of the AGN light curves can be examined using either one of the common statistical tools: A damped random walk (DRW, Kelly et al. 2009, Kozłowski

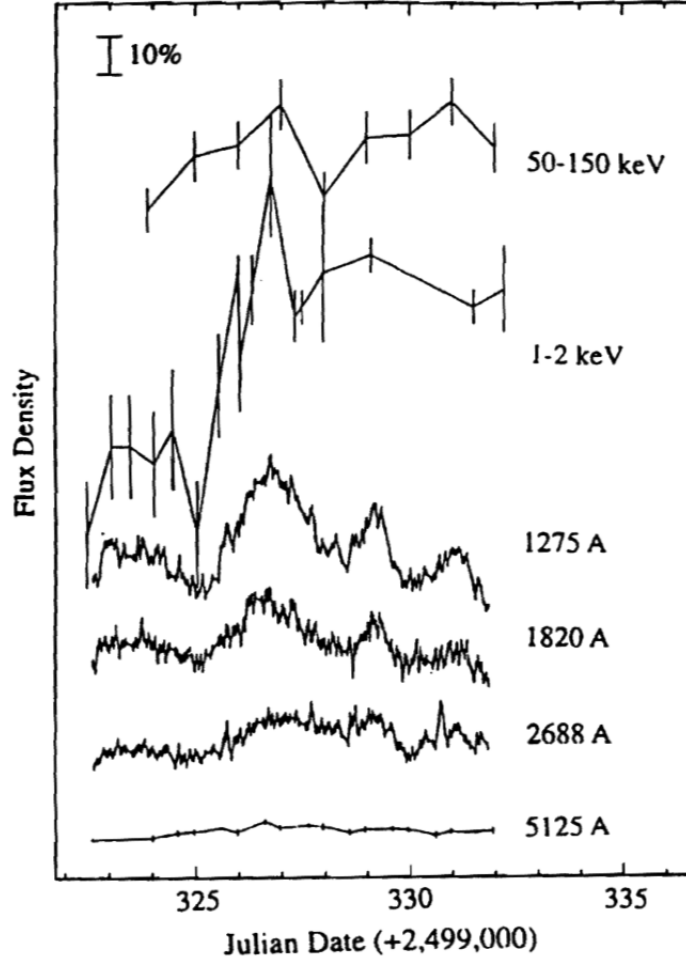


Figure 1.5: Continuum variations at different wavelengths, the light curves are shifted vertically for clarity (Edelson et al. 1996). Variations in the X-ray appear to be correlated with UV/optical variations.

et al. 2010, MacLeod et al. 2010, Zu et al. 2013), power spectral densities (PSDs, Edelson & Nandra 1999, Collier & Peterson 2001, Vaughan & Fabian 2003, Sartori et al. 2018, Smith et al. 2018) or structure functions (SFs, Kozłowski 2016). Generally, a PSD is approximated as a power-law of the form  $P(f) \propto A f^{-\alpha}$ , with  $A$  being the normalization factor, and  $f$ , the temporal frequency (Collier & Peterson 2001). The logarithmic slope  $\alpha \sim 2$  characterizes the PSD at high frequencies and  $\alpha \sim 1$  at low frequencies. The structure function approach is defined as

$$S(\Delta t) = \frac{1}{N(\tau)} \sum_{i < j} [f(t_i) - f(t_j)]^2, \quad (1.8)$$

where  $f$  is a flux measurement at  $t_i$  ( $i = 1, 2, 3, \dots$ ),  $t_j$  its shifted copy for which the time lag  $\Delta t = t_j - t_i$ ,  $N(\tau)$  is the total number of possible pairs, and the sum is measured utilizing all pairs in the domain  $\Delta t = t_j - t_i$  (Collier & Peterson 2001, Kozłowski 2017b). Eqn. 1.8

can be rewritten in terms of the covariance matrix  $\text{cov}(S_i, S_j)$ , the signal variance  $\sigma_s^2$  and the noise variance  $\sigma_n^2$  as

$$S(\Delta t)^2 = 2(\sigma_s^2 - \text{cov}(S_i, S_j)) + 2\sigma_n^2. \quad (1.9)$$

The difference between these methods lies in how the AGN light curves are modeled. In SF/PSD, the light curves (which are seldomly sampled) are binned which means information is always lost as a result, as such, it makes interpreting the results difficult if the covariance matrix above is not correctly estimated (Zu et al. 2013). On the other hand, DRW provides a very different approach to interpolating and modeling AGN light curves. The relative success of the DRW model has previously been shown, where it was statistically able to approximate the observed AGN variability well; when applied on various time-series data to infer reverberation lag (e.g., Fausnaugh et al. 2016, Grier et al. 2017b). The DRW model includes  $\sigma_{\text{DRW}}$  (amplitude of variability) and  $\tau_{\text{DRW}}$  (the damping timescale) as model parameters with an exponential covariance function

$$S(\Delta t) = \sigma_{\text{DRW}}^2 \exp\left(\frac{-\Delta t}{\tau_{\text{DRW}}}\right), \quad (1.10)$$

where  $\Delta t = t_j - t_i$  represents the cadence of the observations (Zu et al. 2013). The two model parameters have been found to correlate with AGN properties such as SMBH mass, the luminosity, Eddington ratio and rest-frame wavelength (e.g., Kelly et al. 2009, MacLeod et al. 2010). However, Kozłowski (2017a) investigated the reported correlations and argues that they are unlikely to be correct on the basis that the experimental length is short to accurately yield the model parameters. In particular, the damping timescale  $\tau_{\text{DRW}}$  which is linked with AGN physics. Furthermore, the results from Kepler monitoring indicate that the DRW model does fall short as it cannot describe the high temporal frequency variability of AGNs. That is, the observed power spectral slopes are much steeper than -2 predicted by DRW (e.g., Edelson et al. 2014, Kasliwal et al. 2015, Aranzana et al. 2018).

From the AGN variability light curves more information can be gleaned, such as variability amplitude or fractional variability. Each light curve will exhibit a certain degree of variability commonly characterized by the intrinsic fractional variability or excess variance  $F_{\text{var}}$  (Rodríguez-Pascual et al. 1997, Edelson et al. 2002, Vaughan et al. 2003)

$$F_{\text{var}} = \frac{\sqrt{\sigma^2 - \delta^2}}{\langle f \rangle}, \quad (1.11)$$

where the quantity  $\langle f \rangle$  is the mean flux

$$\langle f \rangle = \sum_{i=1}^N f_i, \quad (1.12)$$

$\sigma^2$  is the flux variance

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N (f_i - \langle f \rangle)^2, \quad (1.13)$$

and  $\delta^2$  is the mean square uncertainty of the fluxes

$$\delta^2 = \frac{1}{N} \sum_{i=1}^N \delta_i^2. \quad (1.14)$$

The uncertainty on  $F_{\text{var}}$  is measured as

$$\sigma_{F_{\text{var}}} = \frac{1}{2F_{\text{var}}} \sqrt{\frac{1}{N} \frac{\sigma^2}{\langle f \rangle^2}}. \quad (1.15)$$

The calculated fractional variability as a function of observed wavelength generally decreases with increasing wavelength due to the non-variable flux from the host galaxy, which is significant at longer wavelengths (e.g., [Fausnaugh et al. 2016](#)). Another reason is that, longer wavelengths are produced at larger distances. Hence, they have larger delays implying larger region size causing the variations to be smoothed. There are several time scales used to characterize the variability of AGNs (e.g., [Edelson & Nandra 1999](#), [Peterson 2001](#), [Frank et al. 2002](#), [Czerny 2006](#), [Pal et al. 2018](#)). Here, the main focus is on the five variability time scales associated with the standard thin disc ([Shakura & Sunyaev 1973](#)). Namely, the light-crossing, dynamical, hydrostatic equilibrium, thermal and viscous time-scales.

The light-crossing timescale  $\tau_{\text{lc}}$  is defined as the time it takes continuum variations induced in the accretion disc to travel from the innermost part of the disc to the reprocessing site, where they are reprocessed into other wavelengths in the disc (or the broad emission lines in the BLR, and/or narrow emission lines in the NLR)

$$\tau_{\text{lc}} = r/c, \quad (1.16)$$

where  $r$  is the radius of the reprocessing site.

The dynamical timescale  $\tau_{\text{dyn}}$  is the shortest timescale on which changes to the structure of the BLR may occur and is related to the Keplerian velocity as

$$\tau_{\text{dyn}} \sim \frac{r}{v_{\text{Kep}}} = \left( \frac{r^3}{GM} \right)^{1/2}, \quad (1.17)$$

where  $M$  is the mass of the SMBH and  $r$  the radius.

The characteristic time over which fluctuations to hydrostatic equilibrium in the vertical ( $z$ ) direction of the disc are smoothed out is given by

$$\tau_z \sim \frac{H}{c_s} \quad (1.18)$$

where  $H$  is the thickness of the disc and  $c_s$  is the adiabatic sound speed.

The thermal time scale  $\tau_{\text{th}}$  is the characteristic time needed to establish thermal equilibrium (i.e to establish the local balance of heating and cooling)

$$\tau_{\text{th}} \sim \frac{\tau_{\text{dyn}}}{\alpha}, \quad (1.19)$$

where  $\alpha$  ( $\sim 0.1$ ) is the [Shakura & Sunyaev \(1973\)](#) disc viscosity parameter.

The viscous time scale  $\tau_{\text{visc}}$  is the characteristic time over which material diffuses through the accretion disc due to the influence of viscous torques

$$\tau_{\text{visc}} \sim \frac{\tau_{\text{dyn}}}{\alpha(H/r)^2}, \quad (1.20)$$

where  $(H/r)$  is the ratio between the disc thickness and radius.

These time scales can be rewritten to show their dependence on the mass of the SMBH and distance from the center. Assuming a fiducial value of black hole mass  $M = 1 \times 10^7 M_\odot$ , an aspect ratio between the disc thickness and radius  $H/r \sim 0.01$  (e.g., [Netzer 2013](#)), and sound speed  $c_s \sim 10 \text{ km s}^{-1}$  (e.g., [Cantiello et al. 2021](#)), results in measurements in Table 1.1 where the radius  $r$  is measured in terms of Gravitational radius  $r_G = \frac{GM}{c^2}$ . For UV/optical bandpasses, [Cackett et al. \(2021\)](#) gives the upper limit on the radius as  $r \sim 10^4 r_G$ .

The different timescales are related in order of increasing magnitude according to  $\tau_c <$

Table 1.1: Different timescale values assuming a fiducial value for black hole mass.

| $r$<br>( $r_G$ ) | $M$<br>( $M_\odot$ ) | $\tau_c$<br>(days) | $\tau_{\text{dyn}}$<br>(days) | $\tau_z$<br>(days) | $\tau_{\text{th}}$<br>(years) | $\tau_{\text{visc}}$<br>( $10^4$ years) |
|------------------|----------------------|--------------------|-------------------------------|--------------------|-------------------------------|-----------------------------------------|
| $10^4$           | $10^7$               | 6                  | 570                           | 1710               | 15.62                         | 15.61                                   |

$\tau_{\text{dyn}} < \tau_z < \tau_{\text{th}} < \tau_{\text{visc}}$  as shown in Table 1.1.

## 1.5 Black Hole Masses

Astronomers had previously studied the motion of the surrounding matter to infer the existence of black holes at the centre of galaxies (e.g., [Kormendy & Richstone 1995](#)). Today, there exists direct visual images of the SMBH in the centre of our galaxy; the Milky Way (MW, [Event Horizon Telescope Collaboration et al. 2022](#)). Although, the MW is not the only galaxy to be directly imaged, it follows the messier 87 galaxy ([Event Horizon Telescope Collaboration et al. 2019](#)), found at a distance about 53 million light years away from Earth. The two results, serves as the most powerful evidence for the existence of SMBHs at the cores of galaxies. Their existence further supports the widely accepted paradigm that the large observed luminosity of massive galaxies is due to accretion of matter onto them ([Rees 1984](#)). It is therefore important to try to understand their growth rates and evolution over

cosmic time, as well as understand their connection (if any) with their host galaxy. This can be achieved through an accurate mass estimation of the SMBH. The MW has the most accurate mass known of  $4 \times 10^6 M_\odot$  (Ghez et al. 1998, Schödel et al. 2002, Event Horizon Telescope Collaboration et al. 2022), with M87 galaxy harbouring a central SMBH with one of the largest masses known of  $6.4 \times 10^9 M_\odot$  (Macchetto et al. 1997, Gebhardt & Thomas 2009, Event Horizon Telescope Collaboration et al. 2019).

Section 1.2.1 defines an SMBH as having a mass  $\sim 10^6 M_\odot$ . This lower limit is determined empirically through measuring the masses of these objects at the cores of their host galaxies, either through the dynamics of the nearby surrounding material (Section 1.5.1) or through time-dependent variability studies (Section 1.5.2). The latter method will be discussed further in Chapter 2.

### 1.5.1 Dynamical Methods

A direct method for measuring the masses of black holes has been established based on the dynamical motions of the surrounding gas and stars within and around the sphere of influence (few parsec scale) of the black hole (Kormendy & Richstone 1995, Ferrarese & Ford 2005). It is suitable for local or nearby (few tens of Mpc) quiescent galaxies as it requires high angular resolution to fully resolve the inner parts of the galaxy. The black hole masses can also be measured from dynamics of water masers (Miyoshi et al. 1995, Siopis et al. 2009, Greene et al. 2010). An empirical relationship between the mass of the black hole ( $M_{\text{BH}}$ ) and the velocity dispersion ( $\sigma_*$ ) of the host-galaxy bulge ( $M_{\text{BH}} - \sigma_*$ , Ferrarese & Merritt 2000, Gebhardt et al. 2000, Tremaine et al. 2002, Gültekin et al. 2009) was derived and is as illustrated in Figure 1.6a. The distribution of the measured black hole masses with velocity dispersion implies a close connection between the growth of the black hole mass and the galaxy formation. The relation takes the form

$$\log_{10} \frac{M_{\text{BH}}}{M_\odot} = \alpha + \beta \log_{10} \frac{\sigma_*}{200 \text{ km s}^{-1}}, \quad (1.21)$$

where  $\alpha$  and  $\beta$  are the intercept and slope respectively, used to characterize the power-law fit. There have been different values of  $\alpha$  and  $\beta$  reported in the literature (e.g., McConnell & Ma 2013, and references therein). Some of the factors influencing  $\alpha$  and  $\beta$ , are the galaxy sample size, sample selection and statistical technique used to derive them. Recent measurements of the above coefficients are provided by McConnell & Ma (2013) as  $\alpha = 8.32 \pm 0.05$  and  $\beta = 5.64 \pm 0.32$ , for an expanded and revised dynamical measurements of black hole masses, constituting a sample of 72 local quiescent galaxies.

Another important relationship to emerge from the dynamical measurements is the relationship between the black hole mass ( $M_{\text{BH}}$ ) and the luminosity of the bulge ( $L_{\text{bulge}}$ ) component of the host galaxy ( $M_{\text{BH}} - L_{\text{bulge}}$ , Kormendy & Richstone 1995, Magorrian et al. 1998) seen in Figure 1.6b. The distribution of the measured black hole masses also implies a close connection between the growth of the black hole mass and the galaxy formation, with the

fit characterized by

$$\log_{10} \frac{M_{\text{BH}}}{M_{\odot}} = \alpha + \beta \log_{10} \frac{L}{10^{11} L_{\odot}}, \quad (1.22)$$

where  $\alpha$  and  $\beta$  are evaluated by [McConnell & Ma \(2013\)](#), as  $9.23 \pm 0.10$  and  $1.11 \pm 0.13$  respectively.

The principal difference between the  $M_{\text{BH}} - \sigma_*$  and  $M_{\text{BH}} - L_{\text{bulge}}$  relations or correlations is the scatter in the distribution of the measured black hole masses. In the case of  $M_{\text{BH}} - \sigma_*$ , the scatter is relatively small. [Gebhardt et al. \(2000\)](#) touched on the scatter as being consistent with the measurement errors for the galaxies with the most reliable black hole mass measurements. In contrast,  $M_{\text{BH}} - L_{\text{bulge}}$  reveals a relatively large scatter, except in the case of [Marconi & Hunt \(2003\)](#). In both relations, the scatter depends on the sample size and the method used.

These relations ( $M_{\text{BH}} - \sigma_*$  and  $M_{\text{BH}} - L_{\text{bulge}}$ ) based on dynamical methods are essential for two reasons. First, as mentioned above, they imply a close connection between galaxy formation and black hole growth (co-evolution). This also serves as observational evidence for AGN feedback on the host galaxy ([Fabian 2012](#), for a review). Secondly, if we measure the velocity dispersion ( $\sigma_*$ ) or the luminosity of the bulge component ( $L_{\text{bulge}}$ ) of a galaxy, we can use the relationship to estimate the black hole mass ([Doroshenko et al. 2012](#)). The sample discussed here is made up of only nearby galaxies. To further investigate the black hole-galaxy connection, a large sample of black hole in the local and distant universe is needed. However, the problem with dynamical methods is that they are limited to distances of up to 250 Mpc. At distances greater than that they suffer from very poor spatial resolution, despite advances in today's technology, and therefore it is not feasible to measure the masses of distant AGNs using this method.

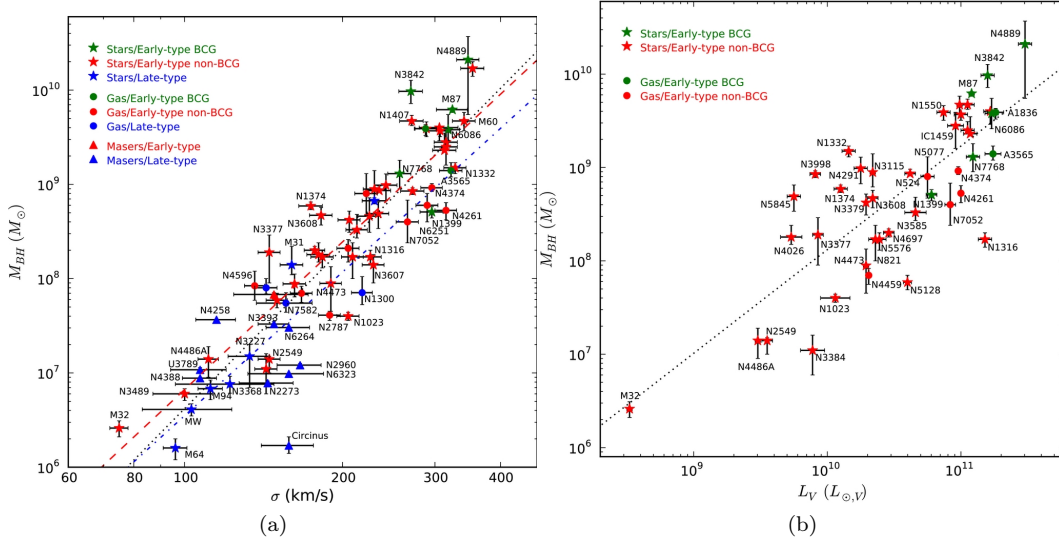


Figure 1.6: The black hole mass measurements based on dynamical methods. *Left:* The correlation between the black hole mass and the velocity dispersion of the host-galaxy bulge. *Right:* The correlation between the black hole mass and the luminosity of the host-galaxy bulge component. The plots are extracted from McConnell & Ma (2013).

### 1.5.2 BLR Reverberation Mapping

The reverberation mapping (RM) method relies on time resolution instead of spatial resolution. This affords us the opportunity to calibrate the local and the distant samples in terms of  $M_{\text{BH}} - \sigma_*$  and  $M_{\text{BH}} - L_{\text{bulge}}$  correlations. In the case of Type 1 Seyferts or Quasars, RM measures the time delay ( $\tau$ ) of the variations of the emission-line fluxes arising from the BLR relative to the variations in the ionizing continuum from the accretion disc. The measured time delay directly allows for the size of the BLR ( $R_{\text{BLR}} = c\tau$ ) to be determined. This  $R_{\text{BLR}}$ , combined with the velocity width ( $\Delta V$ ) of the broad line, yields the mass of the SMBH assuming that the kinematics of the BLR gas clouds are dominated by the strong gravity from the SMBH. Using a simple virial equation, the formulation of the mass of the SMBH is as follows (Blandford & McKee 1982, Peterson & Wandel 1999)

$$M = f \frac{R_{\text{BLR}}(\Delta V)^2}{G}, \quad (1.23)$$

where  $G$  is the gravitational constant.  $\Delta V$  is the velocity width usually measured by either the full-width at half-maximum (FWHM) or the line dispersion,  $\sigma_{\text{line}}$ , of the broad emission line from the mean or root-mean-square (rms) spectrum. Peterson et al. (2004) argued that measuring the SMBH mass  $M$  using  $\sigma_{\text{line}}$  yields more self-consistent measurements than does the FWHM. The advantages and disadvantages introduced by using either will be discussed in Section 2.6, though it is common practice to adopt  $\sigma_{\text{line}}$  from the rms spectrum, as it is a better tracer of the gas that is actually responding to the ionizing continuum (Peterson 2011).  $f$  is a dimensionless virial factor that depends upon the structure, inclination and

kinematics of the BLR. It can either be determined through direct modeling of the BLR (e.g., [Pancoast et al. 2014a;b](#), [Grier et al. 2017a](#)), or can be determined empirically by “forcing” the SMBH mass velocity dispersion ( $M - \sigma_*$ ) relationship for AGNs to match that of quiescent galaxies (e.g., [Onken et al. 2004](#), [Woo et al. 2010](#), [Grier et al. 2013a](#), [Woo et al. 2013](#), [Ho & Kim 2014](#), [Woo et al. 2015](#), [Batiste et al. 2017](#), [Yu et al. 2019; 2020a](#)). The former is seldom done as it requires high-fidelity data ([Horne et al. 2004](#)) and yields  $f$  specific to an AGN. The latter yields different average values of  $\langle f \rangle$  depending on the sample size and velocity-width  $\Delta V$  tracers. The commonly used values are from [Onken et al. \(2004\)](#), who derived the average value  $f = \langle 1.4 \rangle$  using FWHM and  $f = \langle 5.5 \rangle$  based on  $\sigma_{\text{line}}$  in the rms spectrum. Other commonly used values are those derived by [Woo et al. \(2015\)](#), of  $f = \langle 1.12 \rangle$  using FWHM and  $f = \langle 4.47 \rangle$  ( $\sigma_{\text{line}}$ ) in the rms spectrum based on RM sample of 29 AGNs. The most recent measurements are  $f = \langle 1.51 \rangle$  (FWHM) and  $f = \langle 6.61 \rangle$  ( $\sigma_{\text{line}}$ ) from [Yu et al. \(2020a\)](#). These values, even though different, are consistent to within errors. So far RM has yielded  $> 100$  SMBH mass measurements (e.g., [Wandel et al. 1999b](#), [Kaspi et al. 2000](#), [Peterson et al. 2004](#), [Bentz et al. 2009b](#), [Denney et al. 2009a](#), [Barth et al. 2011; 2015](#), [Valenti et al. 2015](#), [Shen et al. 2016b](#), [Fausnaugh et al. 2017](#), [Grier et al. 2018](#), [Du et al. 2018b](#), [Hlabathe et al. 2020](#), [Hu et al. 2021](#)) and [Bentz & Katz \(2015\)](#), for a compilation). The use of RM, though effective in measuring the SMBH masses in nearby and distant AGNs, is time-consuming and requires fairly high quality observations over an extended period. Fortunately, observations reveal a scaling relationship between the BLR size and luminosity  $R_{\text{BLR}} - L_{\text{AGN}}$  (Section 1.6), enabling masses of SMBHs to be determined using a single-epoch (SE) spectrum (Section 1.7).

## 1.6 Size-luminosity Relation

This observed scaling relationship between  $R_{\text{BLR}}$  and  $L_{\text{AGN}}$  is of the form

$$R_{\text{BLR}} \propto L_{\text{AGN}}^{\alpha}, \quad (1.24)$$

where  $\alpha$  is the power-law slope. Using  $\text{H}\beta$  time-lag measurements, [Kaspi et al. \(2005\)](#) measured the best-fitting slope  $\alpha \approx 0.67 \pm 0.05$ , not correcting for host-galaxy starlight. [Bentz et al. \(2006; 2009a\)](#) took into account starlight contamination of optical luminosities of AGNs through high resolution images attained with HST/ACS, and measured the slope to be  $\alpha \approx 0.52 \pm 0.04$  and  $\alpha \approx 0.52 \pm 0.06$ , corresponding to 2006 and 2009 campaigns respectively. The two Bentz et al. studies are consistent with prediction from simple photoionization ( $R_{\text{BLR}} \propto L^{0.5}$ ) ([Davidson 1972](#)). [Bentz et al. \(2013\)](#) redid the  $R_{\text{BLR}} - L$  relation by adding 20 new measurements with the best-fitting slope  $\alpha \approx 0.53 \pm 0.03$ . [Bentz et al. \(2013\)](#) analysis of the  $R_{\text{BLR}} - L_{5100\text{\AA}}$  relation agrees best with prediction from photoionization, with an intrinsic scatter of  $0.19 \pm 0.02$  dex. The photoionization model assumes that all

AGNs have the same ionization parameter  $U$  defined as

$$U = \frac{Q(H)}{4\pi R_{\text{BLR}}^2 n_e c} \quad (1.25)$$

where  $n_e$  is the electron density, and  $Q(H) \propto L$  is the number of ionizing photons emanating from the central source per second. From this a slope of 0.5 is expected if the ionizing parameter  $U$  and  $n_e$  do not vary from AGN to AGN (i.e., same ionization conditions and BLR gas density). Similarly, a slope of 0.5 is predicted if the BLR size is determined using the dust sublimation radius (Netzer & Laor 1993).

The Bentz et al. (2013) sample spans the luminosity range  $42 \leq \log \lambda L_\lambda (\text{erg s}^{-1}) \leq 46$  for AGNs mostly found at  $z < 0.3$ . These measurements are based on the broad Balmer  $H\beta$  line due to its accessibility by most optical telescopes. Grier et al. (2017b) expanded the luminosity range to include  $H\beta$  measurements of AGNs up to redshift  $z \sim 1.1$ . The higher one goes in redshift, lines such as  $\text{MgII}(2800\text{\AA})$  and  $\text{CIV } \lambda 1550\text{\AA}$  start becoming important, therefore warranting the need to build up independent  $R_{\text{BLR}} - L$  relations for these lines. There have been limited attempts focusing on  $\text{MgII}(2800\text{\AA})$  and  $\text{CIV } \lambda 1550\text{\AA}$  broad lines (e.g., Shen et al. 2016b, Hoormann et al. 2019). The generally weak variability of  $\text{MgII}$  (Goad et al. 1999, Trevese et al. 2007, Modzelewska et al. 2014, Cackett et al. 2015) compared to broad Balmer lines ( $H\beta$ ,  $H\alpha$ ), makes the lag measurement difficult. Apart from weak variability, photoionization models have demonstrated that  $\text{MgII}$  has a larger average formation radius compared to Balmer lines (Guo et al. 2020, and references therein). This means it responds with a lower variability amplitude to continuum variations.

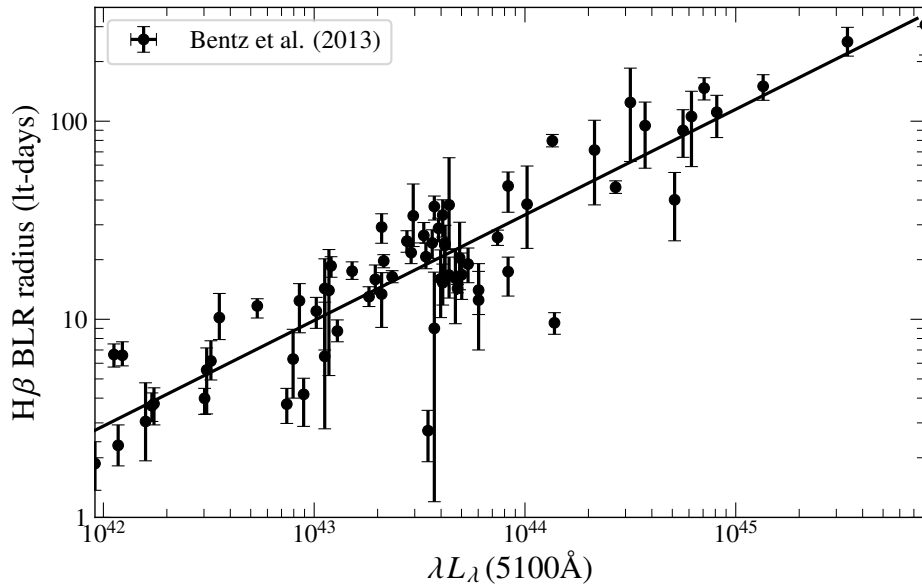


Figure 1.7: Optical continuum luminosity and  $H\beta$  lags for several AGNs from the sample of Bentz et al. (2013). The solid line is the best-fit line with  $K = 1.527 \pm 0.31$  and  $\alpha = 0.533^{+0.035}_{-0.033}$ .

## 1.6.1 Impact of Accretion Rate

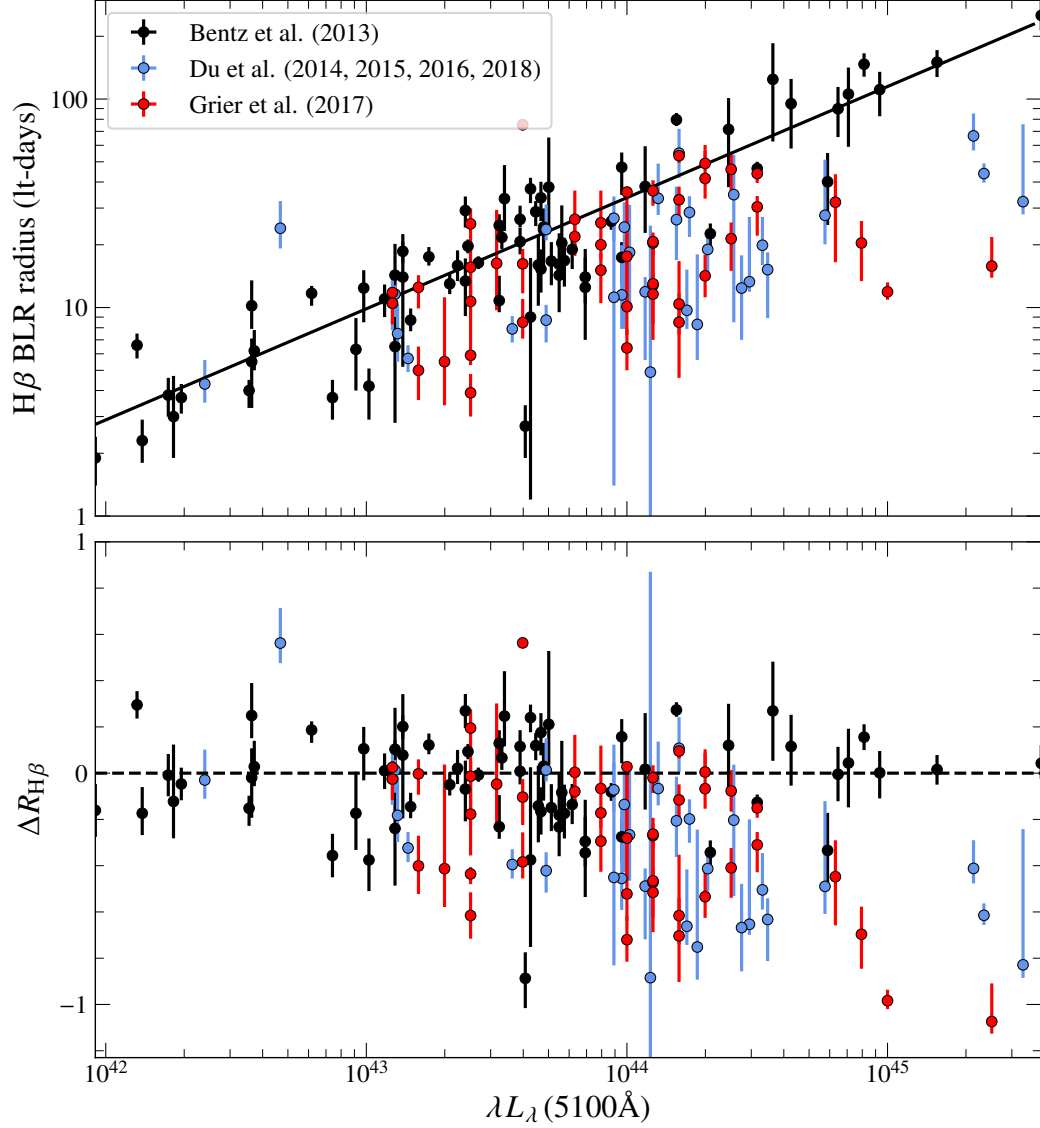


Figure 1.8: Top: The  $R_{H\beta}$  -  $L_{5100}$  relation from different samples. Bottom: The calculated offsets or deviations  $\Delta R_{H\beta}$  from the relation for each sample.

The [Bentz et al. \(2013\)](#) sample has since evolved, following more measurements of the size and luminosity for several individual AGNs shown in Figure 1.8. The [Grier et al. \(2017b\)](#)  $H\beta$ -based sample is made up of sources from Sloan Digital Sky Survey (SDSS) spanning the redshift range  $0.1 < z < 1.1$ , while the [Du et al. \(2014; 2015; 2016b; 2018b\)](#) samples consists of super-Eddington accreting massive black holes (SEAMBHs) spanning a range  $0.01 < z < 0.4$ . The samples from these studies show deviation from the expected trend (i.e., lie below the trend line). The observed lags ( $\tau_{\text{obs}}$ ) are shorter than predicted ( $\tau_{R-L}$ ) or

are offset by several amounts. This offset ( $\Delta R_{H\beta}$ ) is calculated as the ratio between observed and expected lags  $\Delta R_{H\beta} = \log(\tau_{\text{obs}}/\tau_{R-L})$ , shown in the bottom panel of Figure 1.8. The deviations in Grier and Du samples are greater than for the Bentz samples. The dependence of the perceived deviation on other properties has been investigated (e.g., Du et al. 2016b; 2018b, Du & Wang 2019, Martínez-Aldama et al. 2019, Fonseca Alvarez et al. 2020). It is understood, so far, that the accretion rate plays a role in the deviation of the observed lags from the  $R-L$  relation. AGNs with the highest dimensionless accretion rate  $\dot{\mathcal{M}}$  (Eqn. 1.5) experience the largest deviation, further increasing the scatter. These are objects generally accreting above the super-Eddington criterion ( $\dot{\mathcal{M}} > 3$ ) (Du et al. 2018b) as in Figure 1.9. That is, accretion in these objects induces self-shadowing of the disc such that the measured broad-line lags are shorter than expected for a given  $\lambda L_{\lambda}(5100\text{\AA})$ . Wang et al. (2014) explains the self-shadowing as a thickening of the disc due to rapid accretion of matter, causing the disc to reduce the ionizing continuum signal incident to the BLR, thus decreasing or shortening the BLR radius.

To decrease the scatter induced by the dimensionless accretion rate parameter and Eddington

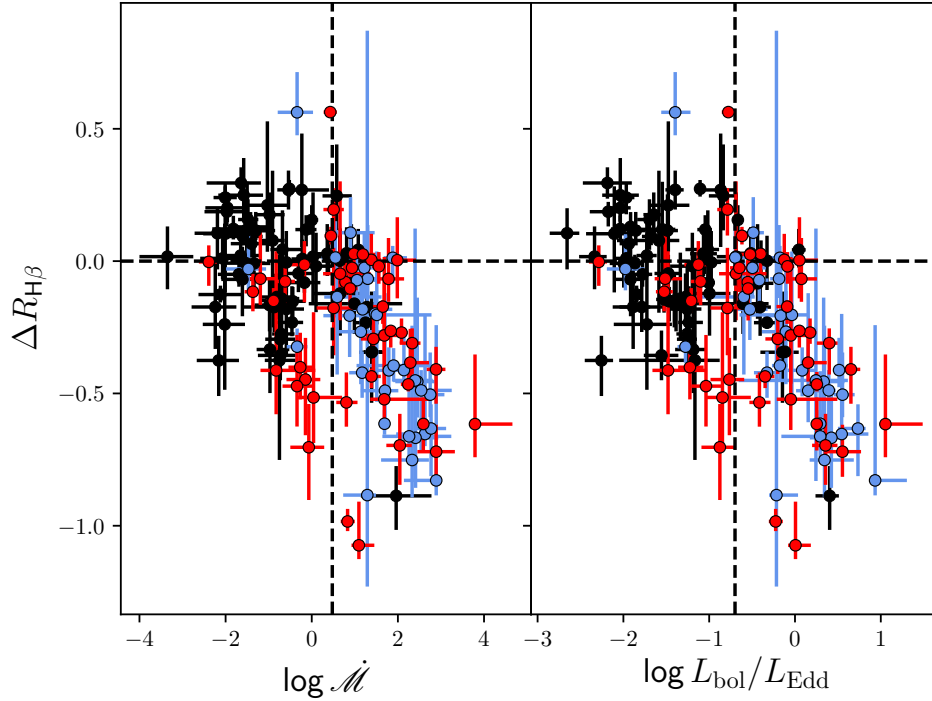


Figure 1.9: Left: Relation between  $\Delta R_{H\beta}$  and  $\log \dot{\mathcal{M}}$ . The horizontal and vertical dashed lines corresponds to  $\Delta R_{H\beta} = 0$  and  $\dot{\mathcal{M}} = 3$ . Right: Relation between  $\Delta R_{H\beta}$  and  $\log \dot{\mathcal{M}}$ . The vertical line corresponds to  $L_{\text{bol}}/L_{\text{Edd}} = 0.2$ .

ratio (Eqn. 1.5), Martínez-Aldama et al. (2019) introduces a way to correct for the bias

introduced by these parameters to the observed lags as

$$\Delta R_{H\beta, X} = \alpha \log X + \beta. \quad (1.26)$$

$X$  is the accretion parameter given by dimensionless accretion rate or Eddington ratio and  $(\alpha, \beta)$  are the coefficients of the fit. Taking into account this correction decreases the scatter as shown in Figure 1.10.

A third parameter affecting the deviation of AGNs in the  $R - L$  relation is  $\mathcal{R}_{\text{Fe}}$ , defined as

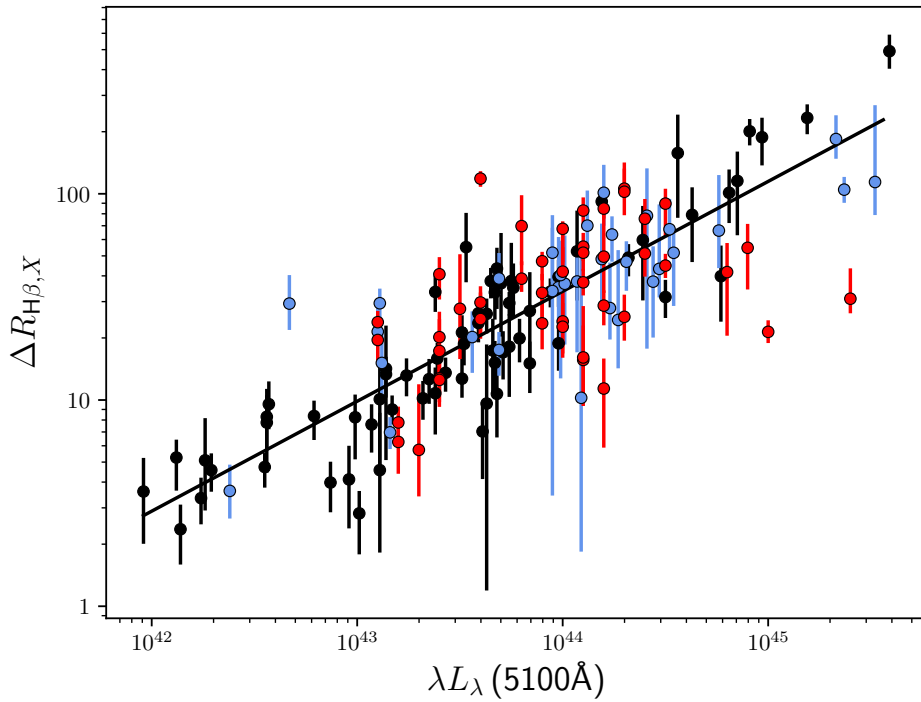


Figure 1.10: The  $R_{H\beta} - L_{5100}$  relation following Eqn. 1.26, where the best-fit coefficients are taken from [Martínez-Aldama et al. \(2019\)](#).

the flux ratio between Fe II and  $H\beta$

$$\mathcal{R}_{\text{Fe}} = F_{\text{Fe}}/F_{H\beta}. \quad (1.27)$$

Figure 1.11 from [Du & Wang \(2019\)](#) shows that  $\mathcal{R}_{\text{Fe}}$  correlates with  $\Delta R_{H\beta}$ , confirming its contribution on the deviation of an AGN from the  $R - L$  relation. [Du & Wang \(2019\)](#) conclude that  $\mathcal{R}_{\text{Fe}}$  is related with the accretion rate and Eddington ratio, which implies the accretion rate is the main reason for the shortened lags. Eqn. 1.26 can be rewritten to include this parameter as

$$\Delta R_{H\beta} = \alpha + \beta \log l_{44} + \gamma \mathcal{R}_{\text{Fe}}, \quad (1.28)$$

where  $l_{44} = L_{5100}/10^{44} \text{ erg s}^{-1}$ . For a sample of 120 AGNs, Yu et al. (2020b) measured the best-fit parameters  $\alpha = 1.53 \pm 0.08$ ,  $\beta = 0.42 \pm 0.03$  and  $\gamma = -0.28 \pm 0.04$  with intrinsic scatter of  $\sigma_{\text{int}} = 0.23 \pm 0.02 \text{ dex}$ . Both the Du & Wang (2019) and Yu et al. (2020b) samples give a similar scatter, an improvement from the scatter of 0.28 dex measured by Du et al. (2018b).

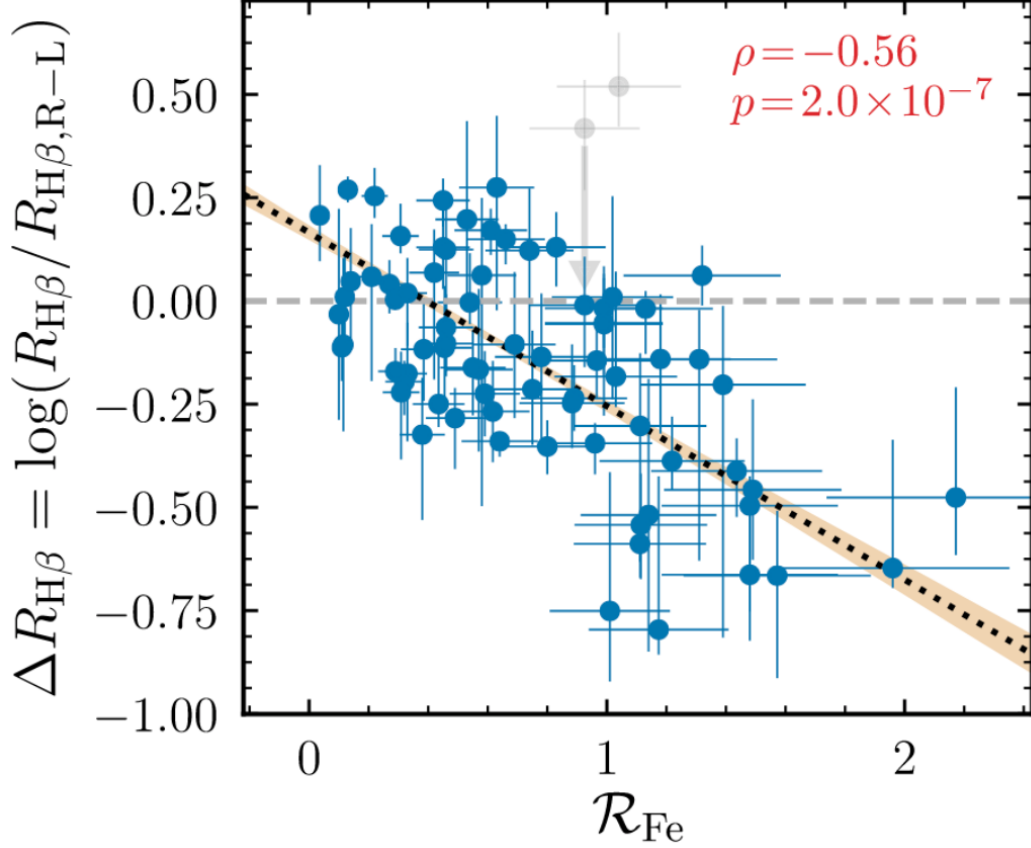


Figure 1.11: This shows  $\mathcal{R}_{\text{Fe}}$  correlates with  $\Delta R_{\text{H}\beta}$ , taken from Du & Wang (2019)

## 1.7 Single-epoch Mass Estimates

The SE method (Wandel et al. 1999b, Vestergaard 2002, Vestergaard & Peterson 2006) takes advantage of the  $R_{\text{BLR}} - L_{\text{AGN}}$  relation (Section 1.6) to provide estimates of SMBH masses in nearby AGNs and distant luminous quasars. For SE-based masses,  $L_{\text{AGN}}$ , along with velocity width,  $\Delta V_{\text{SE}}$ , of the broad emission lines, gives an estimate of the SMBH mass as

$$\log(M_{\text{SE}}) = \alpha \log(L_{\text{AGN}}) + \beta \log(\Delta V_{\text{SE}}) + \text{constant} . \quad (1.29)$$

$\Delta V_{\text{SE}}$  is measured from the single spectrum and  $L_{\text{AGN}}$  can be measured from either the single spectrum using spectral decomposition, or from imaging decomposition, or from multi-

wavelength photometry. The coefficients  $(\alpha, \beta)$  and the constant are calibrated using the RM sample (e.g., Vestergaard & Peterson 2006, Ho & Kim 2015, Woo et al. 2018, Dalla Bontà et al. 2020). This way of estimating the SMBH mass does not require long-term monitoring or high spatial resolution. Different broad lines such as  $H\beta$  (e.g., Wandel et al. 1999b),  $MgII(2800\text{\AA})$  (e.g., McLure & Jarvis 2002), and  $CIV \lambda 1550\text{\AA}$  (e.g., Vestergaard 2002) have been employed as estimators for SE masses for low, intermediate and high- $z$  AGNs. The AGN continuum luminosity at  $5100\text{\AA}$  is typically paired with the  $H\beta$  emission line in estimating the SE-based mass,  $M_{SE}$ . The  $MgII$  and  $CIV$  lines are paired with the UV continuum luminosity at  $1350\text{\AA}$ . The virial SE masses based on these lines are subject to biases due to measurements of the  $\Delta V$  and corrections to the luminosity for host-galaxy contribution. The former also holds true for RM-based measurements. For RM, the line width  $\Delta V_{RM}$  measurement is averaged over multiple spectra instead of one spectrum like in the case of SE. Also in RM, the  $\Delta V_{RM}$  is usually taken as the line dispersion ( $\sigma_{line}$ ) measured from the rms spectrum (the variable part of the spectrum) after deblending non-varying components. For SE,  $\Delta V_{SE}$  is usually measured from the FWHM of the broad line. The measurement of the FWHM can be biased in the case of a complex broad-line profile and/or strong narrow-line component while the measurement of  $\sigma_{line}$  can introduce biases due to blending of the line wings with neighboring lines (Shen 2013).

Of the two often used virial mass estimators ( $H\beta$ ,  $CIV$ ),  $CIV$  emission line is more prone to biases than is  $H\beta$  (e.g., Denney 2012, Runnoe et al. 2013; 2014, Denney et al. 2016). There are several reasons why this is the case.  $CIV$  tends to display an asymmetric profile as a result of gas outflows (Denney 2012), implying its gas is not virialized. It also tends to be blueshifted with respect to the systemic redshift (Sun et al. 2018). Being a high-ionization line (originating closer to the central engine), its velocity width should be broader than the low-ionization line  $H\beta$  (e.g., Peterson et al. 2014), but that is at times not the case, highlighting the non-virialization of its gas, or that its BLR is not stratified (e.g., Trakhtenbrot & Netzer 2012).  $CIV$  widths display a large scatter when compared with  $H\beta$  velocity widths, whereas they should be linearly correlated if from the same BLR.  $CIV$  is also subject to more systematics than  $H\beta$  in the case of low-quality data (Vestergaard & Peterson 2006), due to its weak detection. Such issues render the use of  $CIV$  as a SE virial mass estimator problematic, in that it requires extra care to avoid known potential problems, despite playing a role in the high- $z$  regime.

The  $H\beta$ -based masses are estimated to be uncertain by  $\sim 0.309$  dex if  $\Delta V_{SE}$  is characterized by  $\sigma_{line}$  from the mean spectrum, or  $0.371$  dex if adopted from FWHM from the mean spectrum. The estimated uncertainty using the  $CIV$  line is  $\sim 0.408$  dex if  $\Delta V_{SE}$  is measured from the  $\sigma_{line}$  in the mean spectrum, whereas measurements adopting the FWHM are deemed unreliable. These uncertainty estimates are given in Dalla Bontà et al. (2020) whose calibrated SE masses take into account the effect of Eddington ratio. The uncertainty also arises in the adoption of the dimensionless virial factor,  $f$ , introducing an uncertainty of  $0.4$  dex (Peterson 2010) in the mass estimate. The uncertainty of the  $H\beta$ -based masses may

also arise due to significant host-galaxy contribution to the  $L_{5100\text{ \AA}}$  continuum luminosity, especially for low- $z$  AGNs. A comparison between SE and RM-based mass estimates in this thesis will be discussed in Chapters 5 and 6.

## 1.8 Continuum Reverberation Mapping

Though UV/optical continuum reverberation mapping is not a new technique (e.g., [Collier et al. 1998](#)), it is in recent times that it has gained traction owing to improved multi-wavelength observations, in terms of temporal sampling and S/N. Instead of broad-line delays, these seek to measure delays between continuum light curves at various wavebands within the disc. For the steady-state blackbody accretion thin-disc model with temperature profile  $T(R) \propto (M\dot{M})^{1/4}/R^{-3/4}$  (where the radius  $R = c\tau$ ), continuum time delays in the disc are expected to scale with wavelength according to  $\tau(\lambda) \propto (M\dot{M})^{1/3}\lambda^{4/3}$ , increasing with SMBH mass  $M$  and mass accretion rate  $\dot{M}$  ([Starkey et al. 2016](#), [Cackett et al. 2021](#)). This lag-wavelength dependence is shown in Figure 1.12 for NGC 5548 ([Fausnaugh et al. 2016](#)).

The current problem posed by the continuum studies in which the inter-band delays were detected, is that even though the lags obey the  $\tau \propto \lambda^{4/3}$  relation, they yield accretion-disc sizes 2-3 $\times$  larger than expected from a geometrically-thin and optically-thick standard accretion disc model. For example, [Fausnaugh et al. \(2016\)](#) measured a disc size a factor of 3 larger. Similarly, [McHardy et al. \(2014\)](#), [Edelson et al. \(2015\)](#), [McHardy et al. \(2018\)](#), [Hlabathe et al. \(2020\)](#), and others) measured larger disc sizes than predicted. One of the possible reasons for this deviation is contamination of the continuum lags by broad emission lines and diffuse continuum from the BLR, first proposed by [Korista & Goad \(2001\)](#). This deviation from expected disc sizes is also observed in microlensing studies of high-redshift, high-luminosity quasars ([Poindexter et al. 2008](#), [Morgan et al. 2010](#)).

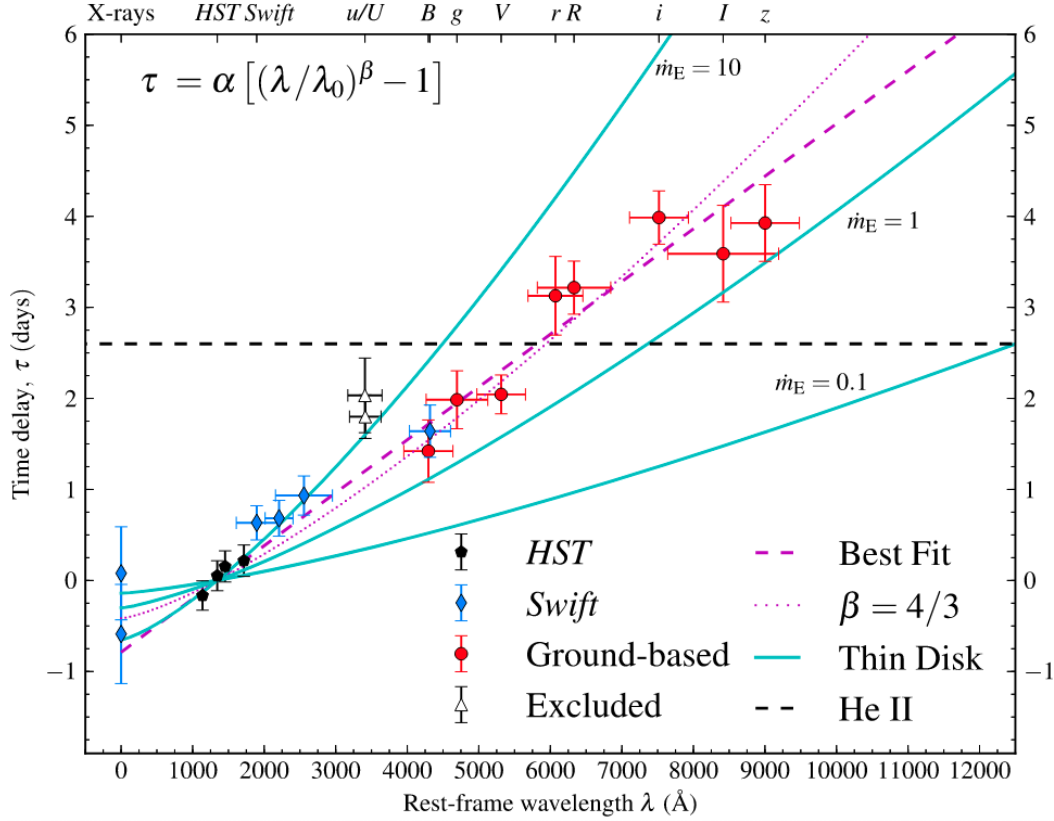


Figure 1.12: Rest-frame wavelength as a function of time delay from [Fausnaugh et al. \(2016\)](#). The solid cyan lines are the different standard thin-disc models. The power-law fit with  $\beta = 4/3$  is indicated by the dotted magenta line and the best-fit line is indicated by the dashed magenta line.

## 1.9 Motivation

Black hole (BH) mass measurements combining several studies obey a scaling relationship with host-galaxy properties. This scaling relationship suggests a strong connection between BH mass and properties of the host-galaxy bulge, as shown in Figure 1.6. Both are well-calibrated in the local universe ( $z < 0.3$ ). For the distant universe ( $z > 0.3$ ), the sample is quite small (e.g., [Li et al. 2021](#)) due to a lack of robust BH mass measurements. Therefore, in order to fully comprehend the BH-galaxy co-evolution over cosmological time, it is useful to populate and compare both local and distant samples for better calibration of these scaling relationships. There are two distinct methods for measuring BH masses as explained in Sections 1.5.1 and 1.5.2. This study makes use of the latter method to obtain time delays and measure BH masses in 3C 120, PG 2304+043 and SDSS J132447.65+032432.6.

In addition, this study aims to undertake continuum RM (Section 1.8)

1. to derive the observed lag spectrum such as Figure 1.12 and compare against  $\tau \propto \lambda^{4/3}$  from thin-disc theory;

2. to fit thin-disc model to the continuum light curves to derive disc parameters such as Eddington ratio  $L_{\text{bol}}/L_{\text{Edd}}$ , mass accretion rate  $\dot{M}$ , and temperature profile  $T(R)$  for a given BH mass  $M$ ;
3. to measure the observed accretion-disc size at some reference wavelength and compare with model-predicted size;
4. to derive the observed disc spectrum or SED for each AGN to see if it approximates the power-law ( $f_\nu \propto \lambda^{-1/3}$ ) spectrum expected for a standard thin-disc model.

Also, to investigate how some of the disc parameters scale with the BH mass  $M$ . Lastly, to measure continuum luminosity at 5100 Å using multi-wavelength photometric observations for each AGN, for contribution in the  $R_{\text{H}\beta}$  -  $L_{5100}$  relation.

### 1.9.1 AGN Key Project

This forms part of an ongoing AGN key project titled Reverberation Mapping of AGN Accretion Flows (Valenti et al. 2015). Its purpose is to employ RM techniques to derive masses of BHs in several AGNs spanning a wide redshift range, in addition with doing multi-band optical reverberation mapping to derive physical properties of the accretion disc. Below are some of the key goals of the project

1. To obtain  $\text{H}\beta$  time delays for AGNs at  $z < 0.3$ ;
2. Additionally, obtain time delays for  $\text{MgII}(2800\text{\AA})$  and  $\text{CIV}(1550\text{\AA})$  broad emission lines for AGNs at  $z > 0.3$ ;
3. To calibrate size-luminosity ( $R_{\text{BLR}}$  -  $L$ ) relations for the above broad lines;
4. To test accretion thin-disc theory wherein:
  - the observed continuum delays are predicted to scale as  $\tau(\lambda) \propto \lambda^{4/3}$
  - the observed delay spectrum mimics the predicted spectrum as  $f_\lambda \propto \lambda^{-1/3}$
5. To derive the temperature profile of the disc  $T(r) = \left( \frac{3 G M \dot{M}}{8 \pi \sigma r^3} \right)^{1/4}$ .

The remainder of the thesis is organized as follows: Chapter 2 covers the fundamentals of the RM technique from assumptions to implementation. Chapter 3 goes over the telescopes and instruments used for data collection. Chapter 4 is based on the RM of the broad-line radio galaxy 3C 120. Chapter 5 is based on the RM of PG 2304+043. Chapter 6 is based on the RM of SDSS J132447.65+032432.6. Chapter 7 puts the results into broader context with similar studies. Lastly, the conclusion in Chapter 8.

Throughout the thesis, a cosmological model with  $H_0 = 73.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.27$  and  $\Omega_\Lambda = 0.73$  is assumed.

## Chapter 2

# Principles of Reverberation Mapping

### 2.1 Fundamentals

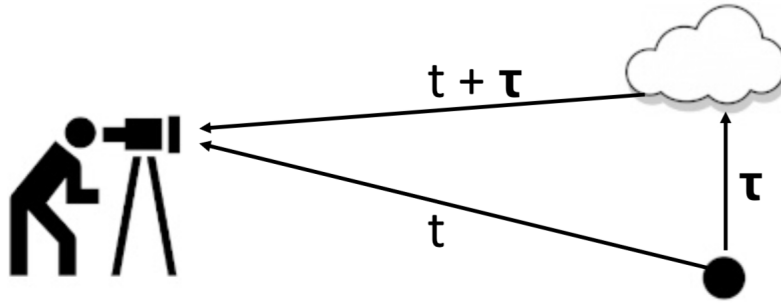


Figure 2.1: From an observer's vantage point, there is a time delay ( $\tau$ ) between direct emission ( $t$ ) from the central source indicated by the filled black circle and reflected emission ( $t + \tau$ ) from the broad-line region gas cloud.

Reverberation mapping (RM, [Blandford & McKee 1982](#), [Peterson 1993](#)) is a widely used technique which seeks to measure the time delay (or lag) between variations in the continuum radiation and corresponding variations in the broad emission lines as a result of light-travel time effects across the broad-line region (BLR), see [Figure 1.3](#) for AGN structure. One of the potential sources of AGN variability is instabilities in the accretion disc ([Section 1.4.5](#)). As matter (i.e., surrounding gas or stars) gets pulled onto the accretion disc causing thermal instabilities within the disc, a stochastic continuum emission is produced. The continuum emission from the disc induces emission lines from high density gas clouds in the nearby BLR (0.01 - 0.1 pc) and more distant NLR (0.3 - 30 pc). Observationally, because the BLR

is closely orbiting the central SMBH, broad emission lines are produced due to high Doppler velocities as seen in the spectra of Quasars and Seyferts (Figure 1.4). Any variability in the continuum is “echoed” by the gas clouds in the BLR after some time. From a point of view of a distant observer (Figure 2.1), any change in the continuum  $\Delta C(t)$  is succeeded by a change in the emission line  $\Delta L(t)$  from the BLR, with a time delay ( $\tau$ ) that depends on the light-travel time across the BLR ( $R_{\text{BLR}} = c\tau$ ).

### 2.1.1 Assumptions

Even though the outermost parts of the BLR have been spatially resolved through observations of 3C 273 obtained at the Very Large Telescope Interferometer using GRAVITY (e.g., Gravity Collaboration et al. 2018), it still remains a challenge for many of the present-day instruments, due to its small physical size ( $<0.1$  milli-arcseconds). RM takes advantage of the intrinsic variability of the broad emission lines seen in the spectra of Type 1 AGN to resolve the central region of an AGN. To do that, there are accompanying RM assumptions (see Peterson 1993; 2001, for an extended review):

- Due to the smaller physical size ( $10^{13} - 10^{14}$  cm across) when compared to the BLR ( $10^{16} - 10^{17}$  cm in radius) of the continuum-emitting source, it is considered as a point source. The nature of the emitted continuum radiation is not isotropic, despite it being generally assumed to be the case.
- The incident continuum radiation from the central source gets reprocessed into broad emission lines almost instantaneously. For the high density gas clouds in the BLR, the recombination time ( $\tau_{\text{rec}} \approx 0.1$  hr) is smaller compared to the light-travel time. This means that the dynamical cloud-crossing times of the BLR are longer than the light-travel time by a factor of  $\tau_{\text{dyn}} = c/\Delta V$ . Consequently, it can be assumed that the BLR structure is nearly stable over the duration of the reverberation monitoring campaign.
- It is generally assumed that the relationship between the observed continuum at  $\lambda \sim 5100 \text{ \AA}$  and the ionizing continuum at  $\lambda < 912 \text{ \AA}$  is approximately linear, though not quite the case.

The implications of these assumptions are discussed in Section 2.6.

### 2.1.2 1-D transfer function

In RM, the variations in the continuum light curve are represented as

$$\Delta C(t) = C(t) - \bar{C}, \quad (2.1)$$

where  $C(t)$  is observed continuum fluxes and  $\bar{C}$  is a constant accounting for the contribution from starlight. The variations in the emission-line light curve are represented as

$$\Delta L(t) = L(t) - \bar{L}, \quad (2.2)$$

where  $L(t)$  is observed emission-line fluxes and  $\bar{L}$  is a constant accounting for the contribution from narrow lines. The  $\Delta C(t)$  and  $\Delta L(t)$  are related according to

$$\Delta L(t) = \int_{-\infty}^{+\infty} \Psi(\tau) \Delta C(t - \tau) d\tau. \quad (2.3)$$

That is, the line light curve variations  $\Delta L(t)$  are a convolution of the continuum with the so-called 1-D transfer function  $\Psi(\tau)$  (Horne 1994). The consideration of  $\bar{C}$  and  $\bar{L}$  offers the only modification to the transfer function described by Blandford & McKee (1982), where a linear relationship is assumed between observed ionizing continuum and emission-line response fluxes. In reality, the relationship between observed continuum and emission-line fluxes may be non-linear (Horne 1994). Eqn. 2.3 can deal with non-linear responses provided the contributions by  $\bar{C}$  and  $\bar{L}$  are small enough that local response remains approximately linear (e.g., Mangham et al. 2019). Depending on where it is in the BLR, each cloud of gas will have a different delay relative to the incident ionizing continuum. The transfer function,  $\Psi(\tau)$ , maps the delay distribution of all clouds that contribute to the observed mean delay  $\tau$ . Thus  $\Psi(\tau)$  contains information about the geometry of the BLR. The ultimate goal of RM is to solve for  $\Psi(\tau)$  or the two-dimensional velocity-delay map  $\Psi(\tau, V)$  (Section 2.5). It turns out solving for  $\Psi(\tau)$  is not a straightforward task as it requires large amounts of data and has only been done in a handful of AGNs (e.g., Denney et al. 2009b, Du et al. 2016a).  $\Psi(\tau)$  can still be solved with modest amount of data by cross-correlating the observables  $\Delta C(t)$  and  $\Delta L(t)$  to measure the temporal lag  $\tau$ , provided  $\Delta C(t)$  and  $\Delta L(t)$  are regularly sampled. The cross-correlation function (CCF) is then

$$\text{CCF}(\tau) = \int_{-\infty}^{+\infty} \Delta L(t) \Delta C(t - \tau) dt. \quad (2.4)$$

Using Eqn. 2.3 to substitute for  $\Delta L(t)$  in Eqn 2.4

$$\text{CCF}(\tau) = \int_{-\infty}^{+\infty} \Delta C(t - \tau) \int_{-\infty}^{+\infty} \Psi(\tau') \Delta C(t - \tau') d\tau' dt. \quad (2.5)$$

Rewriting Eqn. 2.5

$$\text{CCF}(\tau) = \int_{-\infty}^{+\infty} \Psi(\tau') \int_{-\infty}^{+\infty} \Delta C(t - \tau) \Delta C(t - \tau') dt d\tau'. \quad (2.6)$$

Finally, Eqn. 2.6 becomes

$$\text{CCF}(\tau) = \int_{-\infty}^{+\infty} \Psi(\tau') \text{ACF}(\tau - \tau') d\tau', \quad (2.7)$$

where ACF is the autocorrelation function of the continuum with itself (Penston 1991, Peterson 1993). The observed delay  $\tau$  is then the weighted average

$$\tau = \frac{\int_{-\infty}^{+\infty} \tau \Psi(\tau) d\tau}{\int_{-\infty}^{+\infty} \Psi(\tau) d\tau}, \quad (2.8)$$

called the centroid of the  $\text{CCF}(\tau)$ . Different cross-correlation techniques have been developed for measuring  $\tau$  depending on the quality of the data and are discussed below.

## 2.2 Cross-Correlation Analysis

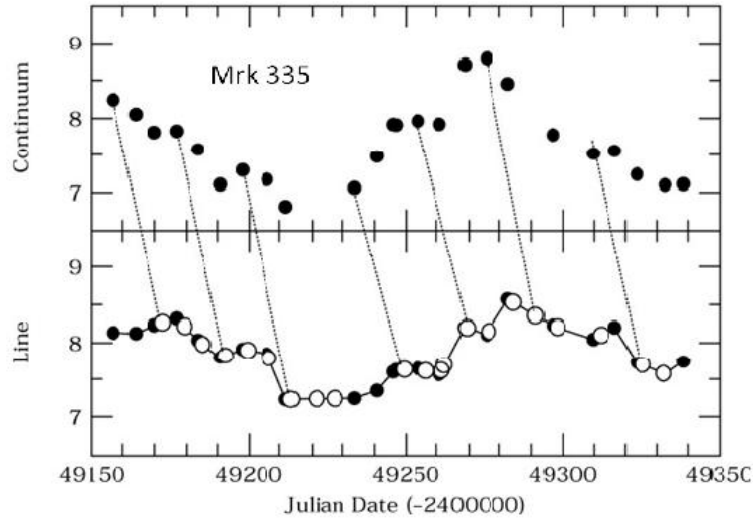


Figure 2.2: Time delay between measurements of variations of continuum and emission-line fluxes for Mrk 335, taken from Peterson (2001).

Let  $C(t_i)$  denote continuum-emission flux measurements, from either spectroscopy or photometry, and  $L(t_i)$  denote the emission-line flux measurements from spectroscopy. White & Peterson (1994) defines the cross-correlation function as

$$\text{CCF}(\tau) = \frac{1}{N} \sum_{i=1}^N \frac{[C(t_i) - \bar{C}][L(t_i - \tau) - \bar{L}]}{\sigma_C \sigma_L}, \quad (2.9)$$

where  $\bar{C}$ ,  $\bar{L}$  are the light curve means and  $\sigma_C$ ,  $\sigma_L$  are the standard deviations of  $C(t_i)$  and  $L(t_i)$  respectively. Let  $\tau = i\Delta t$  (for  $i = 1, 2, 3, \dots, N - 1$  and  $\Delta t = t_{i+1} - t_i$ ) denote the time-shift or lag and  $N$  the length of the time series. Defining  $\text{CCF}(\tau)$  as above means

possible values of  $\text{CCF}(\tau)$  range from  $-1$  to  $+1$ . The end goal of performing cross-correlation analysis is to find the value of  $\tau$  where the two time series are perfectly aligned. It is easy to ascertain  $\tau$  if  $C(t_i)$  and  $L(t_i)$  are uniformly sampled; but in astronomy, especially in time series variability studies,  $C(t_i)$  and  $L(t_i)$  are seldom well-sampled due to bad weather, telescope scheduling (or maintenance), moon phases, etc. These issues lead to gaps in the data, or to data that is noisy.

There are various methods or techniques constructed to deal with uneven data sampling, such as interpolation cross-correlation function (ICCF, Gaskell & Sparke 1986, Gaskell & Peterson 1987), discrete correlation function (DCF, Edelson & Krolik 1988), z-transformed discrete correlation function (ZDCF, Alexander 1997; 2013) methods. Over the years model-based JAVELIN (Zu et al. 2011; 2013) and CREAM (Starkey et al. 2016; 2017) have been developed to deal with uneven data.

### 2.2.1 Interpolation Cross-Correlation Function

In ICCF (White & Peterson 1994), each flux measurement in the line light curve,  $L(t_i)$ , is shifted by an arbitrary value  $\tau$  and linearly interpolated at  $t_i - \tau$  to give a point  $L(t_i - \tau)$ . The interpolation is introduced to account for the uneven sampling of the original data. In most cases, the continuum light curve,  $C(t)$ , is almost always better sampled than  $L(t)$ , so ideally one would want only to interpolate  $C(t)$  and keep  $L(t)$  unchanged (Gaskell & Sparke 1986). One of the modifications suggested by White & Peterson (1994) is that  $\text{CCF}(\tau)$  be computed twice. First, perform the cross-correlation between linearly interpolated continuum-emission flux measurements at  $C(t_i + \tau)$  and emission-line flux measurements  $L(t_i)$ , for a given value  $\tau$ . Secondly, between continuum-emission flux measurements at  $C(t_i)$  and linearly interpolated emission-line flux measurements  $L(t_i - \tau)$ , for a given value  $\tau$ . The final cross-correlation function  $\text{CCF}(\tau)$  is defined as the mean of the two results. This is so that the  $\text{CCF}(\tau)$  does not favor one interpolation over the other.

The time delay  $\tau$  is characterised by two parameters,  $\tau_{\text{cent}}$  and  $\tau_{\text{peak}}$ . The  $\tau_{\text{peak}}$  of the  $\text{CCF}(\tau)$  gives the lag corresponding to the maximum correlation coefficient  $\text{CCF}_{\text{max}}$ . The  $\tau_{\text{cent}}$  of the  $\text{CCF}(\tau)$  gives the average lag, weighted by all correlation values above a particular threshold, typically  $\text{CCF}(\tau) \geq 0.8 \text{CCF}_{\text{max}}$  (Peterson et al. 2004). In the case of a broad peak, choosing  $\tau_{\text{peak}}$  could be biased. To circumvent this, a  $\tau_{\text{cent}}$  is usually preferred over  $\tau_{\text{peak}}$ . Figure 2.3 provides an example of  $\text{CCF}(\tau)$  where a lag  $\tau_{\text{cent}} = 15.6$  days is measured using points in the shaded region, these are all points above  $0.8 \text{CCF}_{\text{max}}$ .

To measure the error or uncertainty associated with the lag  $\tau$  from ICCF, Peterson et al. (1998b) proposed the use of  $n$  Monte Carlo runs in the form of random subset selection (RSS) and flux randomization (FR) methods, or FR/RSS when combined. In the FR/RSS method, the original light curve data is randomly sampled with replacement. At this point, the newly obtained light curve from random sampling contains same number of points as the original light curve but with duplicates. The repeated points are then rejected, resulting in a randomly selected subset that is smaller than the original light curve data. Each flux mea-

surement from the remaining points is perturbed by adding random Gaussian deviate scaled to the measurement uncertainty of that flux point. This process is repeated  $n$  (typically  $10^3$ ) times to build up the cross-correlation centroid distribution (CCCD) and cross-correlation peak distribution (CCPD). The widths of these distributions are used to derive the 68% confidence interval on the lag.

While the ICCF has proven successful, it is, however, subject to several biases such as long-term trends, correlated errors, and outliers. [Welsh \(1999\)](#) demonstrated that detrending (i.e., removing long-term trends), can substantially improve the ICCF lag determination. In some cases, detrending also makes the correlation coefficients stronger (e.g., [Zhang et al. 2019](#)). The correlated errors (e.g., [Peterson 1993](#)) arise as a result of flux calibration errors. Any error in flux calibration biases both the continuum (from spectroscopy) and line light-curve errors by the same amount, leading to a lag that is consistent with zero. [Yu et al. \(2020c\)](#) simulated the effect of outliers on the uncertainties from CCCD and CCPD, and found to result in large uncertainties.

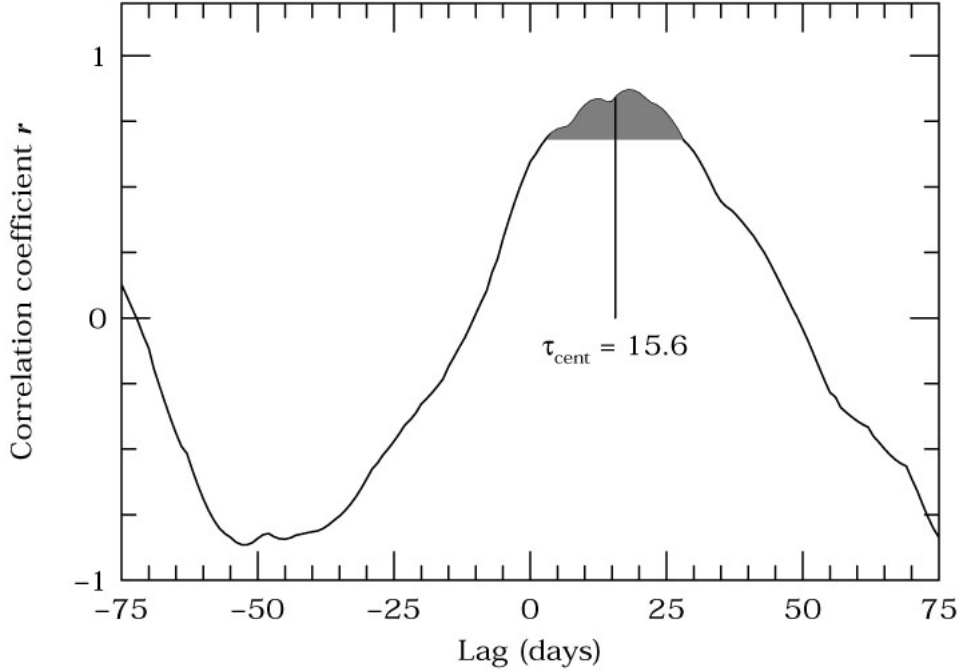


Figure 2.3: The ICCF results between light curves in Figure 2.2, taken from [Peterson \(2001\)](#).

### 2.2.2 Discrete Correlation Function

The ICCF method works best on well-sampled light curves, but in the case of under-sampled light curves it suffers from interpolation errors. The DCF ([Edelson & Krolik 1988](#)) method does not rely on interpolation (making no assumptions about the variability of the light curves), but uses only real light-curve points. Using the same light-curve notations as

Section 2.2.1 for continuum and line light curves, the unbinned DCF is defined as

$$\text{UDCF}_{ij} = \frac{(C(t_i) - \bar{C})(L(t_j) - \bar{L})}{\sqrt{(\sigma_C^2 - e_C^2)(\sigma_L^2 - e_L^2)}}, \quad (2.10)$$

where  $e_C$ ,  $e_L$  are the measurement errors and  $\sigma_C$ ,  $\sigma_L$  are the standard deviations for the continuum and line light curves respectively. Each measured coefficient is associated with the time difference  $\Delta t_{ij} = t_j - t_i$ . Averaging the  $M_l$  coefficients for which the interval  $\tau_l - \frac{\Delta\tau}{2} \leq \Delta t_{ij} < \tau_l + \frac{\Delta\tau}{2}$  is defined, where  $\Delta\tau$  is the bin size, gives the binned DCF as

$$\text{DCF}(\tau_l) = \frac{1}{M_l} \sum_{i,j=1}^{M_l} \text{UDCF}_{ij}, \quad (2.11)$$

and the uncertainty as

$$\sigma_{\text{DCF}}(\tau_l) = \frac{1}{M_l - 1} \sqrt{\sum_{i,j=1}^{M_l} [\text{UDCF}_{ij} - \text{DCF}(\tau_l)]^2}. \quad (2.12)$$

Defining the DCF this way means it is only defined for bins with data points, otherwise it is not defined. Therefore, choosing the right bin size is important. For example, choosing a small bin size increases the resolution of the cross-correlation curve, while a larger bin size ensures high accuracy of the mean defined by Eqn. 2.11. So there exists a tradeoff between the two. For a larger bin, one requires a higher number of data points to get meaningful results (Merc & Gális 2018), which is one of the disadvantages of using this method.

### 2.2.3 Z-transformed Discrete Correlation Function

The ZDCF (Alexander 1997; 2013) method offers a qualitative improvement over ICCF and DCF for measuring time delays for sparse and unevenly sampled light curves. The binning in ZDCF is by equal population (not by time-lag width  $\Delta\tau$  as in DCF) for which Fisher's  $z$ -transform is defined as

$$z = \frac{1}{2} \log \left( \frac{1+r}{1-r} \right), \quad r = \tanh z. \quad (2.13)$$

The convergence of the  $z$ -transform requires a minimum of  $n_{\min} = 11$  points per bin. This means the light curves must not consist of less than 12 epochs. A  $z$ -transform has a known bias in that it leads to overestimated errors. However, because of equal population binning, this bias does not depend on the number of data points, only on  $n_{\min}$ . This is another advantage that the ZDCF has over ICCF in analyzing unevenly sampled light curves, it does not assume an AGN variability model or smoothness of light curves (Zajaček et al. 2019). In ICCF, for example, a variability model is assumed as an approximation to interpolate between data points or measurements. ZDCF also provides a robust error estimation through Monte Carlo implementation on the cross-correlation coefficients, while the ICCF does not provide errors on the coefficients.

### 2.2.4 JAVELIN

Just Another Vehicle for Estimating Lags in Nuclei (JAVELIN, [Zu et al. 2011; 2016](#)) is commonly used to predict continuum-line and/or continuum-continuum time delays. It is used to fit or model AGN aperiodic variability using a damped random walk (DRW) model (Eqn. ??), which has been demonstrated to approximate AGN light curve behaviour quite well on time scales of months to years ([Kelly et al. 2009](#), [Kozłowski et al. 2010](#), [MacLeod et al. 2010](#), [Zu et al. 2013](#)). The application of this DRW model has so far proved successful in modeling AGN variability in reverberation mapping studies to measure time delays (e.g., [Grier et al. 2012](#), [Fausnaugh et al. 2016](#), [Grier et al. 2017b](#), [Fausnaugh et al. 2018](#)). In deriving the time lags  $\tau_{\text{JAV}}$ , JAVELIN fits the DRW model to continuum light curve, and a top-hat transfer function (parameterized by the scaling factor, width and time delay) to response light curves. It assumes the emission-line variability as shifted and smoothed versions of the continuum variability. It also assumes that one of the input light curves is the driver and uses that to build a model of the light curve along with the transfer function, and fits it to the continuum and emission-line light curves. In doing so it optimizes the model parameters and associated uncertainties employing the Monte Carlo Markov Chain (MCMC) method. As part of the output it includes the inferred posterior probability distributions for  $\sigma_{\text{DRW}}$ ,  $\tau_{\text{DRW}}$ , emission-line lag, top-hat smoothing width and scaling ratio between the line and continuum amplitudes.

### 2.2.5 CREAM

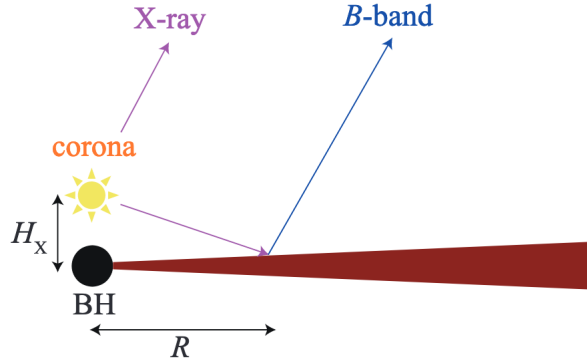


Figure 2.4: Schematic picture of an accretion disc irradiated by a hot variable X-ray point source just above the disc. Image extracted from [Noda et al. \(2016\)](#).

Probing the accretion disc in AGN is key in understanding the growth and evolution of the SMBH. The mechanism behind it can be explained in the context of a lamppost model and optically-thick and geometrically-thin accretion disc ([Shakura & Sunyaev 1973](#), hereafter SS73). Figure 2.4 illustrates the standard picture of a lamppost model. In this model the accretion disc is irradiated by a point-like X-ray source assumed to be

- a hot corona at  $H_X$  above the accretion disc (Haardt & Maraschi 1991),
- or the base of a jet on the rotation axis of the SMBH (Vincent et al. 2016, and references therein).

This X-ray radiation is effectively absorbed and reradiated into optical/UV bands. The CREAM (Continuum **RE**processing **AGN** **MCMC**) software (Starkey et al. 2016; 2017) uses this lamppost to model optical/UV continuum variations and derive accretion disc parameters. CREAM seeks to fit a lamppost  $X(t)$  reverberating accretion disc model to the input continuum light curves  $f_\nu(\lambda, t)$  with time delay distribution  $\psi(\tau|\lambda)$

$$f_\nu(\lambda, t) = \bar{F}_\nu(\lambda) + \Delta F_\nu(\lambda) \int X(t - \tau) \psi(\tau|\lambda) d\tau, \quad (2.14)$$

in order to derive the shape of the true driving light curve that drives the variability.  $\bar{F}_\nu(\lambda)$  and  $\Delta F_\nu(\lambda)$  are the mean and rms spectra respectively, and the driving light curve,  $X(t)$ , is normalised to  $\langle X \rangle = 0$  and  $\langle X^2 \rangle = 1$ . While fitting Eqn. 2.14, CREAM is also able to model inaccurate error bars (under/overestimated) using its noise model characterized by two parameters: an extra variance,  $V_j$ , and rescaling factor,  $f_j$  (Grier et al. 2017b),

$$\sigma_{ij} = \sqrt{(f_j \sigma_{\text{old } ij})^2 + V_j}. \quad (2.15)$$

$\sigma_{ij}$  is the rescaled error bars and the subscript  $i = 1, \dots, N_j$  is the number of observations for telescope  $j$ . The continuum response function is normalized such that  $\int \psi(\tau|\lambda) d\tau = 1$ .

CREAM does not assume one of the input light curves is the driver responsible for accretion-disc variability. Instead, using its noise model, it derives the driving light curve,  $X(t)$ , assumed to be a centrally located source with a stochastic luminosity modelled as a time series

$$X(t) = \sum_{k=1}^{N_k} C_k \cos(\omega_k t) + S_k \sin(\omega_k t). \quad (2.16)$$

The parameters of the driving light curve are the sine,  $S_k$ , and cosine,  $C_k$ , Fourier amplitudes that describe the shape of the lamp-post light-curve variations, and  $\omega_k \equiv k\Delta\omega$  are equally-spaced Fourier frequencies. To prevent chaotic high amplitude variations CREAM includes priors on the  $S_k$  and  $C_k$  parameters that steer the power spectrum of the driving light curve in the direction of a damped random walk (with  $P(\omega) \propto \omega^{-2}$ ),

$$\sigma_k^2 = \langle S_k^2 \rangle + \langle C_k^2 \rangle = P(\omega_k) \Delta\omega = P_0 \Delta\omega \left( \frac{\omega_0}{\omega_k} \right)^2, \quad (2.17)$$

where  $\sigma_k$  is the standard deviation, and the random walk priors are Gaussian with mean  $\langle S_k \rangle = \langle C_k \rangle = 0$ .

CREAM assumes the disc flux  $F_\nu(\lambda, t)$  is described by a black-body spectrum  $B_\nu(\lambda, T)$  inte-

grated over solid angle  $d\Omega$  such that

$$F_\nu(\lambda, t) = \int B_\nu(\lambda, T(t - \tau)) d\Omega. \quad (2.18)$$

$T(t - \tau)$  is the disc temperature at the appropriate look-back time  $\tau$ , and  $B_\nu(\lambda, T)$  is the Planck function given by

$$B_\nu(\lambda, T) = \frac{2hc}{\lambda^3} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}, \quad (2.19)$$

where  $h$  and  $k$  are the Planck and Boltzmann constants. The temperature profile of the disc  $T$  is governed as a power-law of the form

$$T = T_1 \left( \frac{r}{r_1} \right)^{-\alpha}, \quad (2.20)$$

where  $T_1$  is the temperature at  $r_1 = 1$  light day. For a standard thin-disc model of SS73,  $\tau \propto \lambda^{4/3}$  ( $\alpha \equiv 3/4$  in Eqn. 2.20) and

$$T_1^4 = \frac{3GM\dot{M}}{8\pi\sigma r_1^3}, \quad (2.21)$$

where  $M$  is the black-hole mass and  $\dot{M}$  is the mass accretion rate. The response function  $\psi_\nu(\tau|\lambda)$  for the reverberating thin disc is obtained by combining Equations 2.14 and 2.18 and is derived in Starkey et al. (2017). The final result takes the form

$$\psi_\nu(\tau|\lambda) = \sum_{\text{ir}} \sum_{\text{ia}} \Delta\Omega \frac{\partial B_\nu(T(r_{\text{ir}}, \theta_{\text{ia}}), \lambda)}{\partial T} \frac{\partial T}{\partial L_x} \frac{\partial L_x}{\partial F_x} f_c(r_{\text{ir}}) \delta(\tau - \tau'(r_{\text{ir}}, \theta_{\text{ia}}, i)), \quad (2.22)$$

and depends on the temperature parameters  $\alpha$  and  $T_1$ , and the disc inclination  $i$ . The response function also scales with wavelength with a mean delay  $\langle\tau\rangle$  given by

$$\langle\tau\rangle = \frac{\int_0^\infty \tau \psi(\tau) d\tau}{\int_0^\infty \psi(\tau) d\tau}. \quad (2.23)$$

Table 2.1 gives the summary of priors on the CREAM parameters. JAVELIN (Section 2.2.4) and CREAM have been found to perform better statistically, with irregular sampling and seasonal gaps, over the traditional methods (Grier et al. 2017b, Li et al. 2017).

### Accretion-disc Spectrum And Optical Luminosity At $\lambda$

To derive the spectral energy distribution (SED), CREAM employs a flux-flux method similar to that of Choloniewski (1981) and Cackett et al. (2007), known as the flux variation gradient (FVG) method. Fundamentally, the method aims to isolate the variable component from the constant background component. Choloniewski (1981) made the observation that fluxes in one filter show linear correlation relative to fluxes taken in another filter. In the case of CREAM, the response or echo light curves are expected to exhibit this linear relation due to

Table 2.1: Summary of priors on each of the CREAM parameters.

| Parameter                          | $N_{\text{par}}$                         | Prior                                                                                                                                       |
|------------------------------------|------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| $S_k$ and $C_k$                    | $2N_k$                                   | Gaussian ( $\langle S_k \rangle = \langle C_k \rangle = 0$ ,<br>$\langle S_k^2 \rangle = \langle C_k^2 \rangle = \sigma_k^2$ ) <sup>a</sup> |
| $\cos i$                           | 1                                        | Log Uniform                                                                                                                                 |
| $T_1$                              | 1                                        | Log Uniform                                                                                                                                 |
| $\alpha$                           | 0                                        | 3/4                                                                                                                                         |
| $\Delta F_\nu(\lambda)$            | $N_\lambda \times N_{\text{telescopes}}$ | Log Uniform                                                                                                                                 |
| $\bar{F}_\nu(\lambda)$             | $N_\lambda \times N_{\text{telescopes}}$ | Log Uniform                                                                                                                                 |
| $\bar{\tau}(\lambda)$ <sup>b</sup> | $N_\lambda$                              | Uniform                                                                                                                                     |

<sup>a</sup>  $\sigma_k$  is defined in Equation 2.17.

<sup>b</sup> The top-hat centroid lag parameter is optional and used as a substitute for CREAM's disc response function parameters  $T_1$ ,  $\alpha$ , and  $i$  if CREAM is run in top-hat mode.

disc reprocessing relative to the driving light curve,  $X(t - \tau)$ , averaged over the time delay distribution  $\Psi(\tau)$ , between the faint,  $X_F$ , and bright,  $X_B$ , states. The variable (or SED) and constant spectra are represented as  $\Delta F(\lambda)$  and  $\bar{F}(\lambda)$  in Eqn. 2.14. They are the slopes and intercepts of the best linear fits respectively and are related to the host-galaxy flux as

$$f_{\text{gal}}(\lambda) = \bar{F}_\nu(\lambda) + X_{\text{gal}} \Delta F_\nu(\lambda). \quad (2.24)$$

The galaxy-state,  $X_{\text{gal}}$ , is taken the point where the shortest wavelength first crosses the best-fitting line at  $f_\nu(\lambda, t) = 0$ . By assuming that the luminosity at some wavelength,  $\lambda$ , is entirely due to a steady thin standard disc, the host-galaxy subtracted disc spectra can be evaluated as

$$\bar{F}_{\text{disc}}(\lambda) = \bar{F}_\nu(\lambda) - f_{\text{gal}}(\lambda). \quad (2.25)$$

### 2.2.6 MEMEcho

An alternative approach, in the form of MEMEcho (Horne et al. 1991, Horne 1994), is sometimes used in reverberation studies to predict time delay distributions for each of the light curves (e.g., Grier et al. 2013b, McHardy et al. 2018, Horne et al. 2021). The MEMEcho employs the maximum entropy method to fit a linearized echo model

$$\Delta L(t) = \int \Psi(\tau) \Delta C(t - \tau) d\tau, \quad (2.26)$$

to the observed continuum light curve

$$C(t) = \Delta C(t) + \bar{C}, \quad (2.27)$$

and the emission-line response light curve

$$L(t) = \Delta L(t) + \bar{L}(t). \quad (2.28)$$

That is, the continuum light curve,  $C(t)$ , is represented as a sum of the varying components,  $\Delta C(t)$ , and a constant continuum background,  $\bar{C}$ . The  $\bar{C}$  is usually equated to the mean or median of the continuum light-curve data and is to account for possible contaminants to the continuum light curve (such as host-galaxy starlight) and is assumed constant. The line background,  $\bar{L}(t)$ , is a slowly varying component (i.e narrow emission line) and for typical reverberation timescales,  $\bar{L}(t)$  is essentially a constant (e.g., [Peterson et al. 2013](#)). The aim is to recover the transfer function,  $\Psi(\tau)$ , by solving for the convolution integral. The functions  $C(t)$  and  $L(t)$  must be solved in order to recover  $\Psi(\tau)$ . To do this, MEM seeks to find the simplest image,  $p_i$ , that approximates  $C(t)$  and  $L(t)$  by measuring the entropy

$$S \equiv \sum_i w_i [p_i - q_i - p_i \ln(p_i/q_i)] \quad (2.29)$$

relative to a default image,  $q_i$ , and with weights,  $w_i$ . Setting

$$\frac{\delta S}{\delta p_i} = -\ln(p_i/q_i) = 0 \quad (2.30)$$

maximizes the entropy when  $p_i = q_i$ . Eqn. 2.30 is only defined for positive  $p_i \geq 0$ , where  $p_i$  values are evaluated on a uniformly sampled grid with spacing  $\Delta t$ . For each  $p_i$ , the default value  $q_i = (p_{i-1} p_{i+1})^{1/2}$  is the geometric mean of its neighbors. This regulates the entropy such that regions of high curvature are penalized, leaning towards smooth functions with Gaussian peaks and exponential tails.

To model the AGN variability light curves with MEMEcho, one of the input light curves is designated the driving light curve (usually the one with relatively better quality) and others as echo light curves. The modeling is restricted to a delay range  $[\tau_{\min}, \tau_{\max}]$  with uniform time spacing  $\Delta t$ . The default function,  $q_i$ , is specified by the user to control the flexibility of the delay map function. The delay map stiffness is defined by the parameter  $w$  in order to stiffen  $\Psi(\tau)$  relative to the driving light curve. The desired  $\chi^2/N$  is set by the user for maximising the entropy  $S$ . This introduces a trade-off between small and large  $\chi^2$ . The very small  $\chi^2$  value ensures that the model is able to fit even the finer structures in the light curves, but may also introduce spurious features. For each iteration  $\chi^2/N$  is improved upon until the model has converged and the fit deemed satisfactory. The  $\chi^2/N \approx 1$  represents a good fit.

## 2.3 Line Width Measurements

[Peterson et al. \(2004\)](#) presents a recipe for measuring the broad-line width,  $\Delta V$ , in Eqn. 1.23, either using the FWHM and/or the line dispersion,  $\sigma_{\text{line}}$ . These quantities are measured in the same way regardless of whether they are adopted from the mean or rms spectra. The

mean spectrum (in the case of multi-epoch spectra) is constructed as

$$\bar{F}(\lambda) = \frac{1}{N} \sum_i^N F_i(\lambda), \quad (2.31)$$

where  $N$  is the number of spectra and  $F_i$  is the flux of the  $i$ th spectrum making up the time series. The rms spectrum,  $\sigma_{\text{rms}}(\lambda)$ , involves subtracting each  $i$ th flux,  $F_i(\lambda)$ , from the mean  $\bar{F}(\lambda)$ , hence it is sometimes referred to as the residual spectrum

$$\sigma_{\text{rms}}(\lambda) = \left\{ \frac{1}{N-1} \sum_i^N [F_i(\lambda) - \bar{F}(\lambda)]^2 \right\}^{1/2}. \quad (2.32)$$

The FWHM of the line is the easiest quantity to measure of the two and its measurement depends on whether the line profile,  $P(\lambda)$ , is single-peaked or double-peaked. For a single-peaked profile this is trivial as the half maximum of  $P(\lambda)$  is  $0.5P(\lambda)_{\text{max}}$  (where  $P(\lambda)_{\text{max}}$  is the maximum peak of the profile). In this case, the shortest wavelength,  $\lambda_1$ , is such that  $P(\lambda_1) = 0.5P(\lambda)_{\text{max}}$  and the longest wavelength,  $\lambda_2$ , is  $P(\lambda_2) = 0.5P(\lambda)_{\text{max}}$ . The FWHM is taken as the difference of the two wavelengths  $\lambda_2 - \lambda_1$ .

For a complex profile, such as double-peaked, the corresponding peaks are determined as  $P(\lambda)_{\text{max,short}}$  and  $P(\lambda)_{\text{max,long}}$  for short and long wavelengths, respectively. The wavelengths at half maxima are found by moving upward  $\lambda_1$  and moving downward  $\lambda_2$ . This is illustrated in Figure 2.5.

Once the positions of the wavelengths are determined, the FWHM is taken as the difference as above. On the other hand, the line dispersion of the profile is determined as

$$\sigma_{\text{line}} = \left[ \frac{\int (\lambda - \lambda_0)^2 P(\lambda) d\lambda}{\int P(\lambda) d\lambda} \right]^{1/2}, \quad (2.33)$$

where  $\lambda_0$  is the line centroid given as

$$\frac{\int \lambda P(\lambda) d\lambda}{\int P(\lambda) d\lambda}.$$

Henceforth, the broad emission-line widths measured through PrepSpec (Section 3.4.1) are not corrected for the resolution of the spectrograph. This is because the widths of the lines are broader, therefore the effect of not correcting for resolution becomes negligible.

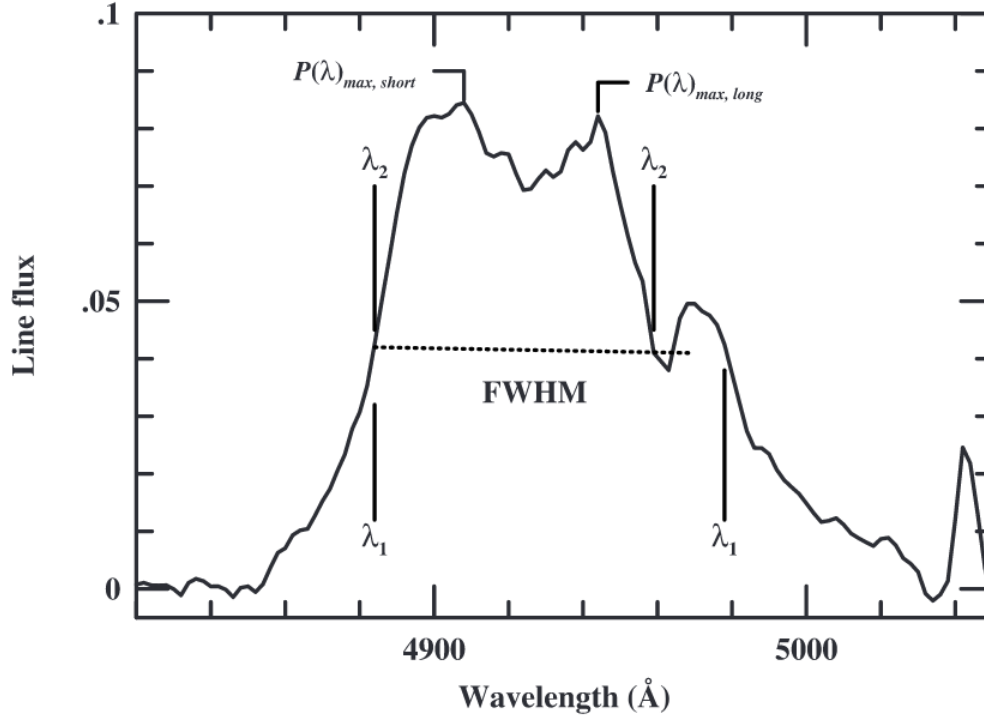


Figure 2.5: Example of measurement of FWHM for a double-peaked profile from [Peterson et al. \(2004\)](#).

### 2.3.1 Line Width Uncertainties

To estimate the uncertainties of both the FWHM and the line dispersion, a similar method as FR/RSS is employed and described in detail by [Peterson et al. \(2004\)](#). Given  $N$  spectra, a random subset selection of the spectra is drawn, regardless of whether or not the selected spectra were selected before. From the drawn subset, the mean and rms spectra are constructed, from which fits to the continuum are subtracted and FWHM and line dispersions are estimated. When this process is repeated numerous times a distribution of the line widths is obtained, from which the mean and standard deviation are determined.

## 2.4 Black Hole Mass

Section 2.2 covers different ways of measuring the time delay,  $\tau$ , and Section 2.3 the line width of the broad emission line,  $\Delta V$ . Combining these two parameters leads to the black hole mass,  $M$ , formulation as encountered before

$$M = f \frac{c\tau(\Delta V)^2}{G}. \quad (2.34)$$

## 2.5 2-D transfer function

So far, we have seen how RM can be used to measure the time lag,  $\tau$ , and consequently the mass of the SMBH,  $M$  (Eqn. 2.34). Ultimately, RM aims to derive the kinematics and structure of the BLR. To do that consider the BLR system in Figure 2.6. Each gas cloud will have a different line-of-sight velocity,  $V$ , with respect to the observer. Therefore, Eqn. 2.3 can be rewritten in 2-dimensional form as a function of both velocity and time delay

$$\Delta L(V, t) = \int_{-\infty}^{+\infty} \Psi(V, \tau) \Delta C(t - \tau) d\tau, \quad (2.35)$$

where  $\Psi(V, \tau)$  is the 2-D transfer function or “velocity-delay map”. The 2-D transfer function,  $\Psi(V, \tau)$ , encodes information about the geometry and kinematics of the BLR. The challenge

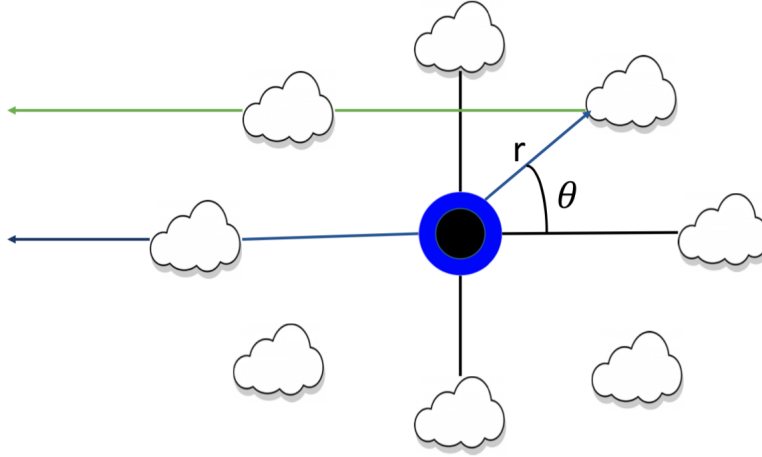


Figure 2.6: Depicted is the accretion disc (blue) and the fast moving gas clouds in the BLR. The time delay ( $\tau$ ) between the direct emission from the continuum source (blue arrow) and indirect emission from the BLR emitted at characteristic wavelengths, such as  $H\beta$ , CIV, MgII etc, due to recombination is shown (green arrow). The observer is situated to the left of the image.

is to recover  $\Psi(V, \tau)$ . Uneven sampling, limited S/N, and systematic errors often get in the way of successfully recovering  $\Psi(V, \tau)$ . From reverberating line profiles velocity-delay maps can be constructed in order to extract detailed information on the geometry and kinematics of the BLR. This is done by dividing the reverberating line profile into distinct velocity bins, and using cross-correlation techniques (Section 2.2) to measure the time delay,  $\tau$ , between the continuum light curve and the line light curve constructed from each velocity bin. Well-constructed velocity-delay maps typically show statistically significant Keplerian or disc-like geometry, and sometimes outflow/inflow signatures (e.g., Denney et al. 2009b, Bentz et al. 2009b).

In order to model different kinematic structures of the BLR, consider Figure 2.6. Although not necessarily the case, the emitting clouds in the BLR are assumed to be distributed

isotropically along a thin spherical shell of radius  $r$  around the central SMBH of mass  $10^8 M_\odot$  (arbitrarily chosen). Given that most emission-line shapes we observe are almost symmetric, this assumption is justifiable. Assume also that the observer sees the system pole-on and the gas clouds are orbiting anticlockwise around the nucleus at speed  $v(r)$ , where  $v(r) = \sqrt{\frac{GM}{r}}$  is the Keplerian or orbital speed. Through simple mathematics, it can be shown that any gas cloud in the BLR will have a time delay given by

$$\tau = \frac{r}{c} (1 + \cos \theta) , \quad (2.36)$$

where  $r$  is the BLR radius, and  $\theta$  is measured from 0, for a cloud on the far end of the nucleus, to  $180^\circ$ , on the line-of-sight between the nucleus and the observer. Hence, the mean delay is given as

$$\langle \tau \rangle = \frac{r}{c} \int_0^{2\pi} (1 + \cos \theta) d\theta / 2\pi = r/c . \quad (2.37)$$

If the gas clouds are assumed to move in Keplerian motion (Figure 2.7), then each gas cloud will have a line-of-sight velocity  $V$  given by

$$V = \pm v(r) \sin \theta , \quad (2.38)$$

where (+) and (−) signs indicate redshift and blueshift, respectively, with respect to the observer. Each shell of radius  $r$  maps onto an ellipse in the velocity-delay plane (Figure 2.8).

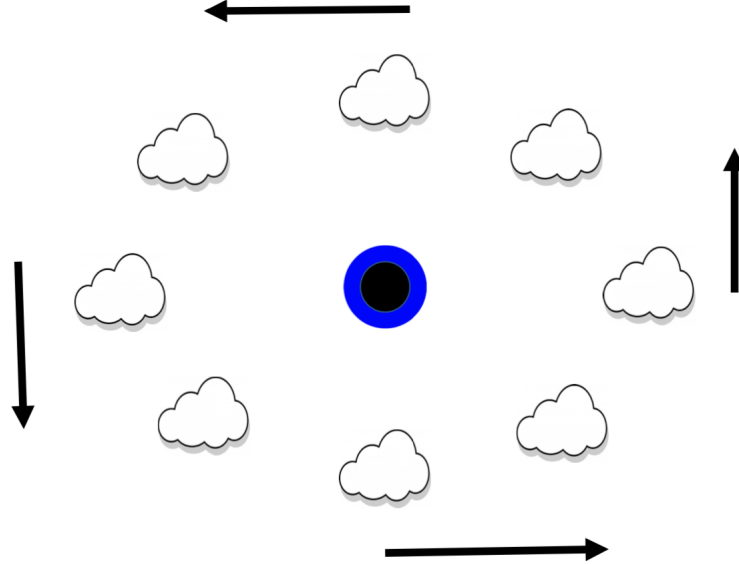


Figure 2.7: The BLR clouds assumed to move in near-circular (Keplerian) motion around the SMBH.

In an infall/inflow model (Figure 2.9), the BLR clouds move inward at a velocity  $-v(r)$

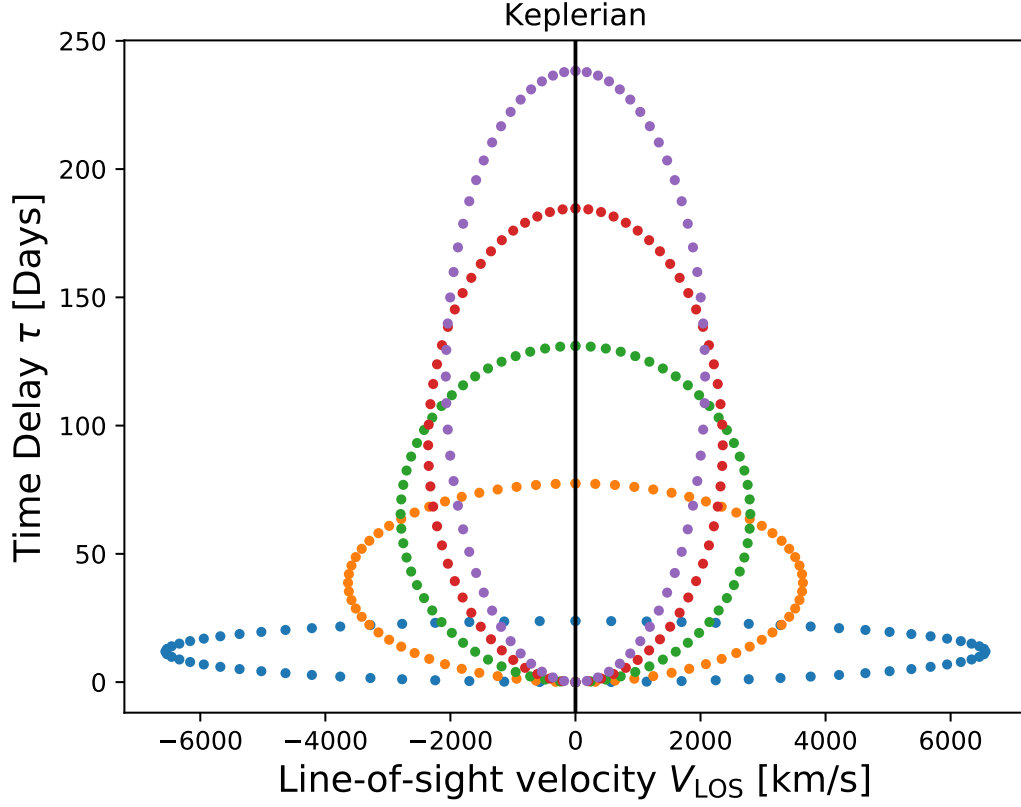


Figure 2.8: Keplerian orbit with time delay measurements that are symmetric about zero velocity. Different colors represent different shell radii from the central SMBH. The blue color maps to the smallest radius and purple color maps to the largest.

which increases with decreasing radius from the central SMBH where gravity dominates. The line-of-sight velocity  $V$  is then given by

$$V = -v(r) \cos \theta. \quad (2.39)$$

Each shell of radius  $r$  maps onto a diagonal line in the velocity-delay plane as can be seen in Figure 2.10. The point where the corresponding lines of different shells intercept (or cross) is called the caustic point (Welsh & Horne 1991). In an outflow model (Figure 2.11), each BLR cloud moves at a constant  $+v(r) = 6000 \text{ km s}^{-1}$  (arbitrarily chosen) where radiation pressure dominates over gravity. The line-of-sight velocity  $V$  then becomes

$$V = +v(r) \cos \theta, \quad (2.40)$$

and each shell of radius  $r$  maps onto diagonal lines in the velocity-delay space, see Figure 2.12.

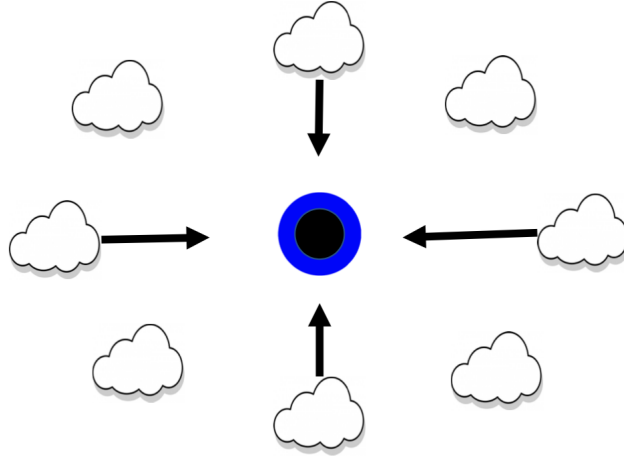


Figure 2.9: The BLR clouds assumed to move inward due to gravitational pull from the black hole.

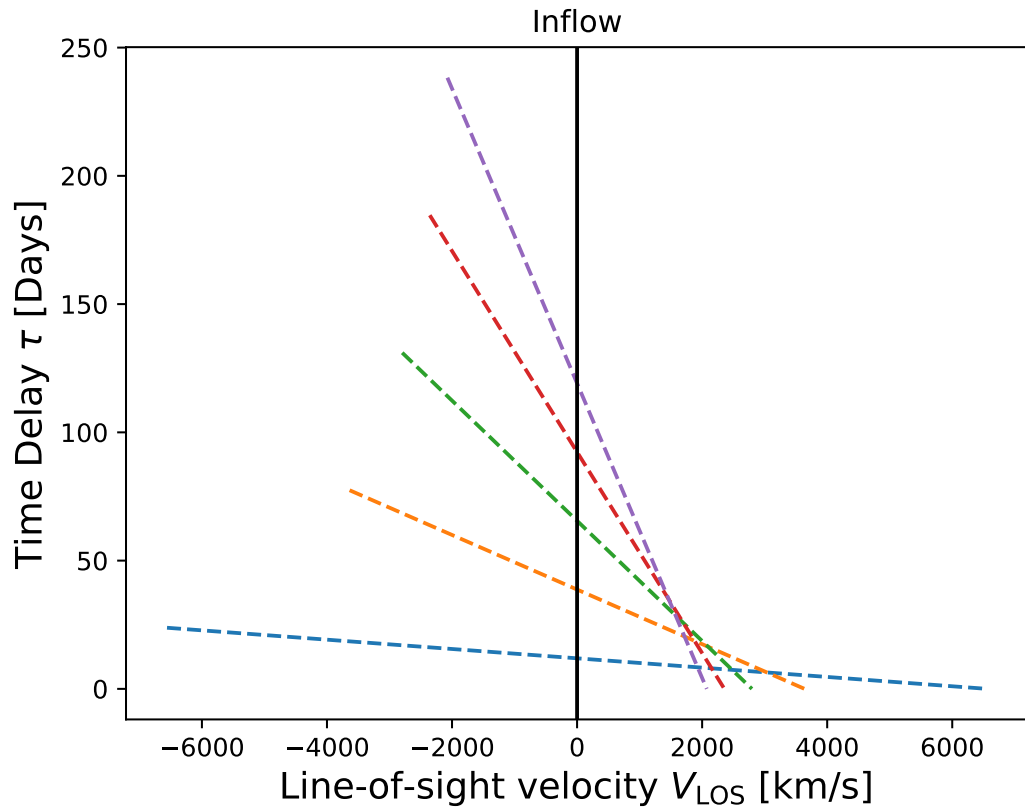


Figure 2.10: Spherically symmetric free-fall inflow with longer delays in the blueshifted emission. The colors have the same meaning as in Figure 2.8.

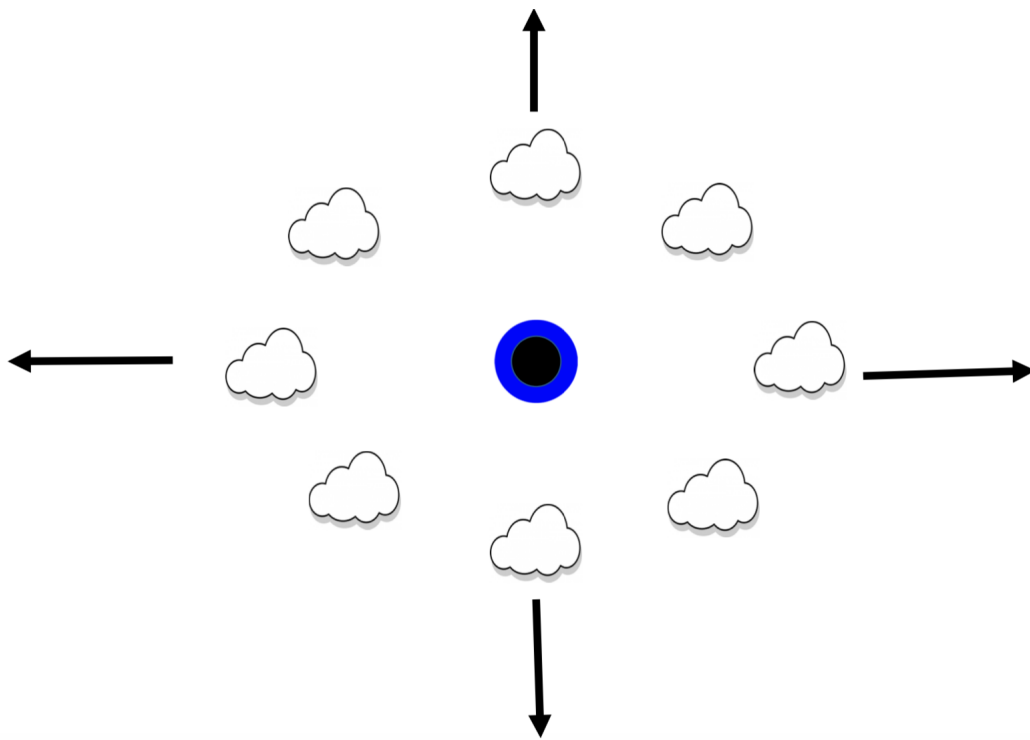


Figure 2.11: The BLR clouds assumed to move outward at a constant speed.

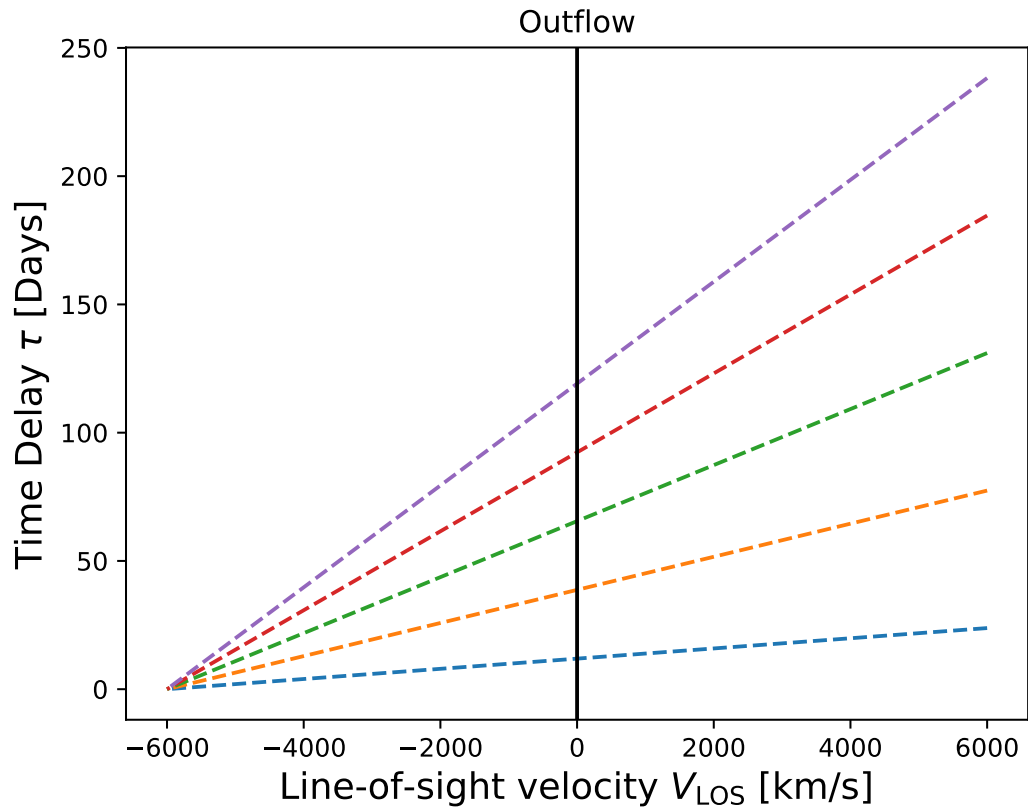


Figure 2.12: Spherically symmetric constant velocity outflow with longer delays in the red-shifted emission. The colors have the same meaning as in Figure 2.8.

## 2.6 Systematic Uncertainties of SMBH Mass Estimators

The reverberation mapping technique, even though it has proven successful in its wide application, does, however, suffer from systematic effects that limit the accuracy of the results. The dimensionless quantity  $f$  in Eqn. 1.23 introduces the largest systematic uncertainty. In principle,  $f$  is hard to measure, as it depends on the geometry and dynamics of the BLR in question.  $f$  is typically determined through “forcing” the active and quiescent galaxies to follow the same  $M - \sigma_*$  relation (e.g., Woo et al. 2010). However,  $f$  is expected to be different for individual AGNs, so assuming an average value,  $\langle f \rangle$ , introduces an uncertainty in the single mass estimates. The SMBH masses determined by assuming this average value are uncertain by 0.4 dex (Peterson 2010), estimated by assuming that the  $M - \sigma_*$  relation for AGNs has the same zero-point and slope as that for quiescent galaxies. The  $f$  value for a specific AGN can be determined by direct dynamical modeling of the BLR as proposed by Pancoast et al. (2014a). This approach was subsequently employed by Pancoast et al. (2014b) and Grier et al. (2017a) to measure  $f$  for individual AGNs. Even so, the scarcity of high-quality reverberation mapping datasets (e.g., Horne et al. 2004) limits efforts to measure  $f$  for most AGNs.

Another source of uncertainty lies in the characterization of the broad emission-line width,  $\Delta V$ , whether FWHM or  $\sigma_{\text{line}}$  (second moment of the line). There are ambiguities attached to both depending on the quality of the data. FWHM is less sensitive to noise in the wings and blending of the line with other features. On the other hand  $\sigma_{\text{line}}$  is less sensitive to the shape of the line profile and narrow line removal (e.g., Shen 2013). It is common in reverberation studies to adopt  $\sigma_{\text{line}}$  measured in the rms spectra (the variable part of the spectrum) as a proxy for estimating SMBH masses, as it yields less-biased line widths (e.g., Collin et al. 2006, Peterson 2011). However, failure to properly account for deblending of contaminants would introduce systematic errors and thus bias the SMBH mass estimate.

The uncertainty in the single-epoch (SE) mass estimate depends on the luminosity in the  $R - L$  relation, where  $L$  is the luminosity usually measured at 5100 Å. At low luminosities, the contribution from the host-galaxy starlight to the 5100 Å luminosity can be significant. The extent of the effect of host-galaxy starlight was shown by Bentz et al. (2006) and Bentz et al. (2009a), when, after accounting for it, led to improved  $R - L$  relation consistent with naive expectation from photoionization. Another systematic error affecting the scatter of the  $R - L$  relation, is the measurement of the time lag and its uncertainty, using methods in Section 2.2. Li et al. (2019), Yu et al. (2019), Zajaček et al. (2019) give an overview and comparison of these methods and generally find that the results from JAVELIN introduces the least bias into the relation.

## 2.7 Accretion-disc RM assumptions and Implications

In addition to Section 2.6, there has been questions raised or asked about the validity of the lamp-post model as it pertains to continuum reverberation mapping. This follows a string

of results in the literature (e.g., McHardy et al. 2014, Fausnaugh et al. 2016, Troyer et al. 2016, Hernández Santisteban et al. 2020) in which predictions from the model don't quite match the observations, prompting for alternative explanations or models. In this Section, we present some of the observed limitations to the standard model.

The lamp-post model (Figure 2.4, Cackett et al. 2007, Starkey et al. 2016) assumes the reprocessed X-ray variability acts as the main driver for the UV/optical variability and are correlated. From this, it is predicted that UV/optical wavelengths lag the X-ray wavelength (Breedt et al. 2010, Shappee et al. 2014). Generally, the longer wavelengths lag behind the shorter wavelengths according to  $\tau(\lambda) \propto \lambda^{4/3}$ , in the process allowing to map the accretion-disc size. It is worth mentioning also that there has been fewer studies that included X-ray variability observations in their campaigns. However, in studies that contain such observations (e.g., McHardy et al. 2014), it is found that the short-term X-ray/UV/optical variations are correlated and that the UV/optical variations track the X-ray variations behind by few to several days. The observed measured lags are longer than predicted by Shakura & Sunyaev (1973). Another finding is that, over long timescales, variations in the UV/optical are not fully replicated in the X-ray variability leading McHardy et al. (2014) to deduce that there may be an additional component to the UV/optical variability invoked from the accretion disc. In the campaign by Marshall et al. (2008), that also included X-ray variability observations, they found X-ray and optical variations to be highly correlated with the optical leading X-ray variations by 15 days over long timescales. They attribute this as being due to accretion-disc flow variations propagating inward, rather than X-ray reprocessing. These findings are not limited to the above studies, see also Edelson et al. (2019) where X-ray observations feature. Edelson et al. (2019) finds in all four AGNs that the observed lags are larger than predicted.

Different observations have shown the emission from the BLR, optical continuum, or the ionizing radiation may become decorrelated. Goad et al. (2016) showed a disconnect between the UV continuum and the broad emission lines that may be due to obscuration or a deficit of ionizing photons. Kara et al. (2021a) also finds that UV continuum and broad emission lines are no longer correlated during a period of obscuration. Further de-coupling of the broad emission lines from the ionizing source, whether due to further reprocessing or obscuration of the ionizing photons, would potentially lead to catastrophic errors in the measurement of time delays.

Several potential descriptions put forward for the lack of agreement between observed accretion-disc size and predicted is perhaps the uncertainty in the black hole mass (Section 2.6). Therefore, uncertainty in the Eddington ratio (being higher or lower) and accretion rate can further effect the estimates of the accretion-disc size and the assumption that this is much smaller than the BLR. The amount of reddening in the direction of the AGN does also affect the Eddington ratio, by underestimating it. The long-term variations that are often not paralleled in X-ray are deemed to be linked to accretion-disc flow or some variability component from the broad-line region. Fausnaugh et al. (2016) proposed an equation

for calculating predicted disc size involving the parameter  $X = 2.54$  which, when increased, brings the disagreement between observed and predicted closer, suggesting its value is underestimated. Furthermore, winds and jets (Yong et al. 2016, Dehghanian et al. 2019) can further effect the reliability of black hole mass measurements and the assumption of virial equilibrium.

Throughout this Chapter, we have presented a range of assumptions that can effect the measurement of the black hole mass. These assumptions can introduce errors into the measurement of the black hole mass from a small factor (e.g. shape of the transfer function, assumption for the value of  $f$ ) to catastrophic error (e.g. whether the thin disc model is accurate). As such, we present statistical errors throughout this work with the assumption of the underlying standard model. We then qualitatively highlight where the results may be effected by the underlying assumptions.



## Chapter 3

# Observations and Derivation of Light Curves

The subsequent chapters make use of time series observations from the Southern African Large Telescope (SALT) and the Las Cumbres Observatory (LCO) robotic telescopes. To avoid repeating material, Section 3.1 introduces SALT, and Section 3.2 introduces LCO. Sections 3.3 and 3.4 describe the derivation of photometric and spectroscopic light curves, respectively, as these are carried out in the similar way in the subsequent chapters.

### 3.1 SALT



Figure 3.1: An aerial view of the SALT telescope in Sutherland.<sup>1</sup>

SALT (Figure 3.1) is one of the largest optical telescopes in the world and is operated by the South African Astronomical Observatory (SAAO)<sup>2</sup>. It is a 10 m class telescope located in

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<sup>1</sup>[saltastro.blogspot.co.za](http://saltastro.blogspot.co.za)

<sup>2</sup><https://www.sao.ac.za/>

the desert of the Karoo in Sutherland, Northern Cape in South Africa. The telescope design (Stobie et al. 2000, Swat et al. 2003, Buckley et al. 2003; 2006) was inspired by the design of 9.2 m Hobby-Eberly Telescope (HET) in McDonald Observatory (West Texas)<sup>3</sup>. It consist of 91 identical spherical segmented mirrors (each 1 m across) that act as one hexagonal primary mirror of diameter 11 m, tilted at an angle of  $37^\circ$  with respect to zenith, and a tracker that follows objects across the field of view (FoV) of the telescope.

Because of its design, SALT can only rotate or move azimuthally, thus limiting observations to targets within a declination range of  $-76^\circ$  and  $+11^\circ$ . During observations, as the tracker moves, the pupil changes (i.e., changing the effective area of the primary mirror). It is because of this that, absolute flux calibration is not possible with SALT. Relative flux calibration can be done with SALT for which standard stars are observed regularly (on the same night or close to the observing date of the target) with the same observing setup or configuration as the target.

There are four astronomical instruments employed on SALT: The SALT Imaging Camera (SALTICAM, O'Donoghue et al. 2006), the Robert Stobie Spectrograph (RSS, Burgh et al. 2003, Nordsieck et al. 2003, Kobulnicky et al. 2003, Smith et al. 2006), the High Resolution Spectrograph (HRS, Barnes et al. 2008, Bramall et al. 2010; 2012), and the Berkeley Visible Image Tube camera (BVIT, Siegmund et al. 2008).

SALTICAM is primarily used as an imaging, acquisition and guiding camera. It consists of two 2048x4096 CCDs with an 8 arcminute FoV and a plate scale of 0.14 per unbinned pixel. SALTICAM has multi-modes of operation: normal imaging, frame transfer, slot mode, and drift scan. These modes can be used along with a wide range of filters over the wavelength range 4300 - 8600 Å.

RSS (previously known as the Prime Focus Imaging Spectrograph, or PFIS) provides long-slit (LS) spectroscopy, multi-object spectroscopy (MOS, Koeslag et al. 2014), Fabry-Perot imaging spectroscopy (FP, Rangwala et al. 2008), and spectropolarimetry (Nordsieck et al. 2003, Brink et al. 2010).

This project uses LS spectroscopy for SALT, thus Section 3.1.1 briefly introduces the LS on SALT.

### 3.1.1 LS

The RSS instrument used in its LS mode has been successfully used for reverberation mapping with SALT (e.g., Park et al. 2017, Zajaček et al. 2019). This mode offers a choice of different wavelength coverage and spectral resolutions (from low to medium resolution), depending on the user specifications, such as the grating, grating tilt angle, articulation angle and slit width. The available slit widths are 0.6, 1.0, 1.25, 1.5, 2.0, 3.0, and 4.0 arcseconds. The choice of configuration depends on the redshift because one needs to ensure the emission lines of interest ( $H\beta$  and two forbidden [O III]) have enough resolution and do fall in the

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<sup>3</sup><https://mcdonald.utexas.edu/>

detector chip gaps. On the other hand the choice of the slit width depends on the desired resolution and throughput, as there is a trade-off between the two. A narrow slit gives a better resolution, but lets in less light. Not only that, the seeing must also be taken into account for every observation and also to ensure that the full AGN nucleus is kept in the slit in all seeing conditions. For each of the AGNs observed with SALT, the observational setup (including the chosen slit width) is expanded upon in the later chapters. Because of the two CCD gaps in the RSS detector (one in the blue and one in the red), the wavelength range is limited to between the gaps for each of the SALT targets in this work.

The pre-processing of the LS data is done with PySALT (Crawford et al. 2010). PySALT is a publicly available user software package based on python/PyRAF, created primarily to help with reducing and analysing SALT data. The basic reduction steps involved in the pre-processing are bias subtraction, gain correction, cross-talk correction, and amplifier mosaicing. These are included as part of the SALT-produced pipeline product data.

From the product data, cosmic rays are cleaned off the images using the PySALT task `saltcrclean` based on the method of van Dokkum (2001). Flat-fielding correction is applied to correct for pixel to pixel variation but not for illumination. To correct for illumination is difficult with SALT because, as explained above, the moving pupil leads to different illumination across the mirror. The `specidentify` task is used to interactively identify arc lines from arc spectra, and applying the solution using `specrectify` to rectify the image in order to get the correct wavelength calibrated spectra. Through examining the images, the central row of the object and FWHM of the object are then used to extract 1-D spectra using `specextract`, using the same extraction width per object. Flux calibration using spectrophotometric standard stars is done using the `specsens` task in PySALT, which takes into account the airmass, exposure time and the extinction curve applicable to the Sutherland observing site. The derived sensitivity curve is used to flux calibrate the spectra using `speccal`. If, for some reason(s), the standard star was not observed, stars from adjacent observing dates are used to flux calibrate the spectra. Spectra of the same AGN taken on the same night are median combined (using `saltcombine`) to produce one spectrum, to increase the S/N and removing any remaining cosmic rays.

## 3.2 LCO

The LCO global network is a set of 0.4 m, 1 m and 2 m robotic telescopes distributed globally. The distribution of these telescopes is split between the two hemispheres, North and South. In total, there are seven observatories or sites (four in the north and 3 in the south). In the north, these are the McDonald Observatory (McD) in Texas, Haleakala Observatory in Hawaii, the Teide Observatory in the Canary Island and Wise Observatory in Israel. In the south, these are the Cerro Tololo Interamerican Observatory (CTIO) in Chile, South African Astronomical Observatory (SAAO) in South Africa and the Siding Spring (SSO)

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<sup>4</sup><https://lco.global/>



Figure 3.2: Las Cumbres Observatory (LCO) Global Robotic Telescope Network. The green dots represent the LCO telescope sites and the yellow dots represent the LCO headquarters.<sup>4</sup>

in Australia. There are about 23 robotic telescopes distributed among these sites. Having the telescopes distributed this way ensures continuous time coverage of astronomical objects that are located anywhere in the night sky (be it North or South) (Brown et al. 2013).

The goal of LCO robotic telescopes is to provide observations (of time domain programs such as reverberation mapping of active galactic nuclei or other monitoring programs) with high cadence, something that is nearly impossible to achieve with traditional telescopes (i.e., manual telescopes requiring human intervention). The unique capabilities of the LCO telescopes have been highlighted or demonstrated in several studies spanning a variety of topics in astronomy (e.g., Valenti et al. 2015, Arcavi et al. 2017a;b, Hlabathe et al. 2020, Kemmer et al. 2020).

In this thesis, LCO provides observations in the form of imaging (Section 3.2.1) and spectroscopy (Section 3.2.2).

### 3.2.1 Imaging

The 1 m telescopes are used for photometric observations. They are equipped with Sinistro cameras consisting of a Fairchild CCD-486 BI, with a  $26.5 \times 26.5$  arcminute FoV and a pixel scale of 0.39 arcsec/pixel. The telescopes can be used along with narrow-band filters, Johnson Cousins/Bessell (U, B, V, R, I) filters, Sloan-primed ( $u'$ ,  $g'$ ,  $r'$ ,  $i'$ ) filters and Pan-Starrs ( $z_s$ ,  $y_s$ ) filters.

The data comes already reduced, courtesy of the LCO BANZAI pipeline (McCully et al. 2018), that includes basic reduction steps such as bad-pixel masking, bias subtraction, dark subtraction, flat-field correction and astrometric correction.

As part of the header information, the images from LCO include a tentative estimate of the

seeing full-width-at-half-maximum (FWHM) size per image. Based on this value and visual inspection, an image with “best” seeing and “worst” seeing are used in the derivation of the optimum aperture size in this thesis/work.

### 3.2.2 Spectroscopy

The 2 m robotic telescopes, the Faulkes Telescope North (FTN) at Haleakala Observatory and the Faulkes Telescope South (FTS) at Siding Spring Observatory, are largely responsible for spectroscopic observations. They are equipped with two, nearly identical, Folded Low Order whYte-pupil Double-dispersed Spectrographs (FLOYDS, [Street et al. 2012](#)). These are low-resolution ( $R \sim 300 - 500$ ) optical spectrographs configured to cover a very large wavelength range 3200 - 10000 Å, with 4800 - 10000 Å in first order (red part of the CCD) and 3200 - 5900 Å in second order (blue part of the CCD) projected concurrently onto the CCD. The dispersion in the first order is 3.51 Å/pixel and 1.74 Å/pixel in the second order, giving different spectral resolutions depending on the slit width used. The available slit widths are 1.2, 1.6, 2.0, and 6.0 arcseconds.

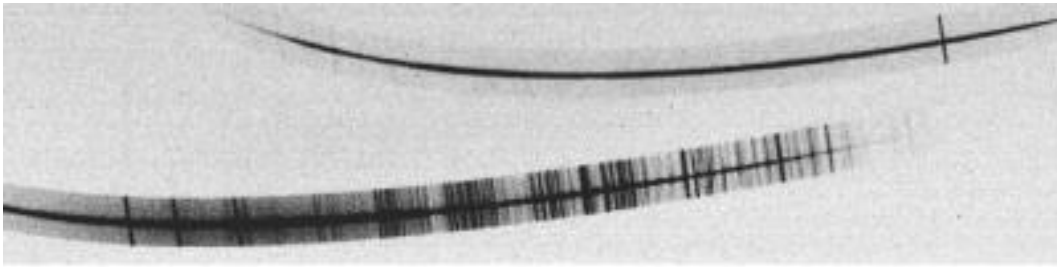


Figure 3.3: The LCO robotic 2 m FLOYDS spectra.<sup>5</sup>

## 3.3 Photometric Light Curve

Photometric light curves are obtained through the use of aperture photometry (AP) using two different imaging tools, AstroImageJ ([Collins et al. 2017](#)) and SExtractor ([Bertin & Arnouts 1996; 2010](#)). For this, a set of comparison stars is selected and AP performed on them using either of the tools, along with the target AGN. AP delivers sky-corrected fluxes measured per specified aperture size of the target and that of the comparison stars. From here on, differential photometry is carried out in the same way from the measured fluxes.

### 3.3.1 Differential Photometry

To perform differential photometry, the measured flux is converted to instrumental magnitude using

$$m = -2.5 \log_{10}(f), \quad (3.1)$$

<sup>5</sup><https://lco.global/observatory/instruments/floyds/>

where  $f$  is the flux and its associated error propagated as

$$\sigma_m = \left| -2.5 \frac{\sigma_f}{f \ln(10)} \right|, \quad (3.2)$$

where  $\sigma_f$  is the error in flux  $f$ . The converted magnitudes are then corrected to the same zero-point ( $t_0$ ). As a zero-point, the first frame ( $m_o$ ) in the set is chosen and the magnitude difference between this frame and the rest ( $m_{\text{frame}}$ ) in the set is calculated as  $\Delta m = m_{\text{frame}} - m_o$  for the comparison stars. From the array of the calculated  $\Delta m$ , a reference star  $\Delta m_{\text{ref}}$  is selected based on the lowest rms variability. The remaining stars are used as check stars in calculating  $\Delta m_{\text{check}} = \Delta m - \Delta m_{\text{ref}}$ . A good reference star should leave intrinsic variations of  $\Delta m_{\text{check}} \sim 1 - 2\%$  as a consistency check. Lastly, this reference star ( $m_{\text{ref}}$ ) is subtracted from the target AGN magnitude as  $m_{\text{AGN}} - m_{\text{ref}}$ , to provide a differential light curve for the target AGN. The same steps are adhered to in the case of each of the filters. While it is common in differential photometry to average multiple comparison stars, rather than a single star, to improve S/N. Here, it is found that using a single star produces better results in terms of the scatter and S/N.

### 3.3.2 Absolute Magnitude Calibration

Next, the differential light curve of the target AGN is calibrated using catalog magnitude of the reference star selected for each filter. The catalog magnitudes are adopted from APASS (Henden A.A. 2016), SDSS (Alam & et al. 2016) and PAN-STARRS (Chambers et al. 2016) photometry tables. The conversion to AB magnitude  $m_{\text{AB}}$  is performed before flux-calibrating to  $\mu\text{Jy}$  (Fukugita et al. 1995)

$$f_\nu [\mu\text{Jy}] = 10^{\frac{23.9 - m_{\text{AB}}}{2.5}}, \quad (3.3)$$

and ultimately to mJy.

### 3.3.3 Intercalibration of Light Curves

The multi-wavelength photometric observations analysed in this work come from different telescopes/sites resulting in small calibration differences, requiring scaling of the individual light curves and adding of small shifts to account for these differences. Therefore, these differences must be modeled or inter-calibrated before combining or merging into a final light curve for each filter. The observing site with the largest data set, in terms of number of observations, is used as a reference (Eqn. 3.4) for scaling other data sets (Eqn. 3.5). The inter-calibration was performed using the Bayesian method presented in Li et al. (2014). This method optimises the flux scaling factor,  $\varphi$ , for point-source correction and flux offset,  $G$ , for extended source correction

$$F(\text{ref}) = \varphi \cdot F(\text{ref})_{\text{obs}}, \quad (3.4)$$

and

$$F(\text{other}) = \varphi \cdot F(\text{other})_{\text{obs}} - G. \quad (3.5)$$

For the reference light curve data, it follows that  $\varphi = 1$  and  $G = 0$ . The uncertainties on the light curve points are then adjusted according to the uncertainties on the best-fit  $\varphi$  and  $G$  parameters (added in quadrature).

## 3.4 Spectroscopic Light Curve

To measure the continuum-line delays, one requires both photometric and spectroscopic light curves. The latter light curves are derived from a series of spectra taken over time. For instance,  $N$  spectra would ideally yield  $N$  flux measurements of the line(s) of interest to end up with the emission-line light curve (flux vs time). Each measurement of flux requires decomposition of the spectrum into different components (such as continuum, broad and narrow emission lines) over a wavelength of interest. PrepSpec as described below is the chosen tool used to perform decomposition of spectra.

### 3.4.1 PrepSpec

AGN spectra are subject to flux differences from night to night due to variations in, e.g., seeing, slit positioning, atmospheric transparency and instrumental flexure. This has the effect of affecting the S/N and overall, the resolution of the spectra. It presents a challenge for AGN variability studies as one would ideally want to isolate the intrinsic variability of the AGN from extrinsic variability due to just-mentioned sources. Failure to properly correct for extrinsic variability will consequently bias the results as that has been pointed out before by [Barth & Bentz \(2016\)](#). One approach is to place the AGN spectra on a uniform flux and wavelength scale by using the [O III]  $\lambda 5007$  narrow line as an internal calibrator. Under RM studies, the [O III]  $\lambda 5007$  line is assumed to remain constant throughout the monitoring campaign. This is because this emission line originates in the far extended, low-density region where the recombination time can take years, so it can be assumed constant over the short timescales (a few months) typical of RM campaigns ([Peterson et al. 2013](#)). The traditional method often deployed is that of [van Groningen & Wanders \(1992\)](#), hereafter vGW92) to account for differences in spectral resolution, flux factors, and wavelengths shifts.

The vGW92 method applies a Gaussian broadening term to minimize the differences in spectral resolution, a linear wavelength shift to correct for different wavelength shifts and a flux scaling factor for flux differences. The application of this procedure has been found to yield a flux calibration uncertainty of about 3 - 5% (e.g., [Park et al. 2012](#), [Barth et al. 2013](#); [2015](#)), determined from the rms scatter of the [O III]  $\lambda 5007$  narrow-line flux. Modifications to the method of vGW92 have been proposed (see [Fausnaugh 2017](#), for description) with the aim of improving the precision ( $\sim 1$  millimagnitude) in the flux calibration. Other studies (e.g., [Kaspi et al. 2000](#), [Hu et al. 2015](#)) opted for the use of comparison stars as an alternative to using the [O III]  $\lambda 5007$  line for flux calibration.

In this work, correction for extrinsic variability is done with PrepSpec. PrepSpec (Shen et al. 2015; 2016b, Horne et al. 2021) incorporates the method of vGW92 in performing spectral calibration. Improving the calibration of the relative spectrophotometry is essential for the measurement of emission-line lags as it shall be seen later.

PrepSpec fits a model to the input spectra which includes the intrinsic variations in both the continuum and broad emission lines as functions of time and wavelength. Expressed in parameterized form

$$\mu(t, \lambda) = p(t) [A(\lambda) + B(t, \lambda) + C(t, \lambda)], \quad (3.6)$$

where  $A(\lambda)$  denotes the average spectrum,  $B(t, \lambda)$  isolates the variable BLR components,  $C(t, \lambda)$  traces the variable continuum, and  $p(t)$  are photometric time-dependent corrections. The assumption that the [O III]  $\lambda 5007$  line is constant ensures that  $p(t)$  corrections can be determined and used to re-scale the flux levels of the input 1-D spectra. The average spectrum  $A(\lambda)$  is the sum of variable  $\bar{F}(\lambda)$  and non-variable  $N(\lambda)$  components as follows:

$$A(\lambda) = \bar{F}(\lambda) + N(\lambda), \quad (3.7)$$

where  $\bar{F}(\lambda)$  includes both the continuum and broad-line components and  $N(\lambda)$  represents the narrow-line component. Unlike other spectral decomposition methods (e.g., Barth et al. 2015) that use power-laws to model variations in the continuum, PrepSpec uses a set of low-order polynomials such that

$$C(t, \lambda) = \sum_{k=0}^{N_c-1} C_k(t) [\eta(\lambda)]^k, \quad (3.8)$$

where

$$\eta(\lambda) \equiv \frac{\log(\lambda^2/\lambda_1\lambda_2)}{\log(\lambda_2/\lambda_1)} \quad (3.9)$$

varies from  $-1$  to  $+1$  across the wavelength span  $\lambda_1$  to  $\lambda_2$ , and  $N_c = 5$  are time-dependent coefficients. This is because PrepSpec does not yet have a power-law continuum fit as an option, so by using piecewise-cubic spline functions of  $\log(\lambda)$ , ensures it can still cope with complicated continuum shapes (e.g., due to inaccurate flux calibrations or host-galaxy starlight). The variations in the BLR are modeled as a sum over lines of the line profile times the line light-curve

$$B(t, \lambda) = \sum_l B_l(\lambda) L_l(t). \quad (3.10)$$

A constraint is imposed such that  $\langle l \rangle = 0$  and  $\langle l^2 \rangle = 1$  to resolve model degeneracies, so that the rms profile  $B_l(\lambda)$  represent variations in the line  $l$ . The light curve of the line is  $L_l(t)$  times the integral of the line flux in the rms spectrum:

$$B_l(t) = L_l(t) \int B_l(\lambda) d\lambda. \quad (3.11)$$

To begin the model in iterated manner, PrepSpec uses a set of initial parameters obtained from the mean spectrum,  $A(\lambda)$ , and optimizes them at each step to minimize  $\chi^2$ . During each stage of the fit or modeling, the model fit can be vetted and adjustment can be made, such as adjusting the velocity window widths around the broad (e.g.,  $H\beta$ ) and narrow emission lines (e.g., [O III]  $\lambda\lambda 4959, 5007$ ). PrepSpec includes a diagnostic grayscale image to inspect the quality of the spectral calibration, especially around the narrow-line regions, often evidenced by small residuals. To deal with such small residuals due to small wavelength shifts, flux calibrations and spectral resolution, PrepSpec includes an additional model  $M(\lambda, t)$

$$M(\lambda, t) = p(t) \left( F - \Delta\lambda(t) \frac{\partial F}{\partial \lambda} + \Delta s(t) \frac{\partial^2 F}{\partial \lambda^2} \right). \quad (3.12)$$

The photometric corrections are represented by  $p(t)$ ,  $\Delta\lambda(t)$  denote the small wavelength shifts,  $\Delta s(t)$  variations in seeing or spectral resolution, and the calibration-adjusted model  $F(\lambda, t)$  is given by Eqn. 3.6. Through its iterative process, the spectra  $A(\lambda)$  and  $B_l(\lambda)$  are optimally adjusted, creating the rms profile for the broad emission lines and their light curves, along with the measurement uncertainties (assuming Gaussian errors). The  $p(t)$  corrections are normalized to median 1 and  $L_l(t)$  to mean 0. Upon the model reaching convergence, the model-fit residuals are inspected for success. PrepSpec outputs the line-width measurements (FWHM,  $\sigma_{\text{line}}$ ) from the mean and rms spectra following Peterson et al. (2004), for each of the broad lines together with the BLR and NLR windows used. The line-width measurements are sensitive to parameter choices, e.g., due to the uncertain separation of NLR and BLR components in the  $A(\lambda)$  spectrum. The broad-line flux measurements are generated as time series, which are then used to measure time delays (later). The successful application of PrepSpec was demonstrated by Shen et al. (2016b), Li et al. (2017) on large samples as part of the Sloan Digital Sky Survey Reverberation Mapping (SDSS-RM) project.

## 3.5 Light-curve Properties

The light curve properties in this thesis are derived following the procedure of Fausnaugh et al. (2018), where the signal-to-noise of variability is defined as

$$(S/N)_{\text{var}} = \frac{\sigma_{\text{var}}}{\bar{\sigma} \sqrt{2/N_{\text{obs}}}}. \quad (3.13)$$

The parameter  $\bar{\sigma}$  is the mean measurement uncertainty between observations and  $N_{\text{obs}}$  is the number of observations. The intrinsic variability  $\sigma_{\text{var}}$  is determined by minimizing

$$-2 \ln \mathcal{L} = \sum_i^{N_t} \frac{[F(t_i) - \hat{F}]^2}{\sigma^2(t_i) + \sigma_{\text{var}}^2} + \sum_i^{N_t} \ln [\sigma(t_i)^2 + \sigma_{\text{var}}^2], \quad (3.14)$$

where  $\hat{F}$  is the mean flux level and is related to the rms fractional variability amplitude as

$$F_{\text{var}} = \frac{\sigma_{\text{var}}}{\hat{F}}. \quad (3.15)$$

$F(t_i)$  is the measurement at time  $t_i$  and  $\sigma(t_i)$  is its variability. The parameter  $\langle S/N \rangle$  is the mean signal-to-noise, and  $R_{\text{max}}$  is defined as the ratio of the maximum to minimum fluxes.

## Chapter 4

# Reverberation mapping of the broad-line radio galaxy 3C 120

3C 120 is a nearby ( $z = 0.033$ ) bright broad-line radio galaxy (BLRG). It was first shown to exhibit a type 1 Seyfert spectrum by [Sargent \(1967\)](#). Radio observations show 3C 120 to consist of a sub-parsec- to kiloparsec-scale superluminal jet ([Walker et al. 1987](#)), responsible for synchrotron emission or radiation. The jet is estimated to be at an inclination angle of about 16 degrees ([Agudo et al. 2012](#)) to the line of sight. Because of its redshift, 3C 120 has been the target of multi-wavelength studies before (e.g., [Chatterjee et al. 2009](#)) due to its accessibility to ground telescopes and its tendency to undergo nuclear activity linked with disc-jet connection ([Marscher et al. 2002](#)). It is known to exhibit strong UV/optical flux variations (e.g., [Winkler 1997](#), [Sakata et al. 2010](#)), with amplitude variations of  $\sim 0.4$  to  $\sim 2$  mag. [Kataoka et al. \(2011\)](#), through decomposition, showed that the jet in 3C 120 dominates radio and  $\gamma$ -ray emission, but only contributes 10% to the optical, UV and X-ray emission. Several RM campaigns have reported the broad-line region (BLR) size in 3C 120, central black hole mass and changes in the nuclear optical luminosity at  $5100 \text{ \AA}$  over time (e.g., [Peterson et al. 1998a](#), [Grier et al. 2012](#), [Pozo Nuñez et al. 2012](#), [Kollatschny et al. 2014](#)). The black hole mass of 3C 120 has also been derived through photometric means ([Pozo Nuñez et al. 2014](#)) and through dynamical modeling of its broad-line region using spectroscopic measurements ([Grier et al. 2017a](#)). 3C 120 has also been the subject of dust RM, in which the infrared signal responds to the continuum variability giving the extent of the dusty torus ([Ramolla et al. 2018](#)).

In this study, 3C 120 is further explored by looking to accurately measure the mass of the central black hole following the high signal-to-noise observations. Additionally, this study aims to derive the continuum delays to test  $\tau \propto \lambda^{4/3}$  prediction from the thin-disc theory of SS73. The results presented in this chapter have been published by myself ([Hlabathe et al. 2020](#)).

## 4.1 Data and Analysis

Table 4.1: Object properties

| Object | RA <sup>(1)</sup><br>(J2000) | DEC <sup>(1)</sup><br>(J2000) | $D_L^{(2)}$<br>(Mpc) | $z^{(1)}$ |
|--------|------------------------------|-------------------------------|----------------------|-----------|
| 3C 120 | 04 33 11.1                   | +05 21 16                     | 139                  | 0.0330    |

<sup>1</sup> Values from NED.

<sup>2</sup> Luminosity distance for the adopted cosmological model.

### 4.1.1 Photometry

Photometric observations of 3C 120 were obtained through multiple filters (Johnson U and V, Sloan Digital Sky Survey  $g'$ ,  $r'$ ,  $i'$ , and PanSTARRS  $z_s$ ). The observations were provided by the LCO 1 m telescopes as part of the AGN key project (Valenti et al. 2015). The monitoring campaign spanned about 465 nights at an almost daily cadence before and after the  $\sim 100$  day gap (due to solar conjunction), from 2016 December to 2018 April. Table 4.2 gives the summary of the observations and adopted wavelength centers <sup>1</sup>.

Aperture photometric extraction was performed with AstroImageJ (AIJ, Collins et al.

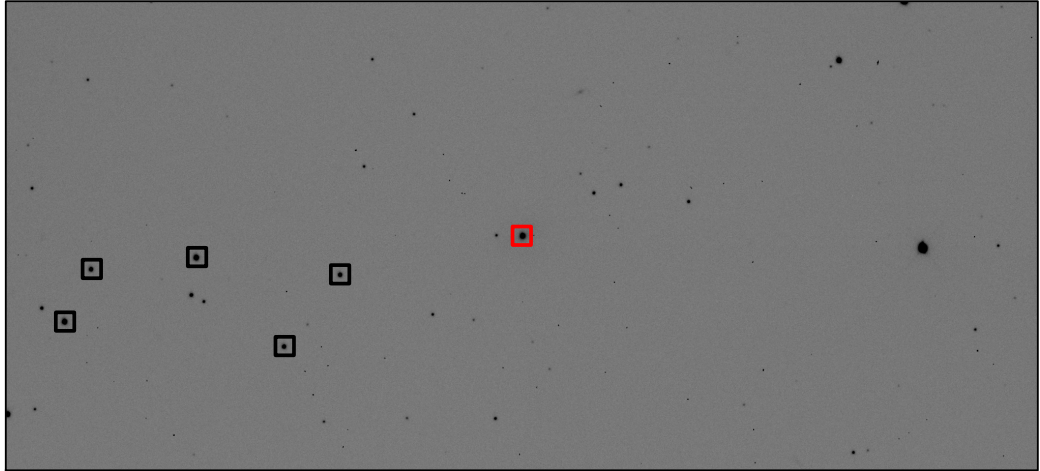


Figure 4.1: A selected CTIO V-band image with best seeing as a cut-out. The chosen comparison stars (black) and the target AGN (red) are shown. The image is 13 arcmin across with North up and East to the left.

2017). Using the V-band best image selected as explained in Section 3.2.1, I proceeded to select several candidate comparison stars on the basis of their relative brightness (Figure 4.1). The seeing FWHM of each comparison star on the selected best image was measured using the AIJ task `Plot seeing profile` and its value recorded (Figure 4.2). Next, I did the

<sup>1</sup><https://lco.global/observatory/instruments/filters/>

Table 4.2: Summary of photometric observations for 3C 120.

| Filter <sup>(1)</sup> | $\lambda_{\text{pivot}}^{(2)}$ | Site <sup>(3)</sup> | Date range <sup>(4)</sup> | $t_{\text{exp}}$ (s) | Epochs <sup>(5)</sup> | Total <sup>(6)</sup> |
|-----------------------|--------------------------------|---------------------|---------------------------|----------------------|-----------------------|----------------------|
| U                     | 3656Å                          | SAAO                | 20170826-20180327         | 300                  | 107                   | 432                  |
|                       |                                | McD                 | 20170810-20180315         |                      | 14                    |                      |
|                       |                                | SSO                 | 20170806-20180207         |                      | 90                    |                      |
|                       |                                | CTIO                | 20170804-20180406         |                      | 221                   |                      |
| $g'$                  | 4770Å                          | SAAO                | 20170306-20180327         | 120                  | 149                   | 508                  |
|                       |                                | McD                 | 20170330-20180315         |                      | 14                    |                      |
|                       |                                | SSO                 | 20170306-20180207         |                      | 91                    |                      |
|                       |                                | CTIO                | 20170309-20180406         |                      | 254                   |                      |
| V                     | 5477Å                          | SAAO                | 20170106-20180327         | 300                  | 156                   | 563                  |
|                       |                                | McD                 | 20170330-20180315         |                      | 14                    |                      |
|                       |                                | SSO                 | 20161228-20180207         |                      | 113                   |                      |
|                       |                                | CTIO                | 20170106-20180406         |                      | 280                   |                      |
| $r'$                  | 6231Å                          | SAAO                | 20170308-20180406         | 120                  | 171                   | 498                  |
|                       |                                | McD                 | 20170405-20180306         |                      | 12                    |                      |
|                       |                                | SSO                 | 20170306-20180404         |                      | 125                   |                      |
|                       |                                | CTIO                | 20170314-20180409         |                      | 190                   |                      |
| $i'$                  | 7625Å                          | SAAO                | 20170308-20180406         | 120                  | 158                   | 480                  |
|                       |                                | McD                 | 20170405-20180306         |                      | 12                    |                      |
|                       |                                | SSO                 | 20170306-20180404         |                      | 124                   |                      |
|                       |                                | CTIO                | 20170314-20180309         |                      | 186                   |                      |
| $z_s$                 | 8660Å                          | SAAO                | 20170308-20180406         | 240                  | 160                   | 460                  |
|                       |                                | McD                 | 20170405-20180306         |                      | 11                    |                      |
|                       |                                | SSO                 | 20170306-20180304         |                      | 106                   |                      |
|                       |                                | CTIO                | 20170314-20180409         |                      | 183                   |                      |

<sup>1</sup> The filter through which the data were taken.

<sup>2</sup> Filter centroid wavelength.

<sup>3</sup> SAAO (South African Astronomical Observatory), McD (McDonald Observatory), SSO (Siding Spring Observatory), CTIO (Cerro Tololo Interamerican Observatory).

<sup>4</sup> Start and end date of observations, we note the  $\sim 100$  day gap due to solar conjunction.

<sup>5</sup> The number of observations taken in that date range per filter.

<sup>6</sup> The total number of observations taken in that filter from all telescopes combined.

same for several randomly selected images (about 20 images sandwiched between “good” and “bad” images) and recorded the measurements. The average FWHM was calculated and converted to aperture radius and sky annuli as recommended by [Collins et al. \(2017\)](#). The aperture radius in pixels was adopted as 12 pixels ( $\sim 5$  arcseconds), the inner sky annulus to be 22 pixels ( $\sim 9$  arcseconds), and outer sky annulus to be 33 pixels ( $\sim 13$  arcseconds). These values were found to be satisfactory, and used to perform aperture photometry on the selected stars and the target using **Multi-aperture** task. The resulting aperture photometry measurements (in the form of a comma separated table) from AIJ included among other parameters, the RA and DEC (in decimal hours and decimal degrees), and sky-subtracted counts (plus associated errors) for the target and selected comparison stars. The same aperture radius and sky annulus radii were adopted for all filters.

To perform differential photometry, the estimated counts were transformed into instrumental

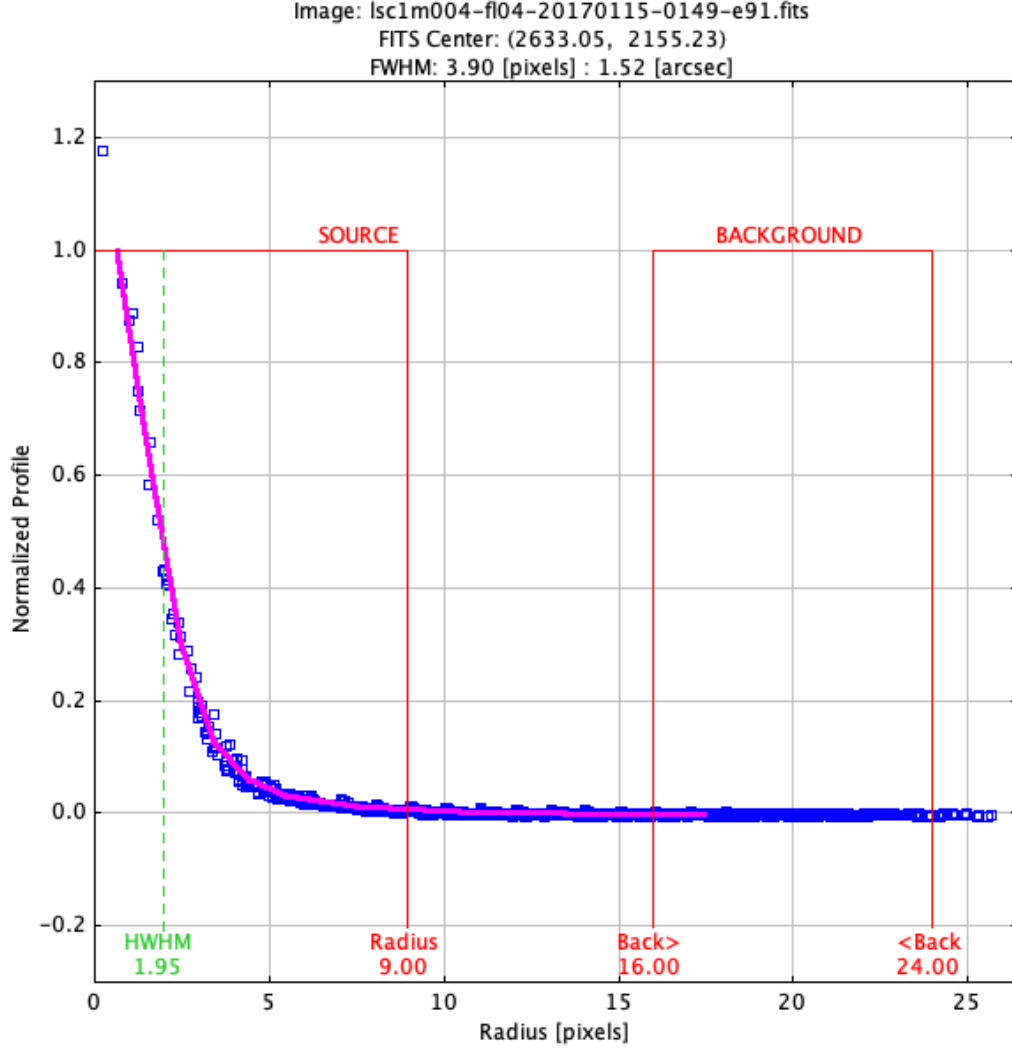


Figure 4.2: The normalized flux of each pixel (blue squares) as a function of radius in pixels, where radius is  $1.7 \times \text{FWHM}$ , inner sky annulus is  $1.9 \times \text{FWHM}$  and outer sky annulus is  $2.55 \times \text{FWHM}$ .

magnitudes and the errors propagated accordingly (Section 3.3.1). Figure 4.3 presents flux-calibrated light curves of 3C 120, where Table 4.3 indicates the star used in the calibration for each filter following Section 3.3.2. The selected comparison stars U-band magnitudes were not available from Vizier catalogues, so the U-band magnitudes were estimated from the B-V and U-B colors following Fitzgerald (1970) and Ducati et al. (2001). In order to be conservative, a 0.2 U-band mag uncertainty was assumed for each star.

From the light curves, the 100 day gap can be clearly seen, splitting the data into year 1 and 2. In year 1, the turnover or trough at  $\text{HJD} - 2450000 = 7830$  is detected in all light curves except U-band (due to being triggered later). In year 2, distinct peaks are detected

Table 4.3: The comparison star catalog magnitude for each filter.

| Filter | Comp <sup>1</sup>    | Comp <sup>2</sup>      | Comp <sup>3</sup>    | Comp <sup>4</sup>    | Comp <sup>5</sup>    |
|--------|----------------------|------------------------|----------------------|----------------------|----------------------|
| U      | $16.5 \pm 0.2^*$     | $16.3 \pm 0.2$         | $17.5 \pm 0.2$       | $16.8 \pm 0.2$       | $17.6 \pm 0.2$       |
| $g'$   | $15.737 \pm 0.076^*$ | $14.994 \pm 0.024$     | $15.881 \pm 0.081$   | $15.071 \pm 0.05$    | $15.918 \pm 0.049$   |
| V      | $15.388 \pm 0.058$   | $14.480 \pm 0.019^*$   | $15.417 \pm 0.035$   | $14.449 \pm 0.044$   | $15.424 \pm 0.031$   |
| $r'$   | $15.182 \pm 0.047^*$ | $14.162 \pm 0.063$     | $14.962 \pm 0.077$   | $14.014 \pm 0.041$   | $15.110 \pm 0.042$   |
| $i'$   | $14.89 \pm 0.06$     | $13.86 \pm 0.04$       | $14.58 \pm 0.04^*$   | $13.54 \pm 0.06$     | $14.8 \pm 0.1$       |
| $z_s$  |                      | $13.7374 \pm 0.0033^*$ | $14.4569 \pm 0.0044$ | $13.3687 \pm 0.0005$ | $14.6546 \pm 0.0057$ |

\* Comparison stars used in the calibration.

<sup>1</sup> 04:33:20.433 +05:20:45.994

<sup>2</sup> 04:33:27.784 +05:20:59.265

<sup>3</sup> 04:33:33.189 +05:20:50.111

<sup>4</sup> 04:33:34.565 +05:20:09.736

<sup>5</sup> 04:33:23.278 +05:19:50.975

at 8043 and 8120, with the turnover at 8210 not caught. During this time, the light curve in each band experiences an increase and decrease in flux. This observed trend continues all the way to 8210. These similar varying structures are well-detected across all 6 bands, with variability signal-to-noise (Eqn. 3.13) ranging from 57.08 in the U and 407.41 in the V (Table 4.5). These high S/N data and well-defined peaks means continuum studies can be carried out, such as measuring inter-band continuum time delays (Section 4.2).

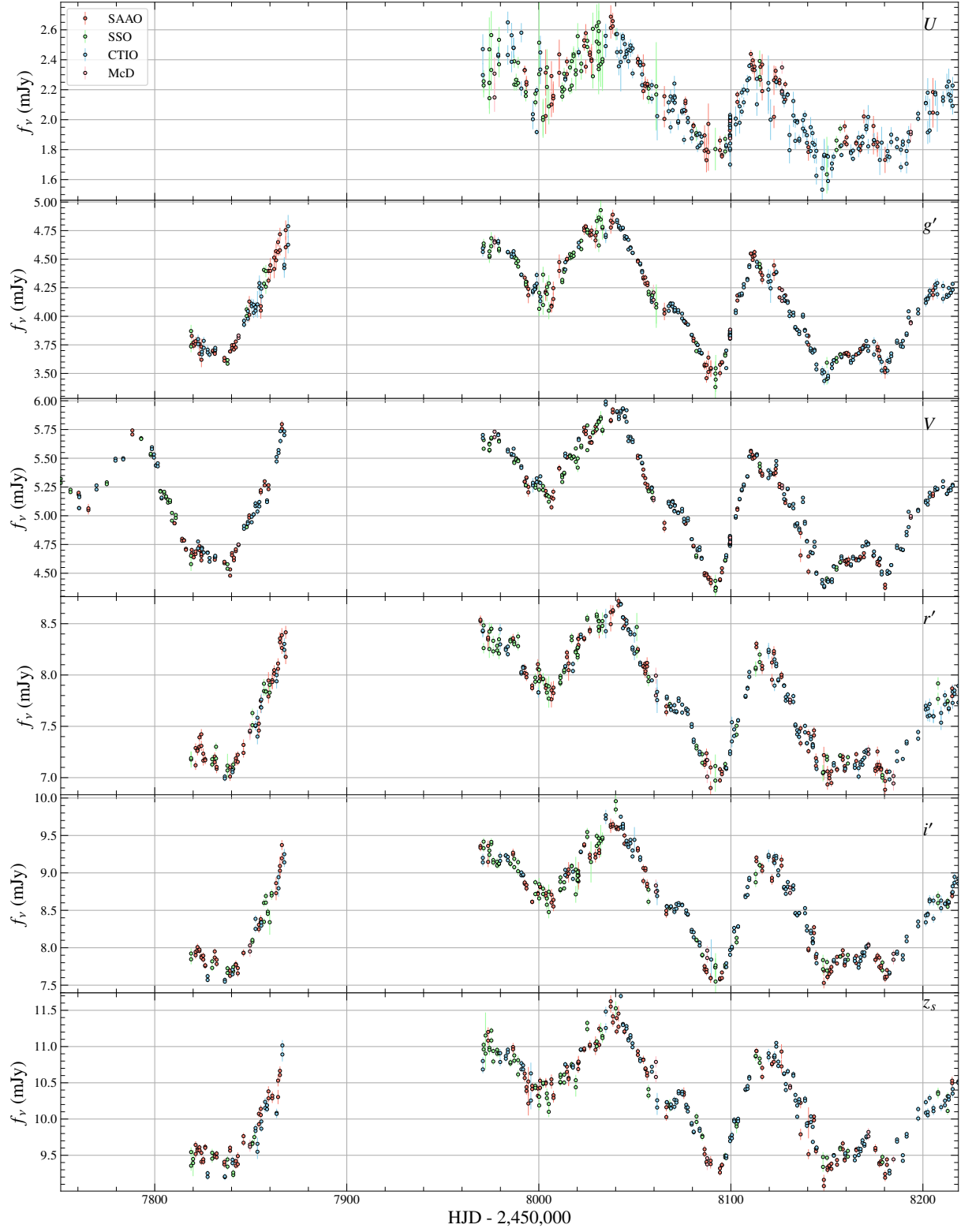


Figure 4.3: LCO continuum light curves for 3C 120 ordered according to increasing wavelength from top to bottom.

### 4.1.2 Spectroscopy

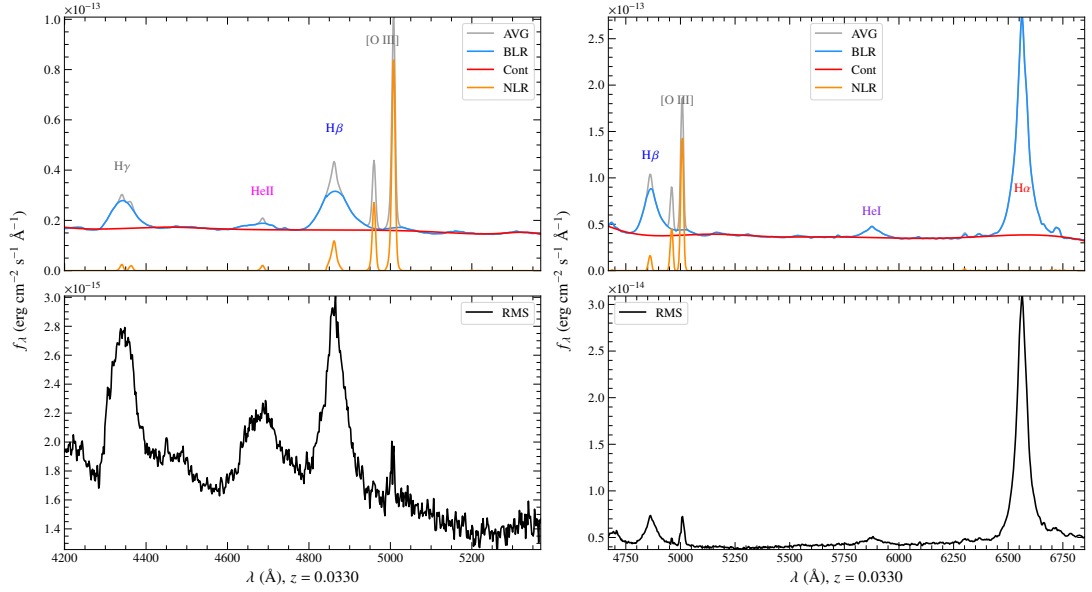
3C 120 was also monitored spectroscopically using the FLOYDS spectrographs (Section 3.2.2). For this purpose, a slit width of 2.0 arcseconds was used (after it was found to be reasonable). With the dispersion of  $3.51 \text{ \AA}/\text{pixel}$  in first order and  $1.74 \text{ \AA}/\text{pixel}$  in second order, the spectral resolution equates to  $17 \text{ \AA}$  and  $9 \text{ \AA}$ , accordingly. The monitoring took place between 2017 March and 2018 March, resulting in 153 epochs at a cadence of  $\sim 2$  days. The spectra were observed in pairs, with 1800 seconds exposure per observation.

The basic reduction steps are carried out using the FLOYDS pipeline, which includes splitting orders, rectification (i.e the spectra are initially curved as shown in Figure 3.3, so this straightens them), cosmic-ray cleaning (van Dokkum 2001), flat-field correction, spectral extraction, wavelength and flux calibration. The pipeline is setup such that the above steps are carried out without human intervention.

As mentioned above, the pipeline separates the 1-D extracted spectra into blue (FTN + FTS) and red (FTN + FTS) spectra. The resulting 1-D spectra were vetted by eye for a sanity check and to discard bad spectra (if any); these may be the result of significantly poor S/N, or the pipeline failing to properly extract the 1-D spectrum. This led to 128 blue spectra (97 FTN, 31 FTS) and 137 red spectra (98 FTN, 39 FTS). The configuration of the FLOYDS spectrographs means that the  $H\beta$  emission line is observed simultaneously in both the blue and red orders. This affords us the opportunity to use the  $H\beta$  flux measurements for consistency check.

To extract the flux measurements of the broad emission lines (i.e.,  $H\gamma$ , He II  $\lambda 4686$ ,  $H\beta$  and He I  $\lambda 5876$ ), the spectra were analysed separately for FTN/FTS, but in the same manner using PrepSpec (Section 3.4.1). The splitting of the 1-D spectra in the analysis was prompted by the noticeable differences in wavelength scales and flux calibrations between FTN and FTS spectra. At the time of doing my thesis, the FLOYDS pipeline was not well-optimized to properly account for fringing. This meant the omission of the  $H\alpha$  line for further analysis due to it being affected by this fringing.

For the blue FTN data, the wavelength range used during PrepSpec modeling was  $4200 - 5370 \text{ \AA}$  (rest frame). For the red FTN data, the spectral decomposition was limited to  $4670 - 6850 \text{ \AA}$  (Figure 4.4). Table 5.4 indicates the spectral windows used in the measurements of broad-line fluxes and velocity widths ( $\text{FWHM}/\sigma_{\text{line}}$ ). The high-ionization He II  $\lambda 4686$  line has broader widths than the Balmer lines and He I, as expected (i.e., originates closer to the black hole), with broader widths in the RMS spectrum than in the mean spectrum. The opposite is the case with the  $H\beta$  line, with broader widths in the mean spectrum. There is uncertainty in the separation of broad lines from contaminants (such as blending with other lines), thus leading to biased (i.e., underestimating) line width measurements. There is also a tendency for PrepSpec to underestimate the statistical errors on the measured line widths, especially in the case of high S/N data such as these. With high S/N data, the uncertainties in line-width measures are dominated by systematic errors such as the ambiguity in sepa-



(a) Mean (top) and rms (bottom) spectrum.

(b) Mean (top) and rms (bottom) spectrum.

Figure 4.4: The mean and rms spectra of 3C 120 constructed using FTN data for both blue and red-sides.

rating the NLR and BLR components, and where to measure the continuum.

Figure 4.5 shows variations of the broad emission lines as derived from PrepSpec, against

Table 4.4: Emission-line widths in the mean and RMS spectra.

| Line                 | FWHM(mean)<br>(km s <sup>-1</sup> ) | FWHM(rms)<br>(km s <sup>-1</sup> ) | $\sigma_{\text{line}}(\text{mean})$<br>(km s <sup>-1</sup> ) | $\sigma_{\text{line}}(\text{rms})$<br>(km s <sup>-1</sup> ) | Window<br>(Å) |
|----------------------|-------------------------------------|------------------------------------|--------------------------------------------------------------|-------------------------------------------------------------|---------------|
| H $\gamma$           | 4402 $\pm$ 5                        | 4469 $\pm$ 14                      | 1703 $\pm$ 1                                                 | 1786 $\pm$ 3                                                | 4270 – 4415   |
| He II $\lambda$ 4686 | 5271 $\pm$ 20                       | 6592 $\pm$ 26                      | 2007 $\pm$ 4                                                 | 2282 $\pm$ 2                                                | 4609 – 4766   |
| H $\beta$ blue-side  | 4754 $\pm$ 4                        | 3273 $\pm$ 8                       | 1923 $\pm$ 1                                                 | 1657 $\pm$ 3                                                | 4782 – 4944   |
| H $\beta$ red-side   | 4412 $\pm$ 5                        | 3874 $\pm$ 12                      | 2002 $\pm$ 1                                                 | 1810 $\pm$ 3                                                | 4782 – 4944   |
| He I $\lambda$ 5876  | 3948 $\pm$ 11                       | 4408 $\pm$ 30                      | 2044 $\pm$ 4                                                 | 2037 $\pm$ 12                                               | 5751 – 6006   |

Measurements from PrepSpec.

V-band continuum light curve (top). Correlated variations are seen in the H $\gamma$ , He II  $\lambda$ 4686, H $\beta$  (blue and red-side) and He I  $\lambda$ 5876 light curves with the continuum. The Balmer H $\gamma$  and H $\beta$  lines exhibit large scatter around HJD-2450000 = 8100-8150, despite evidence of a substantial lag. This scatter is due to limitations in the accuracy of the spectrophotometric calibrations. Both H $\gamma$  and particularly H $\beta$ , have a strong narrow component, so any error in flux calibration using [O III] lines would introduce a scatter in the respective light curves. The Helium lines, He II  $\lambda$ 4686 and He I  $\lambda$ 5876, exhibit well-defined peaks, with He II  $\lambda$ 4686

showing evidence of a shorter lag. The He II  $\lambda 4686$  line variations follow that of the continuum quite closely, while He I  $\lambda 5876$  shows evidence of a substantial lag. The light curve uncertainties from PrepSpec may be underestimated, as previously noted by Shen et al. (2016b). This is the case here as the scatter in the  $H\gamma$  and  $H\beta$  light-curves is not reflected in the light curve errorbars, consequently it may lead to underestimated uncertainties on the lags.

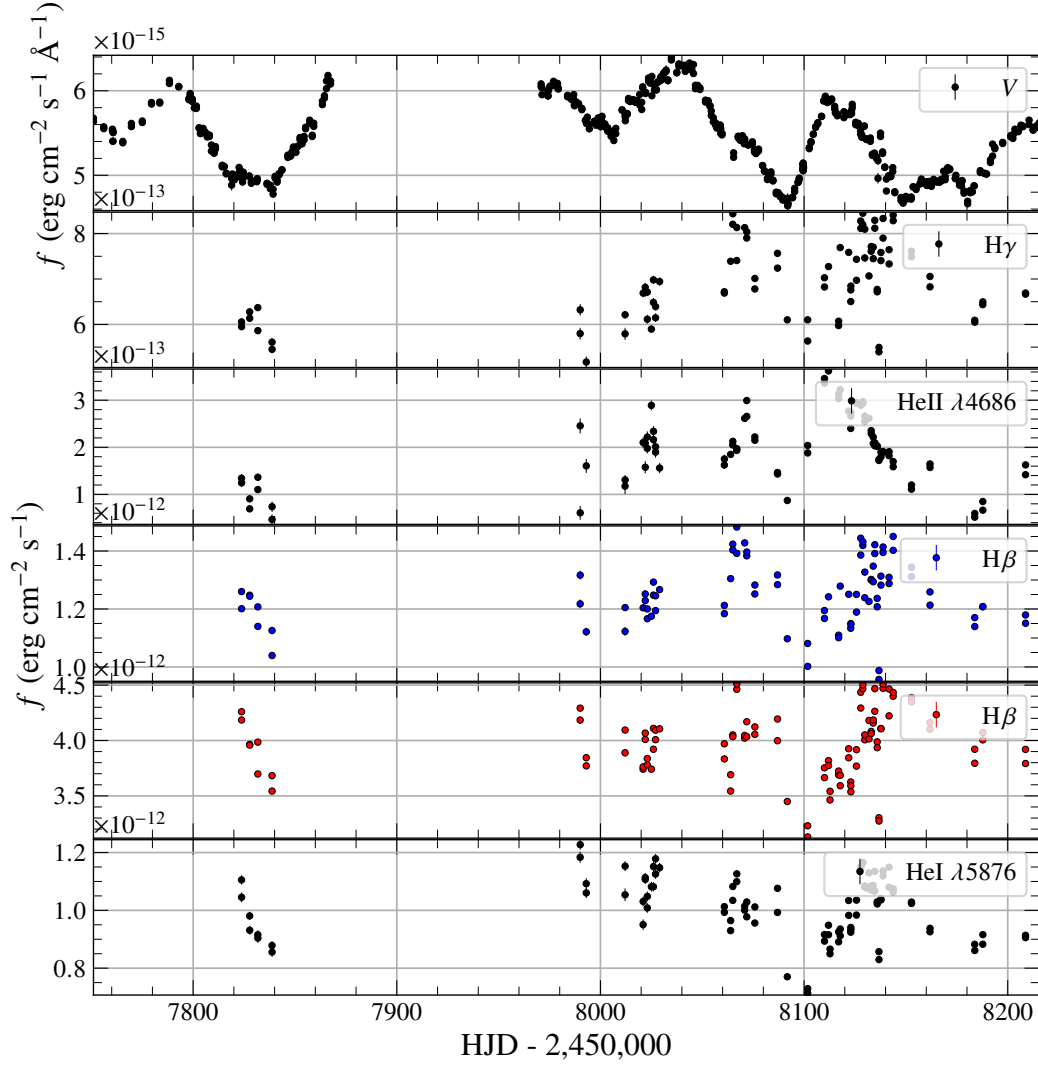


Figure 4.5: The  $H\gamma$ , He II  $\lambda 4686$ ,  $H\beta$  (blue),  $H\beta$  (red) and He I  $\lambda 5876$  broad-line variations for 3C 120 compared against  $V$ -band continuum (top).

Table 4.5: 3C 120 light-curve properties.

| Light<br>Curve       | $N_{\text{obs}}$ | $\Delta t_{\text{med}}$<br>(days) | $\hat{F}$ | $\langle S/N \rangle$ | $F_{\text{var}}$ | $(S/N)_{\text{var}}$ | $R_{\text{max}}$ |
|----------------------|------------------|-----------------------------------|-----------|-----------------------|------------------|----------------------|------------------|
| (1)                  | (2)              | (3)                               | (4)       | (5)                   | (6)              | (7)                  |                  |
| U                    | 380              | 0.02                              | 2.12      | 50.92                 | 0.11             | 57.08                | $1.8 \pm 0.1$    |
| $g'$                 | 476              | 0.002                             | 4.1       | 170.39                | 0.09             | 176.81               | $1.46 \pm 0.05$  |
| V                    | 541              | 0.004                             | 5.1       | 369.77                | 0.08             | 407.41               | $1.38 \pm 0.02$  |
| $r'$                 | 446              | 0.03                              | 7.73      | 211.73                | 0.06             | 168.82               | $1.27 \pm 0.01$  |
| $i'$                 | 439              | 0.05                              | 8.54      | 207.1                 | 0.07             | 183.5                | $1.32 \pm 0.02$  |
| $z_s$                | 425              | 0.24                              | 10.22     | 224.87                | 0.06             | 171.99               | $1.29 \pm 0.01$  |
| $H\gamma$            | 97               | 0.74                              | 1.76      | 137.57                | 0.11             | 92.37                | $1.62 \pm 0.04$  |
| He II $\lambda 4686$ | 97               | 0.74                              | 0.52      | 35.98                 | 0.34             | 70.42                | $6.1 \pm 1.1$    |
| $H\beta$ blue-side   | 97               | 0.74                              | 3.11      | 206.73                | 0.09             | 105.18               | $1.55 \pm 0.01$  |
| $H\beta$ red-side    | 98               | 0.73                              | 4.23      | 319.42                | 0.07             | 138.82               | $1.41 \pm 0.01$  |
| He I $\lambda 5876$  | 98               | 0.73                              | 0.99      | 122.09                | 0.1              | 75.36                | $1.73 \pm 0.03$  |

Column 4 is in units of mJy for the continuum light curves and in units of  $10^{-12}$  erg cm s $^{-1}$  Å $^{-1}$  for the lines.

## 4.2 Time-series Analysis

### 4.2.1 Cross-correlation Analysis

The time delays of the broad emission lines ( $H\gamma$ , He II,  $H\beta$ , He I) were estimated using the interpolation cross-correlation function (ICCF, Section 2.2.1). The delays were measured relative to the V-band light-curve, because of its relative quality in terms of number of observations and better signal-to-noise than other continuum light curves in Figure 4.3. Delays were searched for in the range  $-10$  to  $+50$  days incrementing by 0.25 days. Here,  $n = 10^3$  Monte Carlo realizations were used to derive centroid lag uncertainties.

Figure 4.6 shows the derived cross-correlation centroid distributions (CCCDs) from Monte Carlo resampling of the light curve for each broad emission line. Generally, the lags are well-detected and the CCCDs are well-constrained. Table 4.6 lists the measured lags along with the measured maximum cross-correlation value,  $r_{\text{max}}$ , for each line. The  $H\gamma$  lag of  $18.8^{+1.3}_{-1.0}$  days can be clearly seen despite its low  $r_{\text{max}}$  value. The same can be said for  $H\beta$  line with lags of  $21.2^{+1.6}_{-1.0}$  and  $21.2^{+1.6}_{-1.0}$  days, for the blue and the red-side, respectively. The low  $r_{\text{max}}$  values for the Balmer lines ( $H\gamma$  and  $H\beta$ ) can be attributed to the noise, or the apparent scatter, in the respective light curves that is not evident in the V-band continuum light-curve, rather than to contamination by optical jet emission. Contamination by jet emission is sometimes evidenced by long-term trends in the continuum light curves and there is no evidence of that here. This can potentially result in low  $r_{\text{max}}$  values being measured (e.g., Zhang et al. 2019, Li et al. 2020). The  $H\beta$  lags from the blue and red-side are consistent to within errors, placing reliability on the measurement of the fluxes. They are also consistent with the  $H\gamma$  and He I emission-line lags. The He II lag of  $2.7^{+0.7}_{-0.8}$  days is as expected given how close it traces the V-band continuum light curve, suggesting it is produced really close

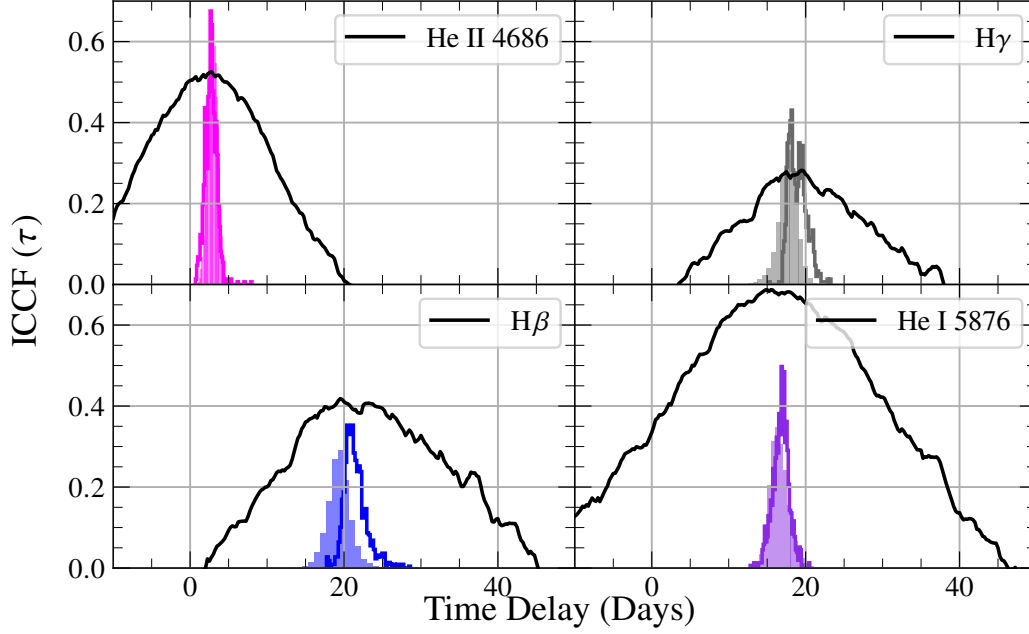


Figure 4.6: The  $\text{ICCF}(\tau)$  are shown in black solid line and the corresponding CCCDs for each emission line are shown in solid histograms for  $10^3$  realizations. The translucent histograms are the posterior delay distributions for  $10^5$  simulations from CREAM’s MCMC method (Section 4.2.2).

to the continuum ionizing source.

Table 4.6: 3C 120 broad emission-line lags relative to V.

| Line<br>Curve                 | $r_{\text{max}}$ | $\tau_{\text{centroid}}$<br>(days) | $\tau_{\text{CREAM}} - \tau_V$<br>(days) | $F_{\text{var}}$ |
|-------------------------------|------------------|------------------------------------|------------------------------------------|------------------|
| H $\gamma$                    | 0.28             | $18.8^{+1.3}_{-1.0}$               | $17.6 \pm 1.3$                           | 0.11             |
| He II                         | 0.53             | $2.7^{+0.7}_{-0.8}$                | $3.0 \pm 0.7$                            | 0.34             |
| H $\beta$ blue-side           | 0.42             | $21.2^{+1.6}_{-1.0}$               | $19.4 \pm 1.7$                           | 0.09             |
| H $\beta$ red-side            | 0.38             | $21.2^{+1.6}_{-1.0}$               | $20.2 \pm 2.4$                           | 0.07             |
| He I                          | 0.69             | $16.9^{+0.9}_{-1.1}$               | $16.6 \pm 1.3$                           | 0.1              |
| $\tau_V = 2.26 \pm 0.18$ days |                  |                                    |                                          |                  |

#### 4.2.2 CREAM Modelling

The good sampling of 3C 120 continuum light curves covering the wavelength range 3500 - 8700 Å allows for accretion-disc parameters to be explored. Being one of the most studied objects, this data-set affords us the opportunity to understand the origin of the

continuum variability, or nuclear activity, in driving the observed variations. Using CREAM’s incorporated blackbody accretion thin-disc model (Section 2.2.5), the temperature profile  $T_1$  of the disc and mass accretion rate  $\dot{M}$  are modeled. For this purpose, CREAM is used to simultaneously fit both emission-line and continuum light curves in a similar manner as Grier et al. (2017b). The adopted model is that of a face-on disc (inclination  $i = 0$ ), with a power-law index  $\alpha = 3/4$  (Model 1). This is because from microlensing studies of Type 1 AGNs (e.g., Poindexter & Kochanek 2010, Blackburne et al. 2015), the data seems to favour an accretion-disc with face-on geometry. The only fitted parameter is the Temperature  $T_1$  (Figure 4.7) to go with the black hole mass  $M = 6.3 \times 10^7 M_\odot$  (Section 4.5). In the second case (Model 2 in Table 4.7), the inclination is varied to see if it plays a role, or has an effect on, the mass accretion rate  $\dot{M}$ .

Table 4.7: Derived accretion-disc parameters from Model 1 and 2.

|                    | Model 1       | Model 2       |
|--------------------|---------------|---------------|
| $T_1$ ( $10^4$ ) k | $1.5 \pm 0.1$ | $1.5 \pm 0.1$ |
| $i$ (deg)          | 0             | $52 \pm 9$    |
| $\alpha$           | $\equiv 0.75$ | $\equiv 0.75$ |

### The Fits From CREAM

Figures 4.8 - 4.12 shows the MCMC fit of CREAM to the 3C 120 light curves for Model 1 (Table 4.7). The CREAM inferred driving light curve is shown in panel-a of Figure 4.8. The left column of Figures 4.8 - 4.11 shows the response transfer functions where the measured mean delays are indicated by the vertical line. The CREAM continuum mean delays are scaled such that  $\langle \tau \rangle \propto (M\dot{M})^{1/3} \lambda^{4/3}$ . The right column shows the response light curves in each filter per contributing telescope (Table 4.2) with  $1\sigma$  error envelopes. Generally, the CREAM derived model approximates the data really well, even light curves with few data points. This is because the multiple light curves are all being fit simultaneously, so the inclusion of multiple well-sampled light curves improves the fits for the sparsely sampled light curves as well. There are fewer outliers as can be seen in Figure 4.10 (panel-h and l) and Figure 4.11 (panel-j). The U light curve from all telescopes exhibits large error bars due to atmospheric extinction. The red error bars are CREAM rescaled error bars from Eqn. 2.15. For the emission lines (Figure 4.12), the error bars are inflated. The original nominal error bars (black) are underestimated due to systematic effects, such as uncertainty in the underlying continuum and blending with other features, or the adopted line windows and stiffness of the splines used to separate BLR, NLR, and continuum features. For high S/N data, the systematic effects dominate the error bars on the emission-line fluxes. The left column of Figure 4.12 are the posterior delay distributions from CREAM's MCMC samples of the mean of top-hat response functions.

CREAM outputs the posterior probability distribution for the fitted parameters, in this case for temperature  $T_1$  (Figure 4.7). From  $10^5$  iterations, the best-fit value  $T_1 = (1.5 \pm 0.1) \times 10^4 \text{K}$  was obtained corresponding to  $\dot{M} = 0.60 \pm 0.15 M_\odot \text{yr}^{-1}$  for  $M = 6.3 \times 10^7 M_\odot$  (Eqn. 2.21). The product  $M\dot{M}$  is well-determined as  $\log(M\dot{M}/M_\odot^2 \text{yr}^{-1}) = 7.58 \pm 0.11$ . The Eddington ratio is estimated to be  $\dot{m}_{\text{Edd}} = \dot{M}/\dot{M}_{\text{Edd}} = L/L_{\text{Edd}} = 0.42_{-0.09}^{+0.10}$ , implying that 3C 120 is accreting below the super-Eddington rate (i.e.,  $\dot{m}_{\text{Edd}} < 1$ ). The quantity  $\dot{m}_{\text{Edd}}$  depends on the calculated black hole mass which is uncertain by 0.4 dex.

Model 2 gives the same best-fit parameter values for  $T_1$  and the Eddington rate  $\dot{m}_{\text{Edd}}$ , while the inclination was determined to be  $i = (52 \pm 9)^\circ$ . This outcome implies that the inclination plays a minimal role in affecting the resulting mass accretion rate  $\dot{M}$ .

$$\log T_1 \text{ (K)} = 4.18^{+0.03}_{-0.03}, L/L_{\text{Edd}} = 0.42^{+0.1}_{-0.09} \text{ for } M_{\text{BH}} = 6.30 \times 10^7 M_{\odot}$$

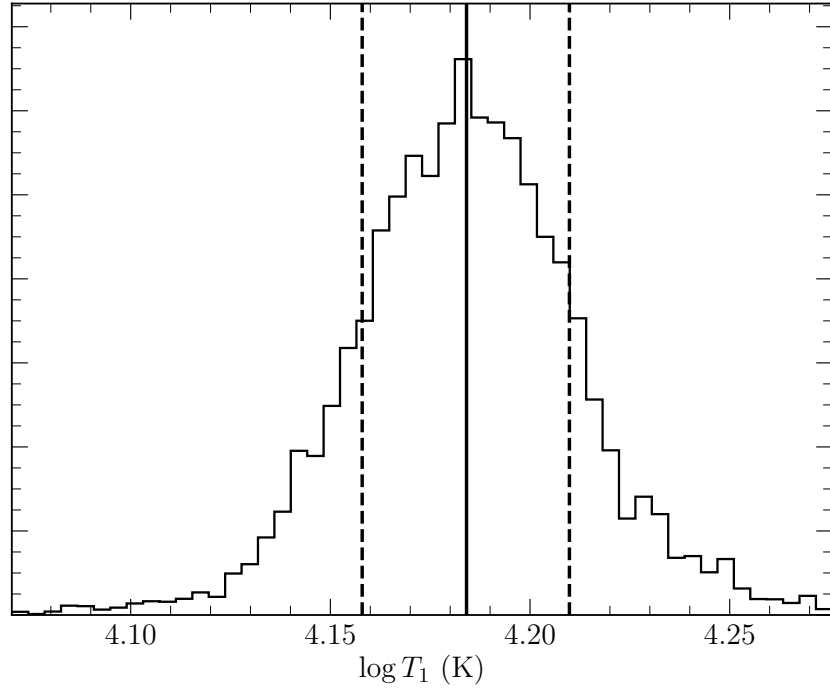


Figure 4.7: The CREAM inferred posterior probability distribution for  $T_1$  with  $i = 0$  and  $\alpha = 3/4$ .

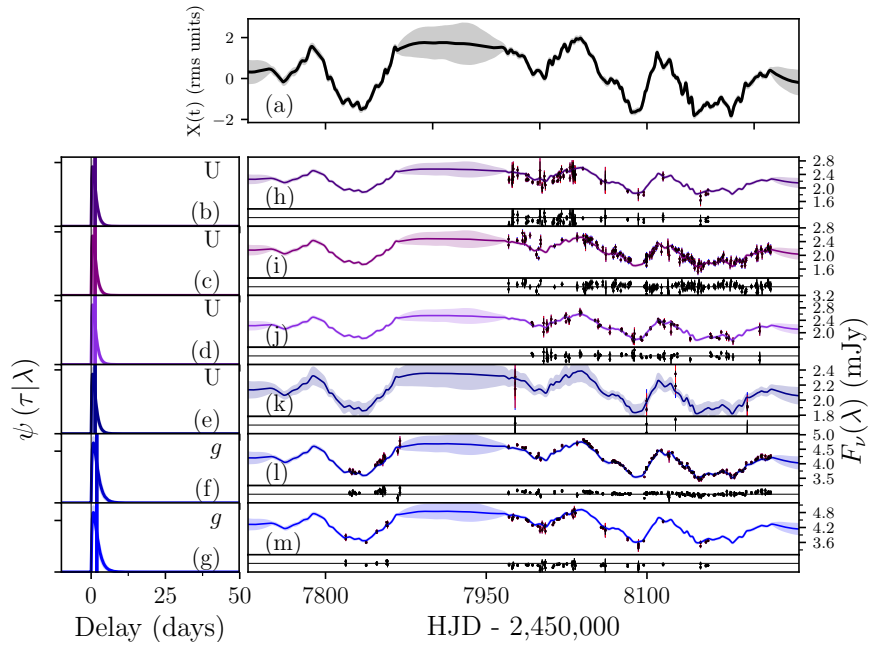


Figure 4.8: The CREAM inferred driving light-curve is shown in panel-a along with fits to the continuum light curves for each filter per telescope (h-m). Panels b-g show the response transfer functions where the measured lags are indicated by the vertical line. The fit residuals are shown beneath the light curve fits.

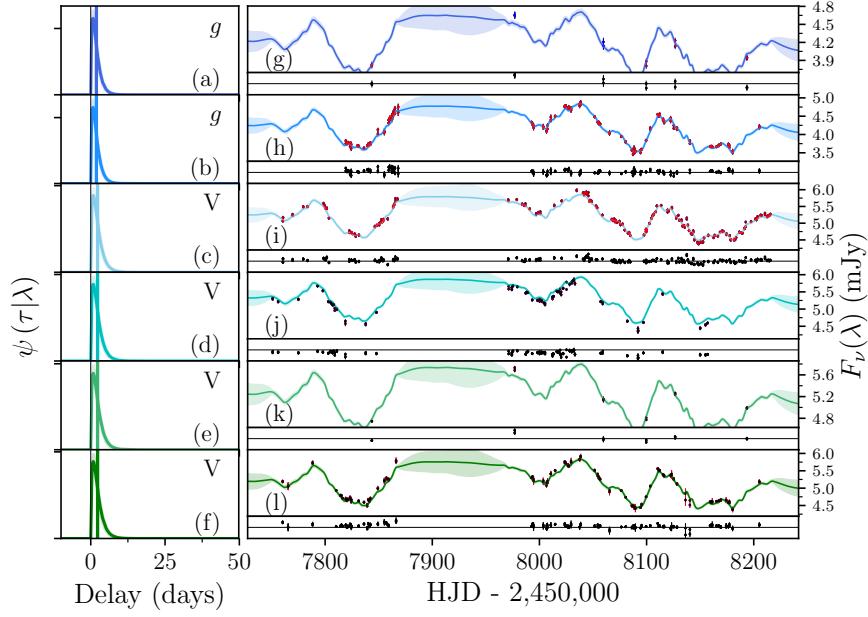


Figure 4.9: CREAM fits to the continuum light curves for each filter per telescope (g-l). Panels a-f show the response transfer functions where the measured lags are indicated by the vertical line. The fit residuals are shown beneath the light curve fits.

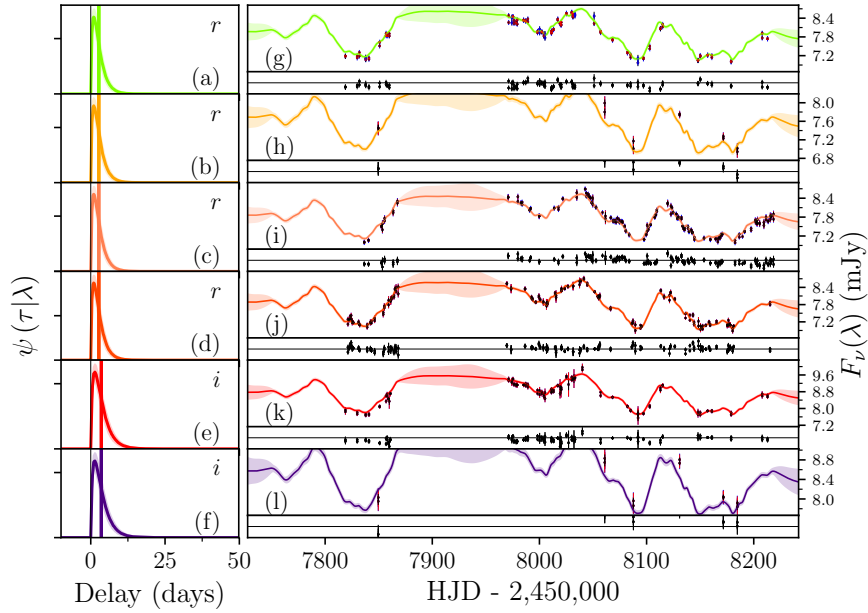


Figure 4.10: CREAM fits to the continuum light curves for each filter per telescope (g-l). Panels a-f show the response transfer functions where the measured lags are indicated by the vertical line. The fit residuals are shown beneath the light curve fits.

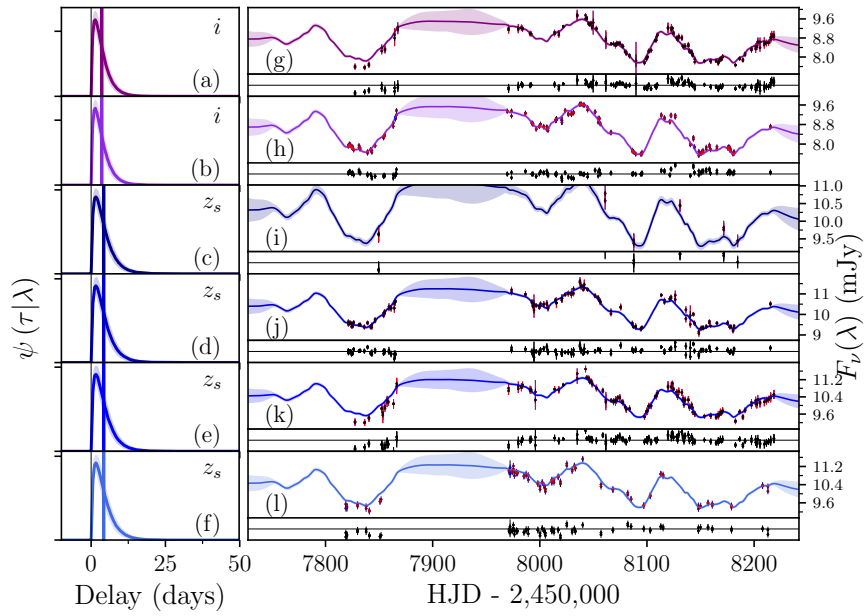


Figure 4.11: CREAM fits to the continuum light curves for each filter per telescope (g-l). Panels a-f show the response transfer functions where the measured lags are indicated by the vertical line. The fit residuals are shown beneath the light curve fits.

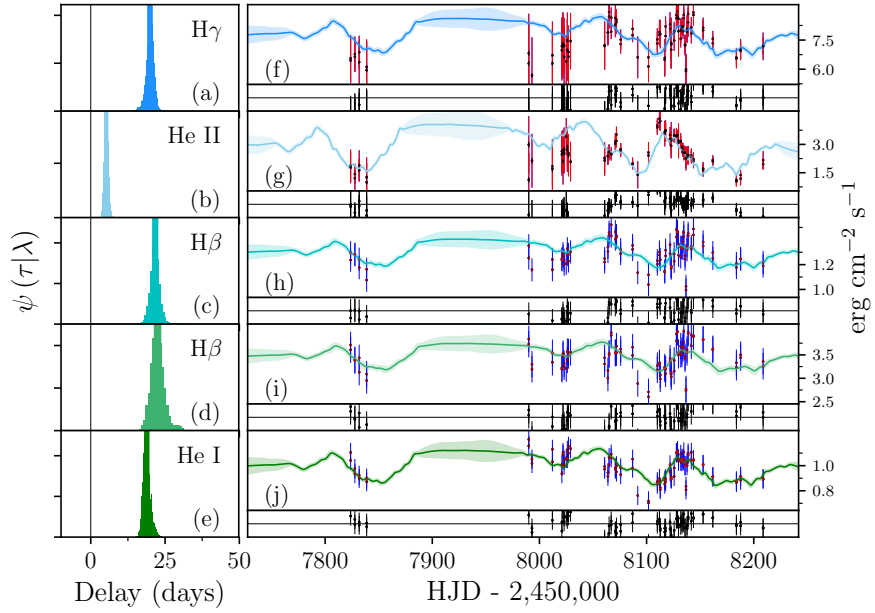


Figure 4.12: Same as Figure 4.8, but for broad emission lines f-j. Panels a-e are the posterior delay distributions from CREAM’s MCMC samples ( $10^5$ ) of the mean of top-hat response functions. The zero lag is indicated by the vertical line. The units are  $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$  (H $\gamma$ , He II) and  $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$  (H $\beta$ , He I).

### 4.3 Lag Spectrum

Table 4.8: 3C 120 continuum lags relative to V in the observed frame.

| Line<br>Curve                 | $\lambda$<br>(Å) | $\tau_{\text{cent}}$<br>(days) | $\tau_{\text{CREAM}} - \tau_V$<br>(days) | $F_{\text{var}}$ |
|-------------------------------|------------------|--------------------------------|------------------------------------------|------------------|
| U                             | 3656             | $0.14^{+0.35}_{-0.36}$         | $-0.94 \pm 0.21$                         | 0.11             |
| $g'$                          | 4770             | $-0.63^{+0.13}_{-0.13}$        | $-0.38 \pm 0.24$                         | 0.09             |
| V                             | 5477             | $0.00^{+0.13}_{-0.12}$         | $0.00 \pm 0.26$                          | 0.08             |
| $r'$                          | 6231             | $1.50^{+0.24}_{-0.24}$         | $0.42 \pm 0.28$                          | 0.06             |
| $i'$                          | 7625             | $2.60^{+0.24}_{-0.24}$         | $1.25 \pm 0.34$                          | 0.07             |
| $z_s$                         | 8660             | $2.86^{+0.24}_{-0.24}$         | $1.9 \pm 0.4$                            | 0.06             |
| $\tau_V = 2.26 \pm 0.18$ days |                  |                                |                                          |                  |

Table 4.8 compares the continuum inter-band delays relative to V from the model-independent ICCF and CREAM thin-disc model. The CREAM delays are measured relative to the derived driving light curve,  $X(t)$ . So to compare with ICCF delays, the CREAM V-band lag must be subtracted from other CREAM delays. The delays from both ICCF and CREAM have the same sign except for U. The ICCF U-band lag is positive and the CREAM U-band lag is negative. This may be due to outliers influencing the ICCF lag to be positive. The ICCF lags have symmetric error bars, and are generally significant to  $2\sigma$ . They are also consistent with CREAM delays to  $2\sigma$ .

Using its sophisticated noise model, the delays from CREAM are scaled such that they follow  $\tau \propto \lambda^{4/3}$ , as expected from the reprocessing thin-disc model of SS73. The ICCF delays follow the same behaviour of increasing delay with wavelength, with the exception of the U-band lag, which is greater than the lag between V and  $g'$ . A larger U lag than expected from the standard thin-disc model has also been measured in several multi-wavelength continuum studies (e.g., [Edelson et al. 2015](#), [Fausnaugh et al. 2018](#), [Cackett et al. 2020](#)), and is believed to be due to contamination by Balmer continuum emission from the BLR ([Korista & Goad 2001](#), [Lawther et al. 2018](#), [Chelouche et al. 2019](#), [Korista & Goad 2019](#)). The larger U lags adds or contributes to a discrepancy between observed and expected disc sizes (e.g., [McHardy et al. 2018](#)). To quantify this discrepancy, the ICCF delays are fitted with the following, to test the  $\tau \propto \lambda^{4/3}$  relation:

$$\tau(\lambda) = \tau_0 [(\lambda/\lambda_0)^\beta - 1] + \tau_V, \quad (4.1)$$

where  $\lambda_0 = 5477$  Å (the reference V-band wavelength) and  $c\tau_0$  is the disc radius at  $\lambda_0$ . The power-law index,  $\beta$ , is set to  $4/3$  for a standard thin accretion disc and also allowed to be a

free parameter during the fit.

If  $\beta$  is fixed to  $4/3$ , the resulting best-fit parameters are  $\tau_0 = 3.51 \pm 0.22$  days ( $\chi^2/4 = 8.44$ ). When  $\beta$  is a free parameter,  $\tau_0 = 2.42 \pm 1.11$  days and  $\beta = 1.79 \pm 0.62$  ( $\chi^2/3 = 10.95$ ). Both cases are shown in Figure 4.13. Generally, the second case yields a poorer fit with large errors on the fitted parameters. So henceforth, the results with  $\beta$  fixed are used. To compare the best-fit value  $\tau_0$  (the normalization disc factor) with expectations from the SS73 thin-disc model, Equation 12 from Fausnaugh et al. (2016) is used

$$\tau_0 = \frac{1}{c} \left( X \frac{k\lambda_0}{hc} \right)^{4/3} \left[ \left( \frac{GM}{8\pi\sigma} \right) \left( \frac{L_{\text{Edd}}}{\eta c^2} \right) (3 + \kappa) \dot{m}_E \right]^{1/3}, \quad (4.2)$$

where the accretion efficiency  $\eta = 0.1$ ,  $X$  is the conversion factor from  $\lambda$  to  $T$  and  $\kappa = 1$  (ratio of external to internal heating). The Eddington ratio is determined to be  $\dot{m}_E = 0.42$  and the black hole mass  $M = 6.3 \times 10^7 M_\odot$ . The bolometric luminosity is estimated as  $L_{\text{Bol}} = \eta \dot{M} c^2$ , with  $\dot{M} = 0.60 \pm 0.15$ . Therefore, the calculated  $L_{\text{Bol}} = (3.4 \pm 0.9) \times 10^{45}$  erg s $^{-1}$ , implying  $L_{\text{Edd}} = (8.1 \pm 2.8) \times 10^{45}$  erg s $^{-1}$ . Assuming  $X$  is given by Wien's law, then  $X = \frac{hc}{\lambda_0 kT} = 3.21$  for  $\lambda_0 = 5477 \text{ \AA}$  and  $T = 1.51 \times 10^4$  K. This results in  $\tau_0 = 2.25$  days, similar to the V-band mean CREAM lag in Table 4.8 of  $2.26 \pm 0.18$  days. Comparing the observed with predicted size evaluates to  $3.51/2.25 = 1.6$ . It implies the observed disc size is 1.6 times larger than predicted. The larger observed disc size is likely due to several reasons. Firstly, the  $\sim 100$  day gap leading to larger ICCF lags measured (i.e., comparable to He II lag). The light curves after 100 day gap were investigated separately and found this to be the case. Secondly, the influence of the ICCF lag by outliers. Thirdly, contamination by disc continuum as evidenced by the Balmer jump at  $3640 \text{ \AA}$  (U to  $g$ ) and Paschen jump at  $8200 \text{ \AA}$  ( $i$  to  $z_s$ ), caused by HI bound-free continuum emission (e.g., Korista & Goad 2019) in (Figure 4.13). Larger disc sizes than predicted have been measured before (e.g., Fausnaugh et al. 2016, Cackett et al. 2018).

If  $X$  is set to the flux-weighted mean radius of 2.49 determined by Fausnaugh et al. (2016), then Eqn. 4.2 results in  $\tau_0 = 1.6$  days. This implies an observed disc size a factor of 2.2 larger than expectations from standard thin-disc theory. Thus, the two different assumptions of  $X$  give consistent results, in that they both predict a disc size that is a factor of  $\sim 2$  less than observed.

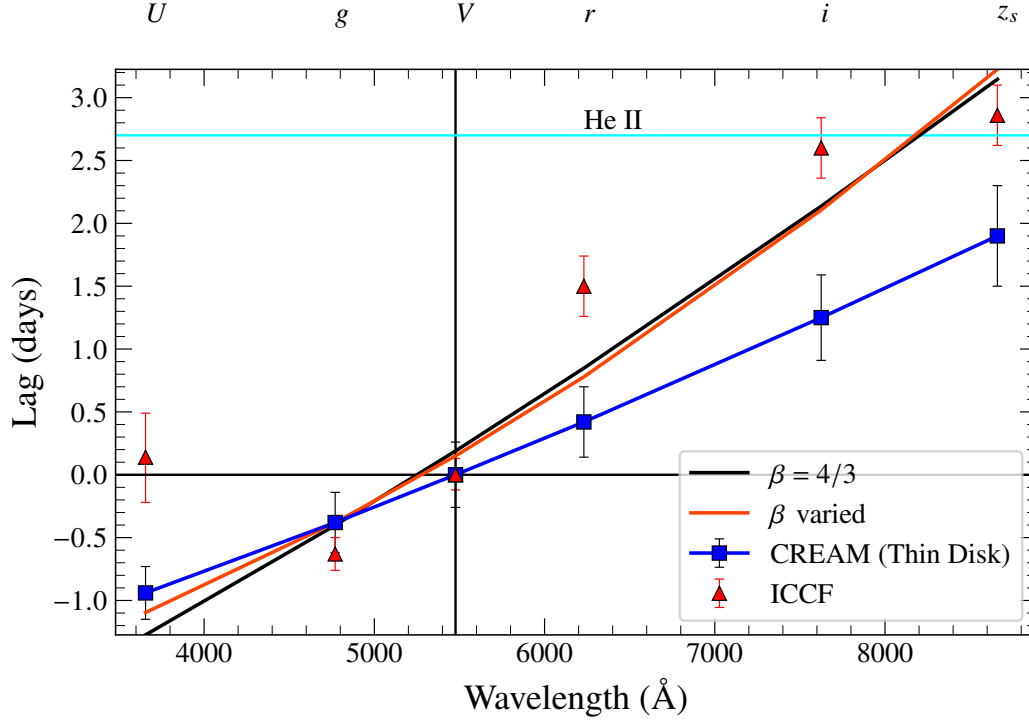


Figure 4.13: The ICCF lag spectrum is shown with  $\beta$  fixed (black) and allowed to vary (orange). The zero lag and reference V-band wavelength are shown by the horizontal and vertical lines respectively. The broad He II line lag is shown by cyan line for comparison.

## 4.4 Accretion-disc Spectrum

Table 4.9: Mean and rms Spectra from CREAM.

| $\lambda$<br>(Å) | $\bar{F}_\nu(\lambda)$<br>(mJy) | $\Delta F_\nu(\lambda)$<br>(mJy) |
|------------------|---------------------------------|----------------------------------|
| 3656             | $7.604 \pm 0.011$               | $0.937 \pm 0.013$                |
| 4770             | $11.308 \pm 0.009$              | $0.96 \pm 0.01$                  |
| 5477             | $11.80 \pm 0.01$                | $0.92 \pm 0.01$                  |
| 6231             | $15.516 \pm 0.013$              | $0.929 \pm 0.013$                |
| 7625             | $14.317 \pm 0.015$              | $0.890 \pm 0.013$                |
| 8660             | $15.442 \pm 0.016$              | $0.817 \pm 0.015$                |

The dust-extinction-corrected values.

We derive the accretion-disc spectrum for 3C 120 following Section 2.2.5. Figure 4.14 shows the response light curves,  $f_\nu(\lambda, t)$ , plotted against the CREAM-inferred driving light curve  $X(t - \tau)$ , not corrected for Galactic foreground extinction. The lack of curvature demonstrated by the response light curves between minimum  $F_{\min}(\lambda)$  and maximum  $F_{\max}(\lambda)$  fluxes for each light curve is immediately evident. The slopes  $\Delta F_\nu(\lambda)$  (Eqn. 2.14) derived from the best-fitting lines denote the rms disc spectrum (i.e., the variable component of the light) and the intercepts at  $X_0 = 0$  denote the mean spectrum,  $\bar{F}(\lambda)$  (Eqn. 2.14). These are listed in

Table 4.9 and plotted in Figure 4.15 after correcting for Galactic extinction (Schlegel et al. 1998).

The difference spectrum between minimum and maximum fluxes is shown in black, and

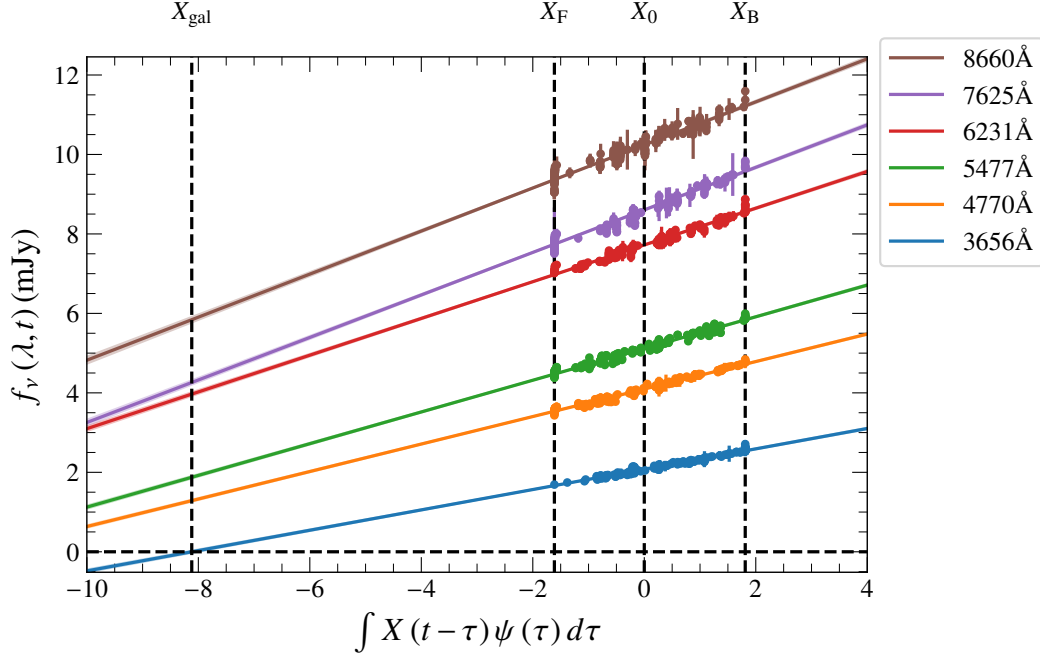


Figure 4.14: CREAM flux-flux analysis: The best-fitting linear trend lines to model response light curves are shown as solid lines for each wavelength. The vertical lines indicate galaxy, faint and bright-state as  $X_{\text{gal}} = -8.12$ ,  $X_F = -1.61$  and  $X_B = 1.81$  respectively.

the variable disc spectrum,  $\Delta F_\nu(\lambda)$ , is shown in red. The variable spectrum mimics the  $f_\nu \propto \nu^{1/3}$  (yellow) spectrum expected from a standard thin accretion disc, as dilution by the red spectrum at longer wavelength decreases flux (McHardy et al. 2018). The mean spectrum increases with wavelength, as expected for an old stellar population (Cackett et al. 2020).

In Figure 4.16, the observed accretion-disc spectrum,  $\bar{F}_{\text{disc}}(\lambda)$ , is compared with the predicted spectrum from a standard thin disc (Collier et al. 1999, Cackett et al. 2007). Collier et al. (1999) gives the predicted spectrum for a thin-disc standard model as

$$f_\nu = 11.2 \text{ Jy} \left( \frac{\tau}{\text{days}} \right)^2 \left( \frac{D}{\text{Mpc}} \right)^{-2} \left( \frac{\lambda}{10^4 \text{ Å}} \right)^{-3} \left( \frac{X}{4} \right)^{-8/3} \cos i, \quad (4.3)$$

where  $D$  is the distance to the AGN and  $i$  is the inclination of the disc. Here,  $i = 0$  for a face-on disc and the distance to 3C 120 is  $D = 139$  Mpc (Table 4.1). The temperature profile of a steady-state blackbody accretion disc is  $T(r) = T_1 \left( \frac{r}{r_1} \right)^{-3/4}$  with  $T_1 = 1.51 \times 10^4$  K (Figure 4.7) the temperature at  $r_1 = 1$  light day and the observed delay spectrum  $\tau(\lambda) \propto$

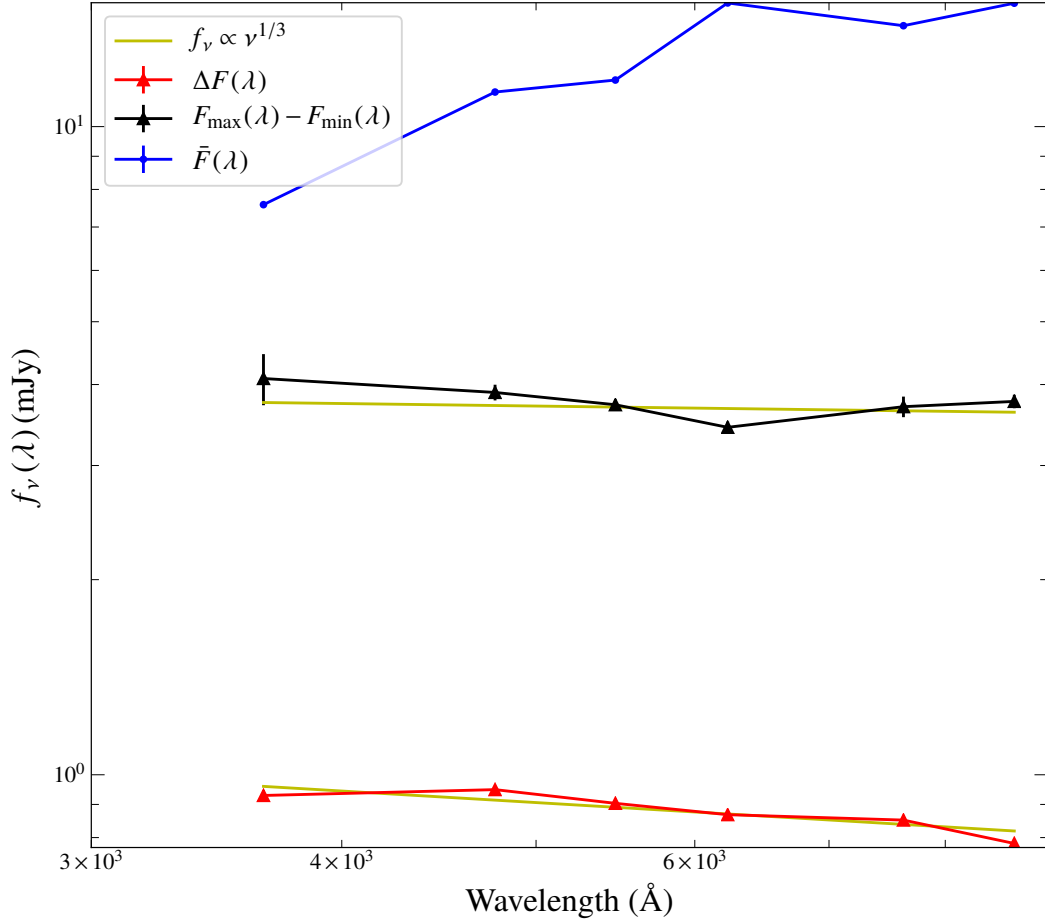


Figure 4.15: The spectral energy distribution of 3C 120 derived from flux-flux analysis. The mean  $\bar{F}(\lambda)$  spectrum (blue) is obtained by evaluating the best-fit linear lines at  $X_0 = 0$ . The difference spectrum between minimum and maximum fluxes is shown in black and the variable  $\Delta F_\nu(\lambda)$  spectrum is shown in red. The two yellow lines represents the expected SED from a standard thin-disc model to both the variable and difference spectra, plotted for comparison.

$\lambda^{4/3}$ . As before,  $X$  is given by Wien's law since a range of radii contributes to emission at  $\lambda$ . Substituting in Eqn. 4.3 results in the predicted spectrum for a blackbody accretion disc (yellow) shown in Figure 4.16. The  $\bar{F}_{\text{disc}}(\lambda)$  spectrum closely resembles  $f_\nu \propto \nu^{1/3}$  for a thin steady-state blackbody disc, but is a factor 4 times fainter than the predicted spectrum. This is consistent with Starkey et al. (2017) for the disc in NGC 5548, indicating that this is not only a problem for 3C 120. More measurements of the variable disc spectrum in several AGNs are required to have a better understanding of the discrepancy. A similar result is obtained when the predicted spectrum of Cackett et al. (2007) is used, where

$$f_\nu = \frac{4\pi R_0^2 \cos i}{D^2} (hc)^{1-(2/b)} \lambda^{(2/b)-3} (kT_0)^{2/b} \frac{I_2(b)}{b}. \quad (4.4)$$

$I_n(b)$  is a numerical function evaluated as

$$I_n(b) = \int_0^\infty \frac{s^{(n/b)-1} ds}{e^s - 1}, \quad (4.5)$$

with  $s = s_0 y^b$  ( $s_0 = hc/\lambda k T_0$ ,  $y = R/R_0$ ). For  $n = 2$ , Eqn. 4.5 evaluates to  $I_2(3/4) = 1.93$  ( $b = 3/4$  for a standard thin disc). For consistency, the radius  $R_0 = r_1$  and  $T_0 = T_1$  the temperature at  $r_1 = 1$  light day. The predicted spectrum as a result of Eqn. 4.4 is shown as the blue dotted (underneath the yellow line) line in Figure 4.16 and matches that of Collier et al. (1999), as expected.

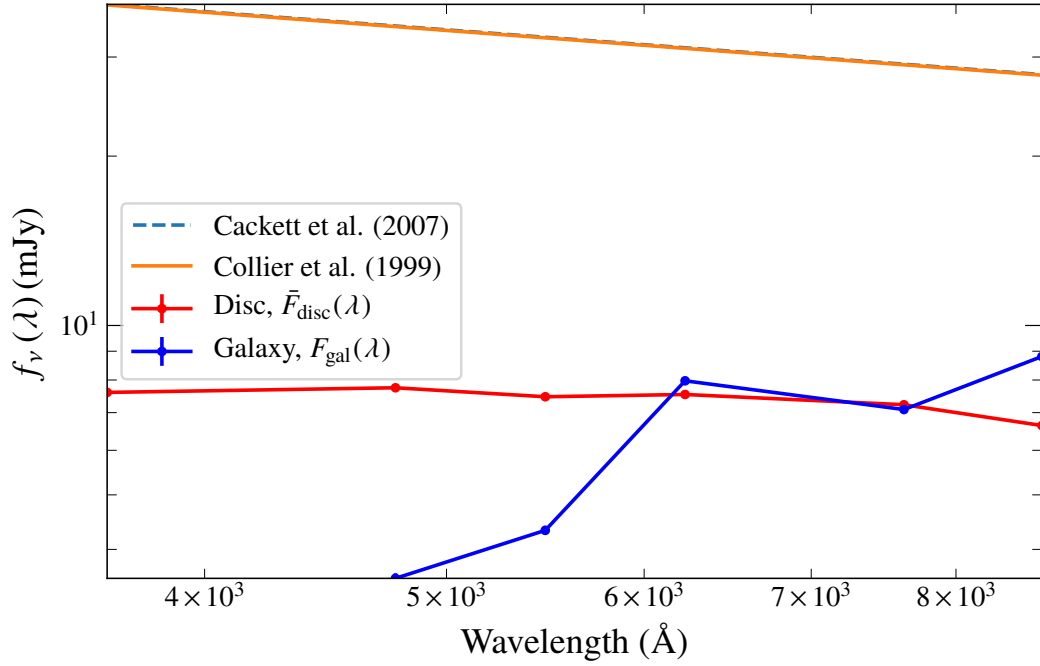


Figure 4.16: The dashed blue line (underneath the orange line) and solid orange line are the predicted spectra from Eqn. 4.3 and 4.4 respectively, for a classical thin-disc model. They are plotted for comparison with observed spectrum in solid red line. The host-galaxy spectrum from Eqn. 2.24 is shown in solid blue line.

#### 4.4.1 Luminosity At 5100Å

In order to determine the optical luminosity at the time of the observing campaign, the host-galaxy contribution must be estimated and disentangled from the AGN fluxes in the respective bands. The host-galaxy fluxes at each wavelength are estimated using Eqn. 2.24. By extrapolating, the value of  $X_{\text{gal}}$  was obtained as  $-8.12$ , corresponding to the value where the shortest wavelength first crosses zero. Table 4.10 lists the host-galaxy,  $f_{\text{gal}}(\lambda)$ , and disc,  $\bar{F}_{\text{disc}}(\lambda)$ , spectra, where  $\bar{F}_{\text{disc}}(\lambda)$  includes already the host-galaxy subtracted fluxes (Eqn. 2.25). The host-galaxy contribution in V of  $f_{\text{gal}}(5477\text{\AA}) = 4.32 \pm 0.08$  mJy is con-

Table 4.10: Host-galaxy and disc spectra for each wavelength.

| $\lambda$<br>(Å) | $f_{\text{gal}}(\lambda)$<br>(mJy) | $\bar{F}_{\text{disc}}(\lambda)$<br>(mJy) |
|------------------|------------------------------------|-------------------------------------------|
| 3656             | 0                                  | $7.604 \pm 0.011$                         |
| 4770             | $3.553 \pm 0.075$                  | $7.75 \pm 0.08$                           |
| 5477             | $4.32 \pm 0.08$                    | $7.47 \pm 0.08$                           |
| 6231             | $7.974 \pm 0.105$                  | $7.54 \pm 0.11$                           |
| 7625             | $7.089 \pm 0.105$                  | $7.23 \pm 0.11$                           |
| 8660             | $8.806 \pm 0.119$                  | $6.64 \pm 0.12$                           |

Extinction corrected values.

sistent, to within flux errors with  $4.58 \pm 0.40$  mJy from [Pozo Nuñez et al. \(2012\)](#), using a similar approach. The host-galaxy at  $5100 \text{ Å}$  is obtained by interpolating the host-galaxy spectrum at  $5100 \text{ Å}$ , giving an interpolated value of  $3.913 \pm 0.077$  mJy. The error on the flux was also obtained by interpolating the  $\pm\sigma$  flux errors.

In earlier campaigns, [Bentz et al. \(2006\)](#) estimated the host-galaxy contribution for 3C 120 at  $5100 \text{ Å}$  using galaxy decomposition method and found it to be  $1.58 \pm 0.29$  mJy, without accounting for Galactic extinction ([Schlegel et al. 1998](#)). Subsequently, [Bentz et al. \(2009a\)](#), using a slightly modified galaxy decomposition method, estimated it to be  $0.56 \pm 0.05$  mJy. The value measured here ( $3.913 \pm 0.077$  mJy) is very different from the two Bentz et al. studies. The difference in the slit width here (2 arcsec) to the overall size of the disc in 3C 120 may account for the difference in the measurements.

To estimate the AGN luminosity appropriate to the current campaign, the observed disc flux at  $5100 \text{ Å}$  is estimated by interpolation, to be  $f_{\text{obs}}[5100\text{Å}(1+z)] = 7.55 \pm 0.08$  mJy. Using distance  $D = 139$  Mpc (Table 4.1), the luminosity at the time of this campaign was  $(9.94 \pm 0.11) \times 10^{43} \text{ erg s}^{-1}$ . It is worth reiterating that the host-galaxy flux contribution in this work was estimated using the flux gradient method (FVG) which takes into account multi-band photometric observations, different from the method of Bentz, who placed a slit width and constrained the galaxy contribution within.

## 4.5 Black Hole Mass

One of the main objectives of this work is to determine the mass of the central black hole in 3C 120, by making use of Eqn. 1.23. The determination of the black-hole mass  $M$ , involves measurements of the emission-line width ( $\sigma_{\text{line}}$  or FWHM) and the time delay ( $\tau$ ). The dimensionless factor  $f$  is different for each AGN ([Pancoast et al. 2014a;b](#)) and because of the difficulty in measuring it, it is often assumed. Here, a mean value of  $\langle f \rangle = 5.5$ , measured by reconciling the  $M - \sigma_*$  relation with that for quiescent galaxies ([Onken et al. 2004](#)), is assumed because it is the most common factor used when measuring the black hole mass from the line width ( $\sigma_{\text{line}}$ ) measured from the rms spectra. To compare with similar studies on 3C 120, the mass  $M$  is measured, based on the  $\text{H}\beta$  emission line from the blue-side. For

Table 4.11: Outcomes of previous reverberation mapping studies on 3C 120 in rest-frame.

| Study               | Campaign    | H $\beta$ lag<br>(days) | $\sigma_{\text{line}}$<br>(km s $^{-1}$ ) | $M_{\text{BH}}^{(b)}$<br>( $10^7 M_{\odot}$ ) | $\log \lambda L_{\lambda}(5100\text{\AA})$<br>(erg s $^{-1}$ ) |
|---------------------|-------------|-------------------------|-------------------------------------------|-----------------------------------------------|----------------------------------------------------------------|
| (1)                 | 1989 – 1996 | $39.4^{+22.1}_{-15.8}$  | $1166 \pm 50$                             | $5.55^{+3.14}_{-2.25}$                        | $44.01 \pm 0.05$                                               |
| (2)                 | 2008 – 2009 | $27.9^{+7.1}_{-5.9}$    | $1689 \pm 68$                             | $8.5^{+2.3}_{-1.9}$                           | $44.12 \pm 0.07$                                               |
| (3)                 | 2009 – 2010 | $23.6^{+1.7}_{-1.7}$    | 1504 <sup>(c)</sup>                       | $5.7^{+2.7}_{-2.7}$                           | $43.84 \pm 0.04$                                               |
| (4)                 | 2010 – 2011 | $27.2^{+1.1}_{-1.1}$    | $1514 \pm 65$                             | $6.7^{+0.6}_{-0.6}$                           | $43.96 \pm 0.06$                                               |
| (5)                 | 2016 – 2017 | $20.2^{+5.0}_{-4.2}$    | $1360 \pm 42$                             | $4.01^{+1.02}_{-0.87}$                        | $43.99 \pm 0.01^*$                                             |
| (6)                 | 2016 – 2018 | $21.2^{+1.6}_{-1.0}$    | $1657 \pm 3$                              | $6.3^{+0.5}_{-0.3}$                           | $43.99 \pm 0.01$                                               |
| Mean <sup>(a)</sup> |             |                         |                                           | <b><math>6.2^{+0.3}_{-0.3}</math></b>         |                                                                |

(1) [Peterson et al. \(2004\)](#), (2) [Kollatschny et al. \(2014\)](#), (3) [Pozo Nuñez et al. \(2012\)](#), (4) [Grier et al. \(2012\)](#), (5) [Du et al. \(2018a\)](#), (6) This work.

<sup>a</sup> Weighted average.

<sup>b</sup>  $M$  masses calculated using  $\langle f \rangle = 5.5$  for comparison.

<sup>c</sup> Measured from single-epoch spectra.

\* The authors do not provide the measurement, we put that here because the two campaigns overlap.

the emission-line width, the second moment of the line  $\sigma_{\text{line}}$  is preferred (measured from the rms spectrum), and is determined as  $\sigma_{\text{line}} = 1657 \pm 3 \text{ km s}^{-1}$ , for H $\beta$  (Section 3.4.1). Combining it with the time delay  $\tau = 21.6^{+1.6}_{-1.0}$  days, relative to V, results in a black-hole mass  $M = (6.3^{+0.5}_{-0.3}) \times 10^7 (f/5.5) M_{\odot}$ .

In the 1989-1996 campaign, [Peterson et al. \(2004\)](#) measured an H $\beta$  delay of  $39.4^{+22.1}_{-15.8}$  days resulting in large uncertainties on their determined mass  $M = (5.55^{+3.14}_{-2.25}) \times 10^7 (f/5.5) M_{\odot}$ . In the following 2008-2009 campaign, [Kollatschny et al. \(2014\)](#) performed a multiple-line lag measurements in 3C 120 and using H $\beta$  line delay  $27.9^{+7.1}_{-5.9}$  days, measured the mass to be  $M = (8.5^{+2.3}_{-1.9}) \times 10^7 (f/5.5) M_{\odot}$ . [Pozo Nuñez et al. \(2012\)](#) in the 2009-2010 campaign, measured a 3C 120 black-hole mass of  $M = (5.7^{+2.7}_{-2.7}) \times 10^7 (f/5.5) M_{\odot}$  using an H $\beta$  delay of  $23.6^{+1.7}_{-1.7}$  days. Using high-fidelity data, [Grier et al. \(2012\)](#) measured an H $\beta$  delay of  $27.2^{+1.1}_{-1.1}$  days using JAVELIN ([Zu et al. 2011](#)), yielding smaller uncertainties on the lag and thus on the resulting mass  $M = (6.7^{+0.6}_{-0.6}) \times 10^7 (f/5.5) M_{\odot}$  in the 2010-2011 campaign. Recently, [Du et al. \(2018b\)](#) detected a similar H $\beta$  lag  $20.2^{+5.0}_{-4.2}$  days as this work (published as [Hlabathe et al. 2020](#)), but measuring a different mass  $M = (4.01^{+1.02}_{-0.87}) \times 10^7 (f/5.5) M_{\odot}$  for the 2016-2017 campaign. This is because their H $\beta$  line-width measurement is different (i.e., smaller), perhaps due to the significantly blueshifted H $\beta$  profile in the rms spectrum. These measurements do not take into account the uncertainty in the assumed  $f$ . Figure 4.17 compares 3C 120 masses from different campaigns as a function of the H $\beta$  time delay. Generally, the masses are consistent with each other to  $2\sigma$ .

Without assuming the mean value of the virial factor  $f$ , Grier et al. (2017b) measured the mass to be  $M = (6.92^{+1.38}_{-1.55}) \times 10^7 M_\odot$  from dynamical modelling (Pancoast et al. 2014a;b) of the BLR in 3C 120. This way of measuring the mass avoids the uncertainty introduced by assuming the mean value of  $f$ . Instead, the mass is measured independently of  $f$ . The measured mass is then used to infer,  $f$ , specific for the AGN in question. For 3C 120, the inferred  $f$  was measured as  $f_\sigma = 5.75 \pm 2.25$  and  $f_{\text{FWHM}} = 6.46 \pm 2.53$ , using  $\text{H}\beta$  emission-line parameters from Grier et al. (2012). The assumed mean factor  $\langle f \rangle = 5.5$  here, is consistent to within  $1\sigma$  with  $f_\sigma = 5.75 \pm 2.25$  from modelling, hence giving consistent black-hole masses.

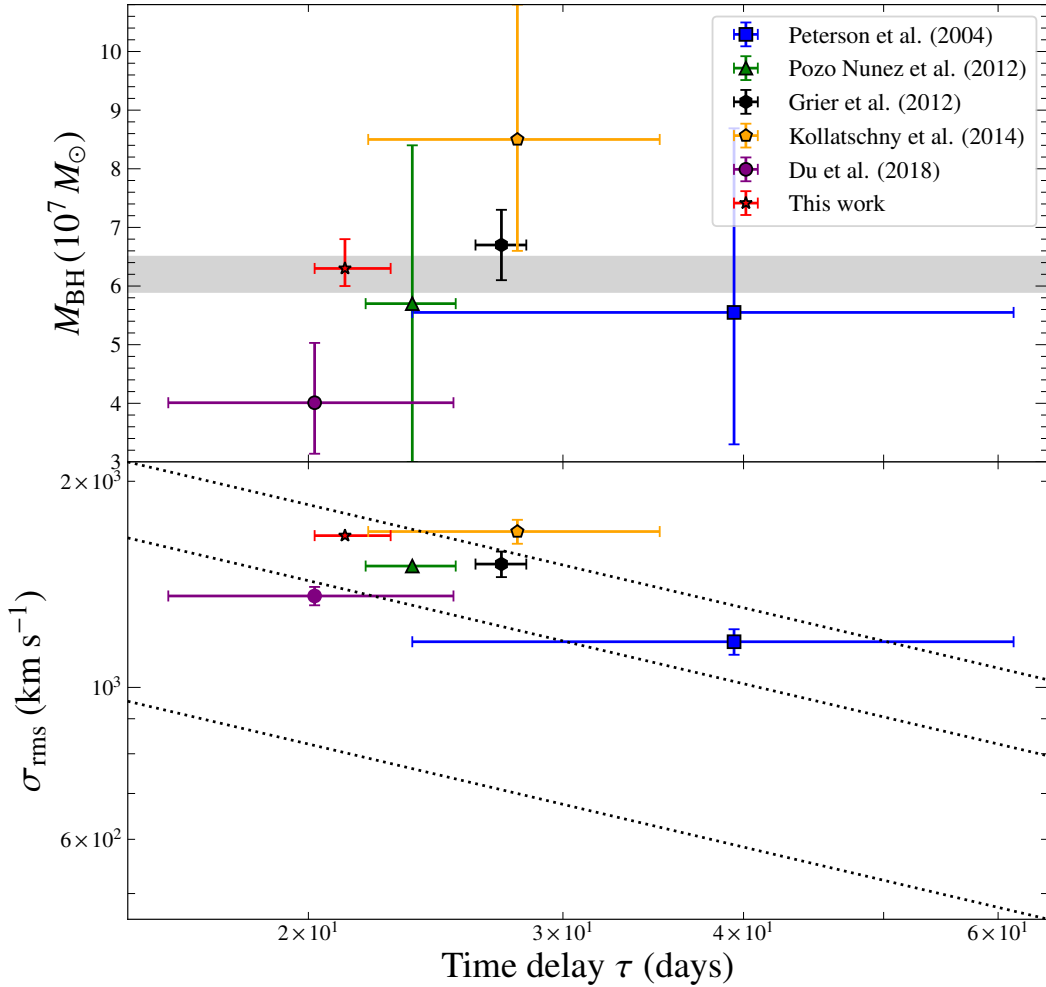


Figure 4.17: Top: The measured BH masses from different campaigns as a function of  $\text{H}\beta$  time delay. The shaded area highlights the  $1\sigma$  error envelope on the weighted average. Bottom: The  $\text{H}\beta$  line width as a function of its delay from the corresponding campaigns. The dotted lines are the lines of constant black-hole mass, arbitrarily chosen as  $2 \times 10^7$ ,  $6 \times 10^7$ ,  $1 \times 10^8 M_\odot$  from bottom to top, for comparison.

## 4.6 Velocity-resolved Lag Measurements

Probing the structure and kinematics of the BLR is the sought-after goal of reverberation mapping (Section 2.5). The better S/N data here allows for the derivation of the velocity-resolved profile for 3C 120 by looking at the  $H\beta$  emission line. Previous works by Grier et al. (2013b; 2017b), Du et al. (2018b) have successfully resolved the structure and kinematics of the BLR in 3C 120 before. In a similar manner, the  $H\beta$  profile is divided into 11 velocity bins in the continuum-subtracted spectra from  $-4000$  to  $4000 \text{ km s}^{-1}$ . The rest-frame wavelength of  $H\beta$  is used to separate the blueshifted and redshifted measurements. The  $H\beta$  line fluxes are integrated to build a light curve corresponding to each bin. The light curves from each bin are then cross-correlated with the V-band continuum to derive the centroid lag (Section 4.2.1). These measured lags are plotted as a function of line-of-sight velocity in the velocity-resolved profile.

Figure 4.18 shows the derived velocity-resolved profile for 3C 120; the two outer bins on the wings were made intentionally broader to maximise the S/N. The profile shows a symmetric pattern about zero velocity, allowing us to deduce that this is a rotationally-dominated system. The lag at the center is  $\sim 25$  days, decreasing to  $\sim 17$  days on the wings. A consistent morphology was deduced by Grier et al. (2013b) for an earlier campaign.

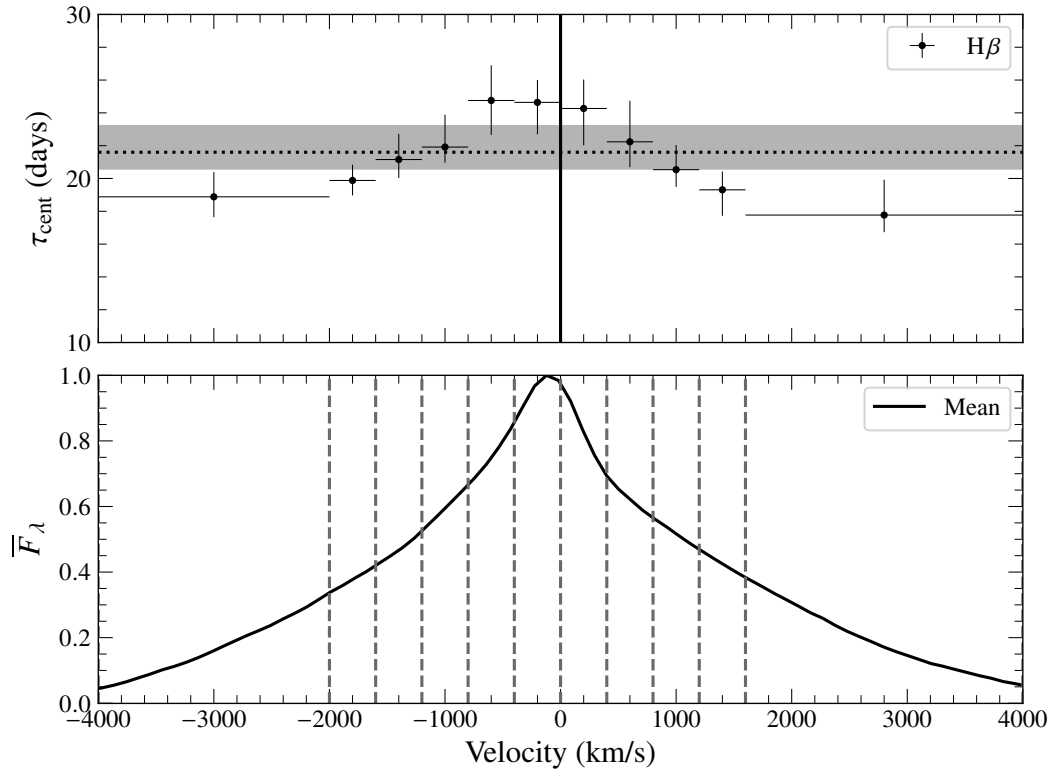


Figure 4.18: Velocity-resolved profile for 3C 120. Top: The measured  $H\beta$  centroid lag from each bin as a function of velocity. The grey band is the  $1\sigma$  error envelope on the average  $H\beta$  lag in Table 4.6. The horizontal error bars represent the width of each bin. Bottom: The normalized mean spectrum with velocity bins shown by vertical dotted lines.



## Chapter 5

# Reverberation mapping of PG 2304+043

This chapter focuses on multi-wavelength photometric and spectroscopic observations of Palomar-Green (PG) 2304+043 or 2304+042, originally part of the [Boroson & Green \(1992\)](#) sample. It follows a similar flow as the previous chapter on 3C 120 in terms of deriving the observed inter-band continuum delays and comparing them with the [Shakura & Sunyaev \(1973\)](#) model, along with deriving accretion-disc parameters, such as the temperature profile of the disc and the mass accretion rate. It also seeks to measure the observed accretion-disc size in comparison with the model predicted size. Lastly, this study aims to derive the mass of the central black hole in PG 2304+043 using a reverberation mapping (RM) data-set and compare with single-epoch (SE) measurements.

PG 2304+043 (Table 5.1) has a previous mass estimate of the central black hole of  $M = (3.98 \pm 0.92) \times 10^8 M_{\odot}$  from SE spectroscopy ([Vestergaard & Peterson 2006](#)), using the  $H\beta$  emission-line width from [Boroson & Green \(1992\)](#). Its monochromatic luminosity at  $5100 \text{ \AA}$  was derived to be  $\lambda L_{5100\text{\AA}} = 10^{44.1 \pm 0.1} \text{ erg s}^{-1}$  ([Schmidt & Green 1983](#)). Adopting the same bolometric correction of  $L_{\text{Bol}} = 9.26 (\lambda L_{5100\text{\AA}})$  ([Richards et al. 2006](#)), leads to a bolometric luminosity,  $L_{\text{Bol}} = 10^{45.1 \pm 0.1} \text{ erg s}^{-1}$ . Approximating the Eddington luminosity, as defined in Eqn. 1.3, yields  $L_{\text{Edd}} = (5.2 \pm 1.2) \times 10^{46} \text{ erg s}^{-1}$  for  $M = (3.98 \pm 0.92) \times 10^8 M_{\odot}$ . The Eddington ratio is then estimated to be  $\dot{m}_{\text{Edd}} = \dot{M}/\dot{M}_{\text{Edd}} = L_{\text{Bol}}/L_{\text{Edd}} = 0.025 \pm 0.006$ . The Eddington accretion rate from Eqn. 1.7 results in  $\dot{M}_{\text{Edd}} = 8.84 \pm 2.04 M_{\odot} \text{ yr}^{-1}$  and the black-hole mass accretion rate is  $\dot{M} = 0.22 \pm 0.07 M_{\odot} \text{ yr}^{-1}$ . These values have not been corrected for the host-galaxy contribution as noted in [Vestergaard & Peterson \(2006\)](#).

[Shangguan et al. \(2018\)](#) re-measured the mass of the black hole in this object adopting the recent virial mass calibration of [Ho & Kim \(2015\)](#). They measure the mass as  $M = 4.79 \times 10^8 M_{\odot}$  (with no errorbars) using a monochromatic luminosity at  $5100 \text{ \AA}$  of  $\lambda L_{5100\text{\AA}} = 10^{44.04} \text{ erg s}^{-1}$ , adjusted to their cosmology, and the same  $H\beta$  emission-line width from [Boroson & Green \(1992\)](#).

## 5.1 Data and Analysis

Section 5.1.1 presents multi-wavelength LCO photometric observations of a nearby radio-quiet galaxy PG 2304+043. The photometric observations were supplemented with spectroscopic observations from SALT as presented in Section 5.1.2.

Table 5.1: PG 2304+043 properties

| RA <sup>(1)</sup> | DEC <sup>(1)</sup> | $z^{(1)}$ | FWHM(H $\beta$ ) <sup>(2)</sup> | $M^{(2)}$                               | $\lambda L_{5100}^{(2)}$ |
|-------------------|--------------------|-----------|---------------------------------|-----------------------------------------|--------------------------|
| (J2000)           | (J2000)            |           | (km s <sup>-1</sup> )           | ( $M_{\odot}$ )                         | (erg s <sup>-1</sup> )   |
| 23 07 02.912      | +04 32 57.220      | 0.04200   | 6487                            | $(3.98 \pm 0.92) \times 10^8 M_{\odot}$ | $10^{44.1 \pm 0.1}$      |

<sup>1</sup> Values from NED database.

<sup>2</sup> Based on SE spectroscopy from Vestergaard & Peterson (2006).

### 5.1.1 Photometry

The multi-wavelength (BV  $ugriz_s$ ) photometric observations of PG 2304+043 were obtained during the period between 2018 June to 2018 December ( $\sim 6$  months) employing the LCO 1m telescopes (Section 3.2). The observations were triggered in BV $r$  at the start of the campaign. Later, more filters ( $ugiz_s$ ) were added when PG 2304+043 appeared to be undergoing significant variability. The quasi-simultaneous observations in all 7 filters carried on until the target became inaccessible. Table 5.2 presents the summary of the observations for the whole campaign.

Aperture photometry was performed with SExtractor (SEx, Bertin & Arnouts 1996; 2010). SEx is an image analysis tool designed to optimally go through a large set of astronomical images simultaneously, and create catalogues as output. The catalogues are then used for further processing, such as performing differential photometry. Differential photometry measures the flux of a target object enclosed within an aperture relative to one or more comparison stars. Here, a circular aperture of fixed size was adopted for all observations.

First, careful visual inspection of the images was done using DS9 (Joye & Mandel 2003). Through visual inspection, an image with “best/good” seeing and “worst/bad” seeing were selected from the set. A curve-of-growth was constructed for an image with good seeing and an image with bad seeing. A curve-of-growth is calculated as the signal-to-noise ratio (S/N) as a function of aperture radius. For a range of aperture radii, flux from both the candidate comparison star and the sky were measured. The sky was next corrected for, by subtracting its contribution from the comparison’s flux (also propagating the errors), and then estimating the S/N. A comparison was drawn between the two curves-of-growth derived from good and bad seeing images, so as to come up with an optimum aperture radius which would give reasonable S/N under extreme seeing conditions. The idea is to enclose as much flux from the source as possible while minimizing the contribution from the background/sky. This procedure led to an optimum aperture radius of  $\sim 5$  arcseconds (13 pixels) as shown

Table 5.2: Summary of observations for PG 2304+043.

| Filter <sup>(1)</sup> | $\lambda_{\text{pivot}}^{(2)}$ | Site <sup>(3)</sup> | Date range <sup>(4)</sup> | $t_{\text{exp}}$ (s) | No. of Epochs <sup>(5)</sup> | Total <sup>(6)</sup> |
|-----------------------|--------------------------------|---------------------|---------------------------|----------------------|------------------------------|----------------------|
| $u'$                  | 3540Å                          | SAAO                | 20181006-20181010         | 300                  | 6                            | 100                  |
|                       |                                | McD                 | 20181102-20181227         |                      | 18                           |                      |
|                       |                                | SSO                 | 20180916-20181201         |                      | 33                           |                      |
|                       |                                | CTIO                | 20180902-20181207         |                      | 43                           |                      |
| B                     | 4361Å                          | SAAO                | 20180625-20181204         | 180                  | 39                           | 226                  |
|                       |                                | McD                 | 20180618-20181223         |                      | 30                           |                      |
|                       |                                | SSO                 | 20180615-20181104         |                      | 82                           |                      |
|                       |                                | CTIO                | 20180614-20181211         |                      | 75                           |                      |
| $g'$                  | 4770Å                          | SAAO                | 20181006-20181010         | 180                  | 6                            | 98                   |
|                       |                                | McD                 | 20181102-20181227         |                      | 18                           |                      |
|                       |                                | SSO                 | 20180916-20181201         |                      | 32                           |                      |
|                       |                                | CTIO                | 20180902-20181207         |                      | 42                           |                      |
| V                     | 5448Å                          | SAAO                | 20180625-20181204         | 180                  | 38                           | 223                  |
|                       |                                | McD                 | 20180618-20181223         |                      | 27                           |                      |
|                       |                                | SSO                 | 20180615-20181104         |                      | 82                           |                      |
|                       |                                | CTIO                | 20180614-20181211         |                      | 76                           |                      |
| $r'$                  | 6215Å                          | SAAO                | 20180625-20181204         | 180                  | 38                           | 217                  |
|                       |                                | McD                 | 20180618-20181221         |                      | 26                           |                      |
|                       |                                | SSO                 | 20180615-20181104         |                      | 80                           |                      |
|                       |                                | CTIO                | 20180614-20181201         |                      | 73                           |                      |
| $i'$                  | 7545Å                          | SAAO                | 20181006-20181010         | 180                  | 6                            | 98                   |
|                       |                                | McD                 | 20181102-20181227         |                      | 18                           |                      |
|                       |                                | SSO                 | 20180916-20181201         |                      | 32                           |                      |
|                       |                                | CTIO                | 20180902-20181207         |                      | 42                           |                      |
| $z_s$                 | 8700Å                          | SAAO                | 20181006-20181010         | 300                  | 6                            | 95                   |
|                       |                                | McD                 | 20181102-20181227         |                      | 18                           |                      |
|                       |                                | SSO                 | 20180916-20181201         |                      | 31                           |                      |
|                       |                                | CTIO                | 20180902-20181206         |                      | 40                           |                      |

<sup>1</sup> The filter through which the data was taken.

<sup>2</sup> Filter centroid wavelength.

<sup>3</sup> SAAO (South African Astronomical Observatory), McD (McDonald Observatory), SSO (Siding Spring Observatory), CTIO (Cerro Tololo Interamerican Observatory).

<sup>4</sup> Starting date and end date of observations.

<sup>5</sup> The number of observations taken in that date range per filter.

<sup>6</sup> The total number of observations taken in that filter from all telescopes combined.

in Figure 5.2. The same aperture radius was adopted for all filters.

The default values in the SEx configuration file were left unchanged except for aperture, level of saturation, pixel scale, detect minarea, detect analysis and detect threshold. The aperture was set to the value derived above. The saturation values and pixel scale values were read from the fits header. The detection parameters were set to 7, 3, 3 for detect minarea, detect threshold and detect analysis, respectively. These were set to avoid false detections such as cosmic ray hits, bad pixels, etc. For each frame, a corresponding catalogue with detected sources from SEx was obtained. The catalogues contain information (included in the parameter file) such as measured fluxes, magnitudes, positions, flags, etc

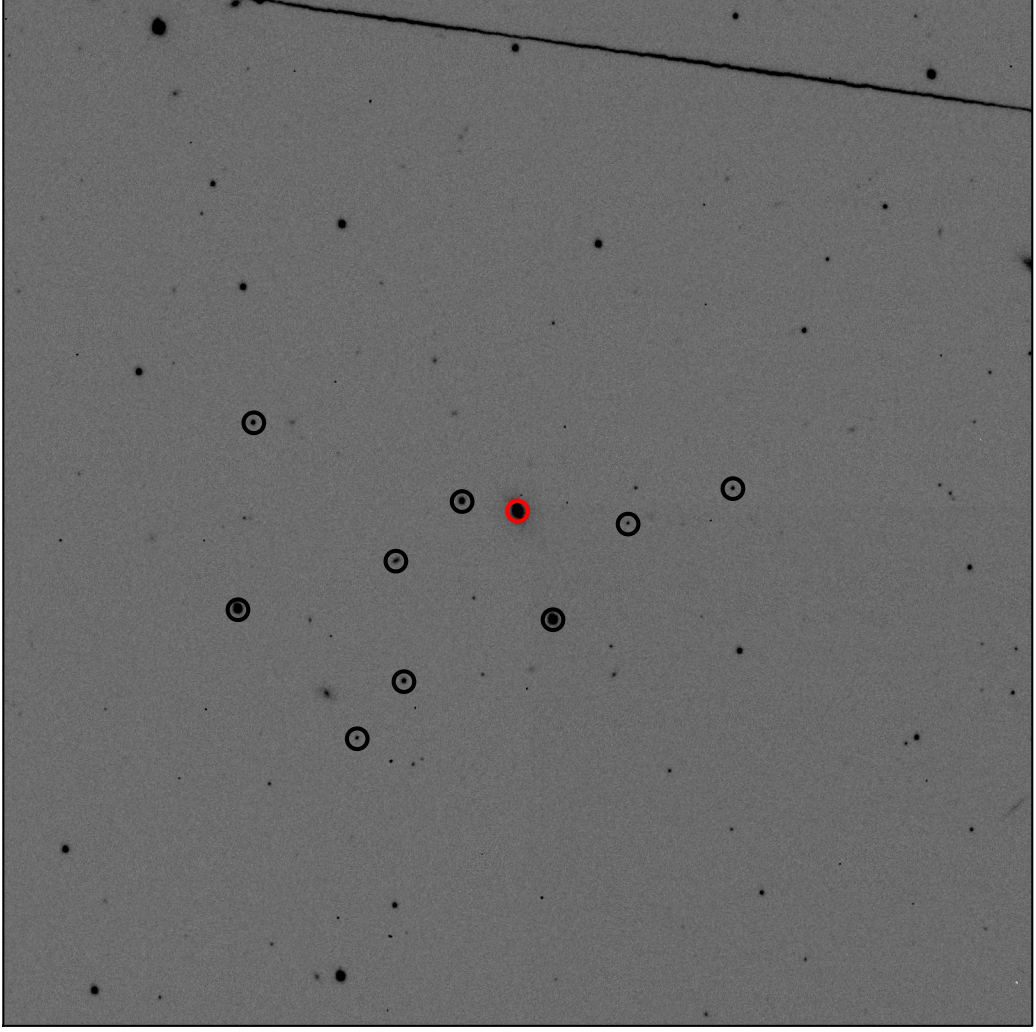


Figure 5.1: A cut-out V-band image of PG 2304+043 (red) along with the chosen comparison stars (black). The image is 10 arcmin wide with North direction up.

for each source. These catalogues were then used to perform differential photometry.

To perform differential photometry (Section 3.3.1), potential comparison stars were selected from the field of view (FoV) of a CCD image with good seeing. These stars were chosen on the basis that they appeared brighter than the surrounding stars, were situated in close proximity to the target and were unsaturated. In total, 9 comparison stars were chosen (Figure 5.1). Figure 5.3 shows the residuals,  $\Delta m_{\text{check}} - \Delta m_{\text{star}}$ , plotted for all selected comparison stars for V filter, for consistency check (Section 3.3.1). The inter-calibrated continuum light-curves for PG 2304+043 are presented in Figure 5.4, in which the CTIO data set was used as reference (Section 3.3.3).

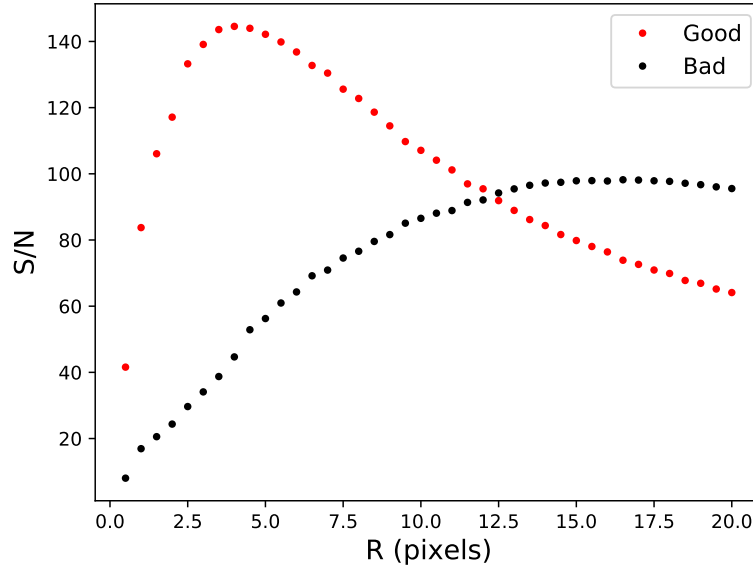


Figure 5.2: The curve of growth for V band images with good and bad seeing as a function of aperture radius.

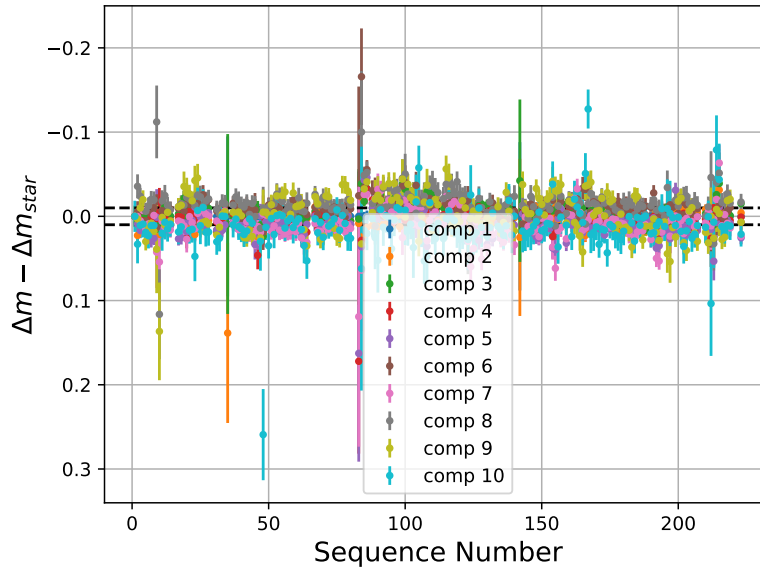


Figure 5.3: The residuals plot for all selected comparison stars for V filter. The horizontal dotted lines mark the 1% threshold.

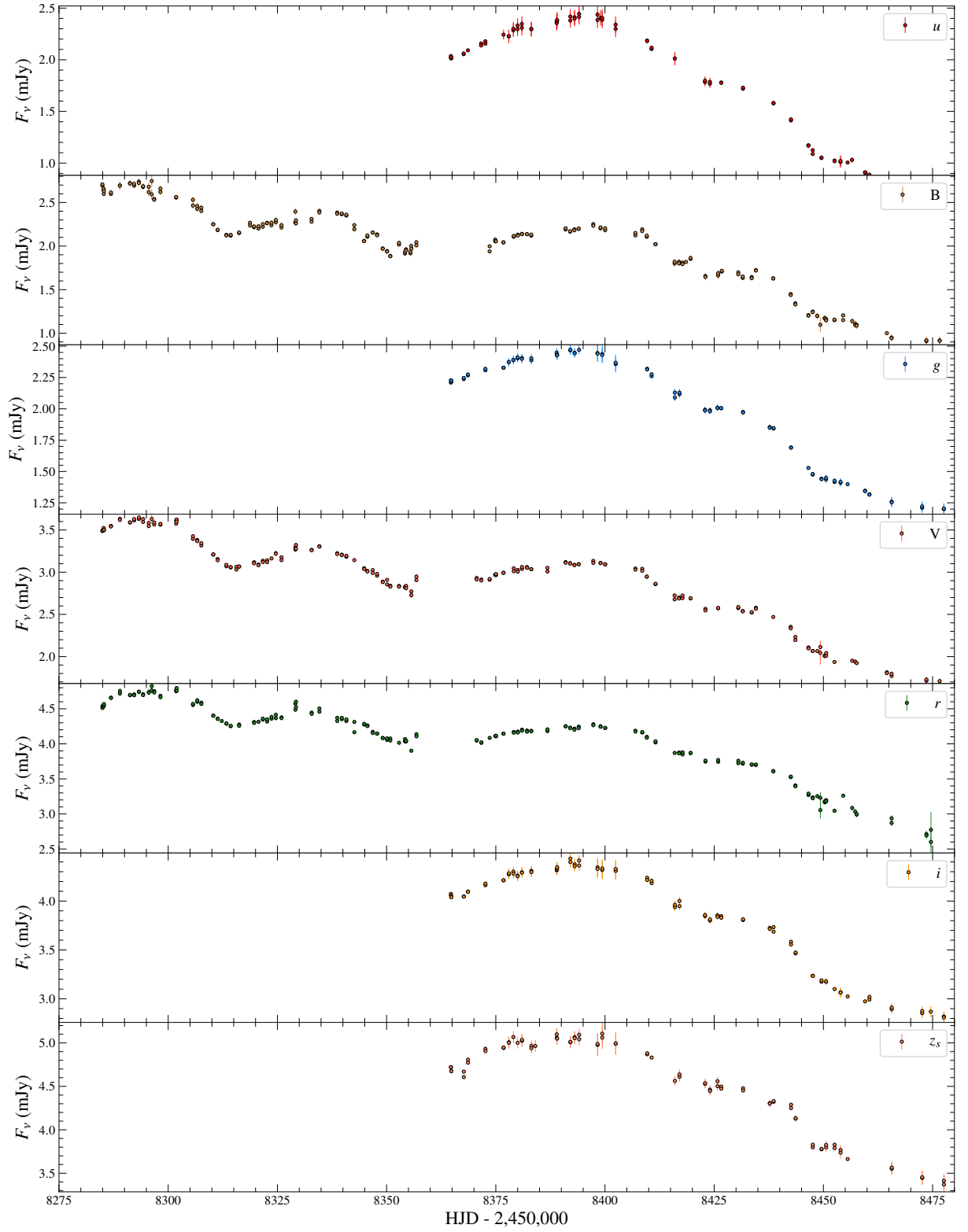


Figure 5.4: LCO light curves from CTIO, McD, SAAO and SSO ordered by increasing filter wavelength (*u*, *B*, *g*, *V*, *r*, *i*, *z<sub>s</sub>*). These have not been corrected for Galactic extinction.

### 5.1.2 Spectroscopy

A total of 18 spectroscopic observations of PG 2304+043 were obtained with SALT (Section 3.1). The observations were spread over 51 nights, from 2018 September 09 to 2018 October 30. The RSS longslit (Section 3.1.1) with a PG2300 grating, a grating angle of  $36.125^\circ$  and articulation angle of  $72.25^\circ$  was used to ensure that both  $H\beta$  and  $[O\ III]\lambda 5007$  were present in the spectra. A slit width of 4.0 arcsecond was also used, wide enough to include all of the AGN emission-line flux. This setup resulted in spectral coverage from  $4588\text{\AA}$  to  $5593\text{\AA}$ , with a spectral resolution  $R \sim 1026$ , corresponding to a central wavelength  $5116.8\text{\AA}$ . The exposure time was 240 seconds per single spectrum.

Figure 5.5 shows the final flux-calibrated spectrum (i.e., the mean) of PG 2304+043 following Section 3.1.1. The reduced spectra were then corrected for flux differences from one night

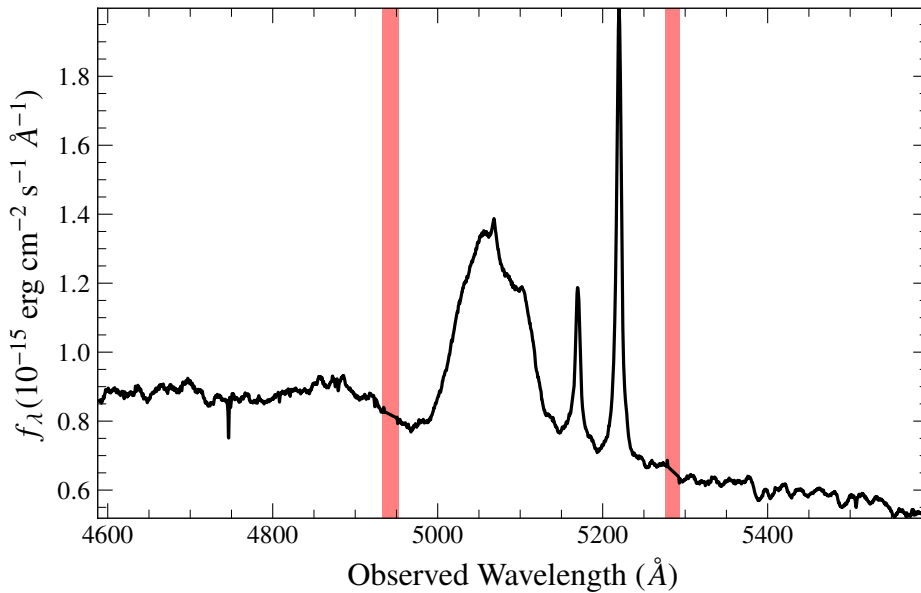


Figure 5.5: The mean spectrum of PG 2304+043. The vertical red shaded regions are meant to highlight the blue and red SALT chip gaps.

to the next, due to, for example, seeing, slit positioning, atmospheric transparency, etc. For this procedure, PrepSpec software as described in Section 3.4.1 and in more detail by Shen et al. (2016b), was used. The wavelength range was restricted to  $4755 - 5050\text{\AA}$  (rest-frame wavelength) during the modeling with PrepSpec to avoid the chip gaps in the SALT spectra. The chip gaps have an effect of potentially introducing errors to continuum modeling using polynomial(s) as part of the PrepSpec routine (or any other continuum model). This meant that one does not have enough continuum to constrain on either side of the  $H\beta\lambda 4861$  and  $[O\ III]\lambda 5007$  emission-line profiles. This may potentially affect the measured line fluxes (by underestimating them) and, consequently, the time lag estimate. Two spectra taken on dates 20181016 and 20181023 were omitted from PrepSpec modeling due to significantly poor S/N.

Table 5.3: S/N of the spectra per pixel in the continuum. The S/N of the spectrum is measured in the region from 5240-5280 Å (observed-frame).

| Spectrum | S/N    |
|----------|--------|
| 20180909 | 146.91 |
| 20180913 | 77.99  |
| 20180916 | 23.63  |
| 20180920 | 48.87  |
| 20180926 | 36.06  |
| 20180928 | 55.96  |
| 20181001 | 72.54  |
| 20181003 | 57.96  |
| 20181005 | 56.89  |
| 20181007 | 55.05  |
| 20181009 | 59.06  |
| 20181012 | 45.05  |
| 20181014 | 216.62 |
| 20181016 | 35.00  |
| 20181023 | 25.12  |
| 20181025 | 37.49  |
| 20181027 | 55.84  |
| 20181030 | 287.07 |

PG 2304+043 exhibits a broad asymmetric, or double-peaked,  $H\beta$  profile in the mean spectrum (top panel of Figure 5.6) and required an integration window 4782 – 4944 Å (free of possible contaminants and away from the chip gaps). The  $H\beta$  double-peaked structure is further revealed in the rms (or residual) spectrum, with two blue and red peaks (bottom panel of Figure 5.6). The [O III]  $\lambda\lambda 4959, 5007$  line residuals have vanished on the rms spectrum, as expected. The rms spectrum also indicates that, during the campaign  $H\beta$  was weakly varying or had little flux. Its degree of variability  $F_{\text{var}}$  is quantified in Section 5.1.3. The line widths from both the mean and rms profiles as measured from PrepSpec, following the methods of Peterson et al. (2004), are listed in Table 5.4. Line widths (FWHM and  $\sigma_{\text{line}}$ ) measured in the mean spectrum are slightly broader than the rms spectrum. Based on the selected spectral window and blending with other lines, the measured line widths may be underestimated. Vestergaard & Peterson (2006) quote a  $\text{FWHM}(H\beta_{\text{mean}})$  of 6487 km s<sup>-1</sup>, assuming a 10% statistical error on the width, from a single-epoch (SE) spectrum. In this study, a  $\text{FWHM}(H\beta_{\text{mean}}) = 5559 \pm 6$  km s<sup>-1</sup> is measured from multi-epoch spectra. The difference between these two line-width measurements may be due to systematics or biases associated with SE and RM (see, e.g., Shen 2013, for a review). The  $H\beta$  line has a complex profile and a visible narrow-line component. The measurement of the FWHM is susceptible to this narrow-line component. Its treatment or removal can lead to different results from one campaign to the next. Another factor may be the luminosity of the central source at the time of the campaign, with higher luminosities corresponding to longer time delays and narrower widths (Wang et al. 2020).

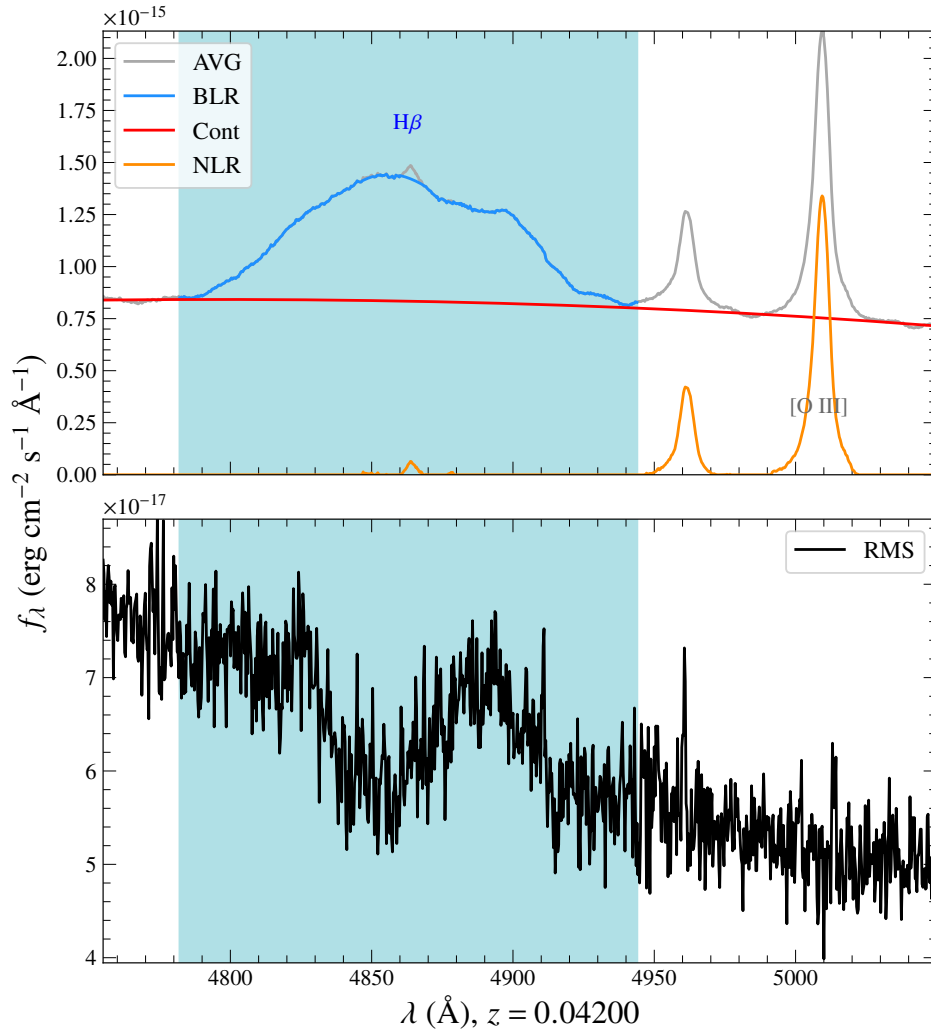


Figure 5.6: Mean (top) and rms (bottom) spectrum of PG 2304+043. Also shown is the  $H\beta$  spectral window used.

Table 5.4: Balmer  $H\beta$  linewidths and spectral window.

| Line     | FWHM(mean)<br>(km s <sup>-1</sup> ) | FWHM(rms)<br>(km s <sup>-1</sup> ) | $\sigma_{\text{line}}$ (mean)<br>(km s <sup>-1</sup> ) | $\sigma_{\text{line}}$ (rms)<br>(km s <sup>-1</sup> ) | Window<br>(Å) |
|----------|-------------------------------------|------------------------------------|--------------------------------------------------------|-------------------------------------------------------|---------------|
| $H\beta$ | $5559 \pm 6$                        | $5484 \pm 24$                      | $1894 \pm 2$                                           | $1805 \pm 8$                                          | 4782 – 4944   |

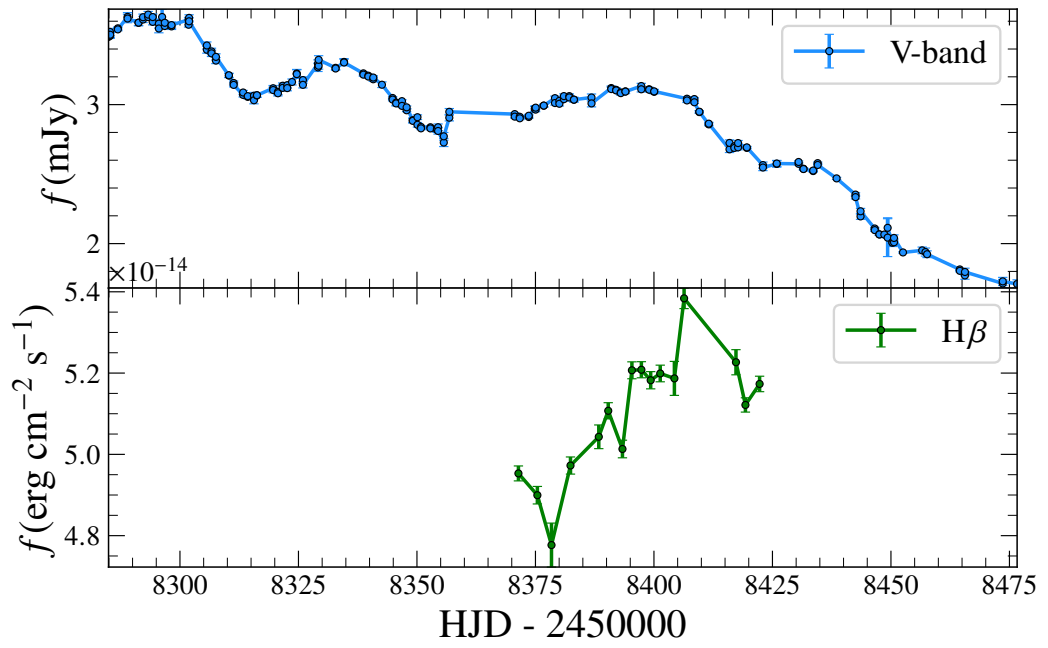


Figure 5.7: V-band continuum and  $H\beta$  light curves are shown, so as to resolve the correlated structures (if any).

### 5.1.3 Light curves

The flux-calibrated light curves for each wavelength are presented in Figure 5.4. The *BVr* light curves span about  $\sim 192$  days, while the *ugiz<sub>s</sub>* light curves span about  $\sim 100$  days, due to being triggered later in the campaign. This means that the *ugiz<sub>s</sub>* do not cover the variability in the first half of the campaign (i.e., the two peaks at  $\sim 8295$  and  $\sim 8334$  days). The difference in the light curve duration may pose problems for ICCF in measuring the inter-band lags. The different start times ( $t_1$ ) in the second half of the campaign between *BVr* light curves and *ugiz<sub>s</sub>* light curves may bias the ICCF results. It can lead to overestimated time delay, or a delay that does not reflect a true delay but reflect a delay due to being triggered later. The light curves do exhibit quite similar behaviour in the second half of the campaign, even though the variations are mild and decreasing.

The derived  $H\beta$  emission-line light curve is shown in Figure 5.7. On average, the  $H\beta$  light curve exhibits a steep rise in flux while the continuum appears to be declining. This behavior could reflect uncertainty in the measurements of  $H\beta$  flux due to e.g., systematic errors from calibration problems, or to the AGN behaving in a different way. By eye, the correlated structures with the continuum are not obvious, and thus we rely on the cross-correlation tools to provide the lag results and level of significance (Section 5.3).

The light curve properties (Table 5.5) are derived as explained in Section 3.5. The continuum light curves are all above the 10% variability level considered adequate for reverberation studies (Rodríguez-Pascual et al. 1997). Generally, the fractional variation decreases with increasing wavelength for the continuum light curves. On the other hand, the  $H\beta$  light curve gives an amplitude variability of 0.03, not sufficiently significant to yield a reliable lag measurement.

Table 5.5: PG 2304+043 light curve properties.

| Light curve          | $N_{\text{obs}}$ | $\Delta t_{\text{med}}$<br>(days) | $\hat{F}$ | $\langle S/N \rangle$ | $F_{\text{var}}$ | $(S/N)_{\text{var}}$ | $R_{\text{max}}$ |
|----------------------|------------------|-----------------------------------|-----------|-----------------------|------------------|----------------------|------------------|
| (1)                  | (2)              | (3)                               | (4)       | (5)                   | (6)              | (7)                  | (8)              |
| <i>u</i>             | 72               | 0.40                              | 1.90      | 77.16                 | 0.27             | 74.82                | $2.75 \pm 0.09$  |
| <i>B</i>             | 197              | 0.15                              | 2.02      | 114.32                | 0.23             | 192.93               | $3.02 \pm 0.16$  |
| <i>g</i>             | 85               | 0.09                              | 1.98      | 181.40                | 0.22             | 121.61               | $2.06 \pm 0.08$  |
| <i>V</i>             | 192              | 0.24                              | 2.95      | 196.55                | 0.16             | 249.81               | $2.13 \pm 0.04$  |
| <i>r</i>             | 189              | 0.31                              | 4.10      | 247.55                | 0.12             | 204.86               | $1.85 \pm 0.11$  |
| <i>i</i>             | 86               | 0.09                              | 3.81      | 184.36                | 0.14             | 96.95                | $1.58 \pm 0.04$  |
| <i>z<sub>s</sub></i> | 79               | 0.87                              | 4.49      | 140.15                | 0.12             | 66.74                | $1.52 \pm 0.05$  |
| $H\beta$             | 16               | 2.98                              | 5.11      | 222.66                | 0.03             | 15.74                | $1.13 \pm 0.01$  |

Column 4 is in units of mJy (and in units of  $10^{-14}$  erg cm $^{-2}$ s $^{-1}$  for  $H\beta$ ).

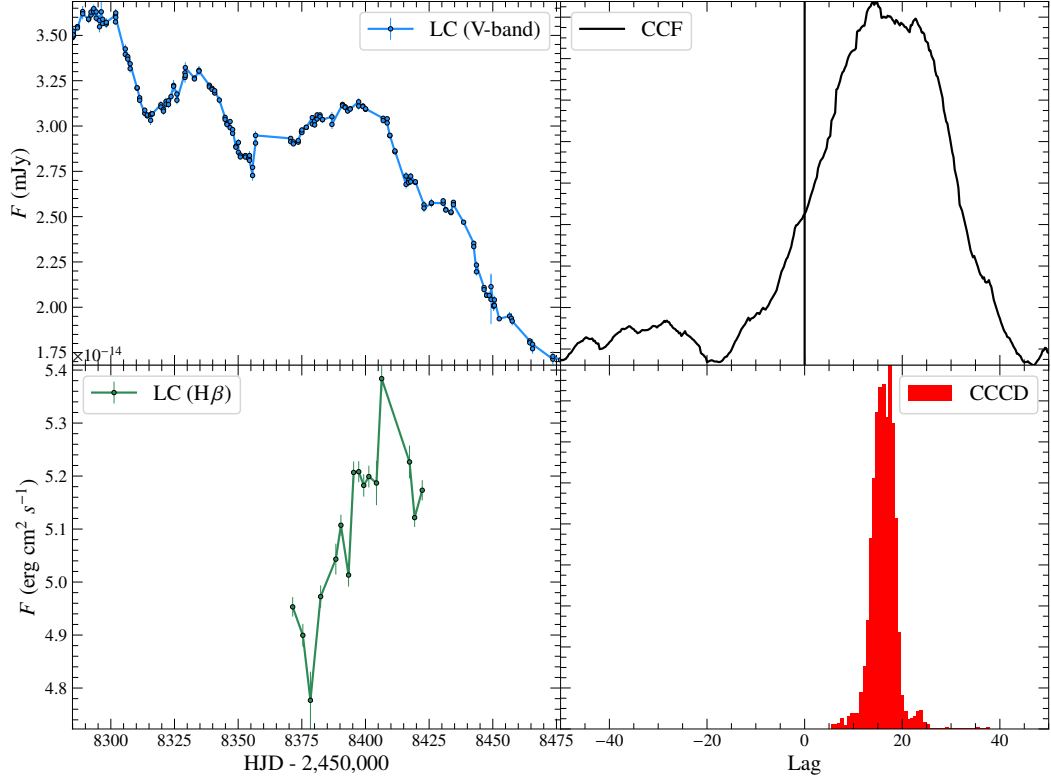


Figure 5.8: The variations in the V (blue) and the broad  $H\beta$  fluxes (green) are as shown. The measured CCF (black) and CCD from FR/RSS (red) are also shown.

## 5.2 Spectroscopic Lag Measurements

The ICCF method as implemented in Section 2.2.1 was used to ascertain the  $H\beta$  emission-line lag relative to V-band light curve. Besides being well-sampled, the V-band has relatively less (compared to other continuum light curves in Figure 5.4) contribution from the host galaxy and emission lines from nebulae and stars. By considering a symmetric delay range from  $-50$  to  $+50$  days separated by  $0.25$  days, Figure 5.8 presents the ICCF results between the V-band and  $H\beta$  flux variations. According to the ICCF, the  $H\beta$  light curve lags the continuum by  $16.2^{+2.1}_{-2.2}$  days, which is consistent to within uncertainties with a delay of  $16.8^{+3.4}_{-2.3}$  days (Figure 5.9) measured using a z-transformed discrete cross-correlation function (zDCF, Section 2.2.3). Even though the ICCF signal looks strong, with maximum correlation coefficient  $r_{\max} = 0.88$  (as is also the case with zDCF), it does not look realistic by eye. No obvious correlated structures are seen with the continuum, and shifting the line light curve by the estimated delay (Figure 5.10) does not seem to reveal the correlated features.

Detrending (Welsh 1999) both light curves with first order polynomials results in an estimated lag of  $\sim 5$  days. A lag of 5 days is too small compared to an expected delay of about  $\sim 38$  days from size-luminosity relation (Bentz et al. 2013) using the luminosity in Table 5.1, and almost twice the  $\sim 16$  day delay from ICCF and zDCF. The  $H\beta$  light curve duration in

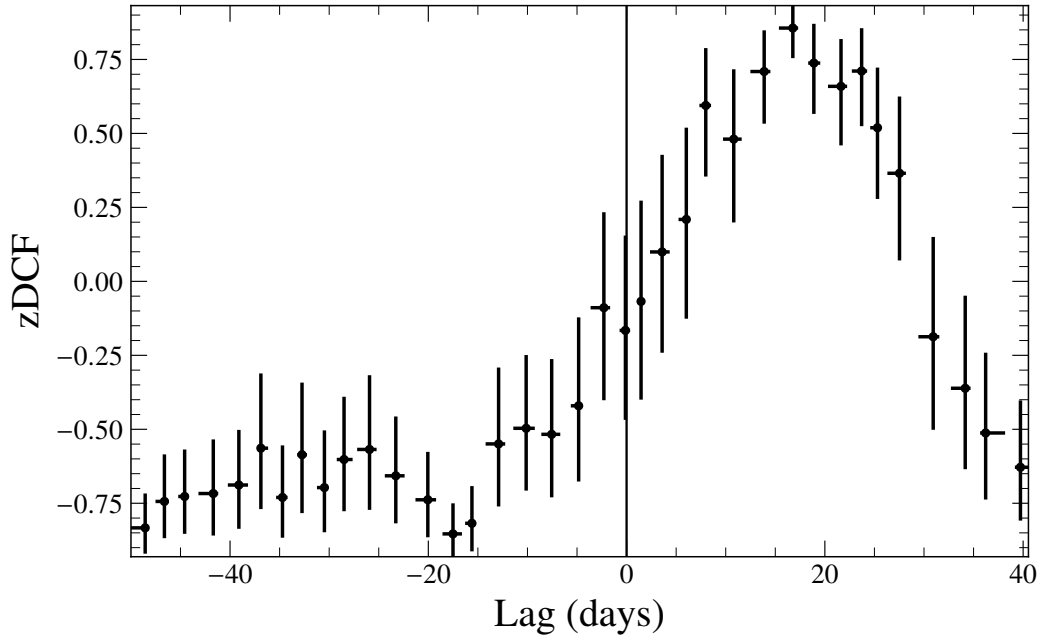


Figure 5.9: The zDCF lag between V-band and  $H\beta$  variations. The vertical line marks the zero delay.

this campaign is  $\sim 50$  days (i.e., not extended enough to cover the expected delay).

The measured  $H\beta$  lag uncertainties and taking into account the strong correlation signal, means there may be more structure in the light curves than one can see with an eye that is giving rise to the result (to be discussed later).

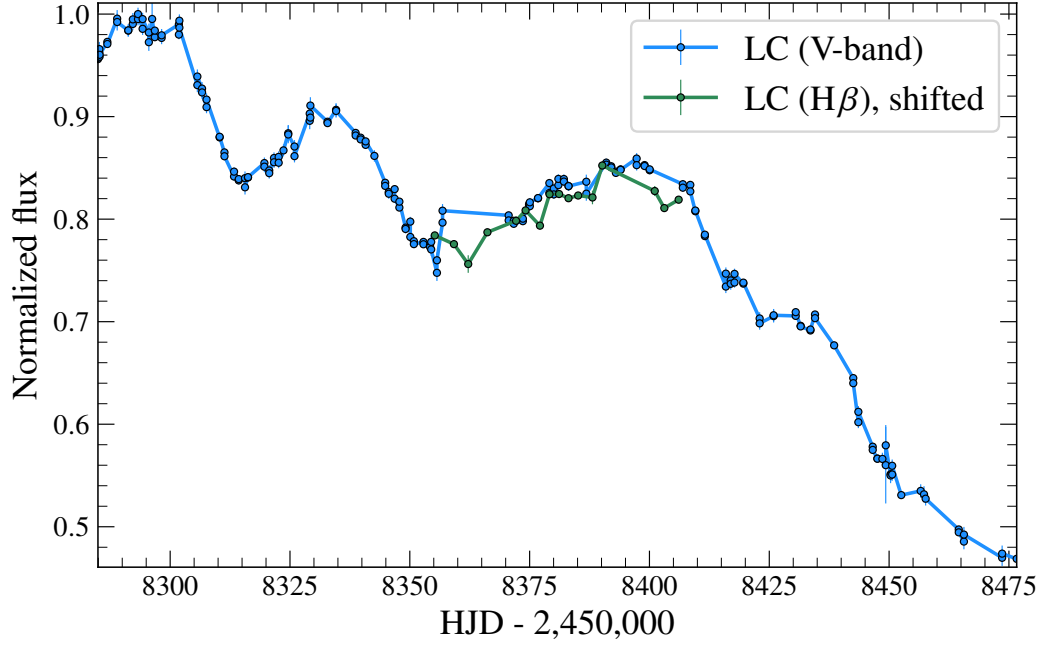


Figure 5.10: The normalized V and H $\beta$  light curves. The H $\beta$  light curve is shifted backwards by an estimated delay of 16 days.

### 5.3 Continuum Lag Measurements

The continuum lag measurements (Table 5.6) are carried out using three different approaches (ICCF, JAVELIN, and CREAM). To avoid any biases (such as overestimating the lags) that may arise due to different start times presented by the continuum light curves of PG 2304+043, the lag analyses is limited to the  $ugiz_s$  light curves. Prior to the time-lag analysis, the light curves are detrended (Welsh 1999) employing first order polynomial.

Table 5.6: The  $ugiz_s$  inter-band continuum delays relative to  $g$ .

| Light Curve | $\lambda$<br>( $\text{\AA}$ ) | $\tau_{\text{centroid}}$<br>(days) | $\tau_{\text{JAVELIN}}$<br>(days) | $\tau_{\text{JAVELIN}}$<br>(days) | $\tau_{\text{CREAM}} - \tau_g$<br>(days) | $r_{\text{max}}$ |
|-------------|-------------------------------|------------------------------------|-----------------------------------|-----------------------------------|------------------------------------------|------------------|
| (1)         | (2)                           | (3)                                | (4)                               | (5)                               | (6)                                      | (7)              |
| $u$         | 3540                          | $-0.85^{+0.46}_{-0.50}$            | $-0.63^{+0.24}_{-0.25}$           | $-1.61^{+0.91}_{-0.51}$           | $-0.34 \pm 0.20$                         | 0.99             |
| $g$         | 4770                          | $0.00^{+0.49}_{-0.46}$             | $0.00^{+0.02}_{-0.02}$            | $0.00^{+4.58}_{-4.53}$            | $0.00 \pm 0.24$                          | 1.00             |
| $i$         | 7545                          | $1.03^{+0.47}_{-0.49}$             | $0.63^{+0.28}_{-0.30}$            | $1.24^{+0.32}_{-0.48}$            | $0.87 \pm 0.35$                          | 0.99             |
| $z_s$       | 8700                          | $0.12^{+0.56}_{-0.58}$             | $0.61^{+0.11}_{-0.17}$            | $0.62^{+0.18}_{-2.03}$            | $1.3 \pm 0.4$                            | 0.97             |

<sup>4</sup> Reverberation lag

<sup>5</sup> Photometric lag

<sup>6</sup>  $\tau_g = 1.04 \pm 0.17$  days

### 5.3.1 ICCF

The  $g$  continuum light curve was chosen or assumed to be the driver in deriving the inter-band delays with ICCF (Section 2.2.1). The delay range was constrained within the interval  $\tau = [-20, +20]$  days (i.e., generally continuum delays are smaller than 10 days, so choosing this range is sensible) using the interpolation grid spacing  $\Delta t = 0.1$  days. For  $n = 3000$  Monte Carlo runs, the detected centroid lags and associated  $1\sigma$  uncertainties are given in Table 5.6 and shown in Figure 5.11. The measurement of  $r_{\max}$  indicate the light curves are strongly correlated relative to  $g$  light curve. The CCCDs are well-constrained with single peaks and appear almost symmetric. The lags increases with wavelength except for the  $z_s$  lag (i.e., smaller than the interpolation between  $g$  and  $i$ ). The lag wavelength-dependence, in terms of standard thin-disc theory of SS73, will be investigated in Section 5.4.

### 5.3.2 JAVELIN Modeling

Over the years, the use of JAVELIN (Section 2.2.4) in deriving time delays of spectroscopic (Zu et al. 2011) and/or photometric light curves (Zu et al. 2013) has gained traction owing to its advanced modeling of AGN variability light curves. Here, JAVELIN is used to fit  $ugiz_s$  continuum light curves to derive both reverberation lags and photometric lags. In JAVELIN, the chosen driving light curve is first fitted with a DRW model using its `Cont_Model` functionality to derive priors on the DRW parameters. The derived priors or constraints are then used to model the response light curves as delayed and smoothed versions of the continuum model using `Rmap_Model`. In this case, the  $g$  light curve was again chosen as the driver on the basis of its relative quality. The delay range was again restricted to within  $[-20, +20]$  days in deriving posterior delay distributions for the response light curves employing 40000 MCMC runs, enough to achieve adequacy or convergence.

For comparison with reverberation lags using `Rmap_Model`, the same method in the form of `Pmap_Model` is adapted to measure the relative delay between two photometric band-passes. This method works in a similar way to the original form, in that the response light curves relative to the driver are treated as delayed and smoothed versions. The addition of `Pmap_Model` functionality in JAVELIN allows for estimating effective accretion disc sizes at those emitting bandpasses or wavelengths. This modified model includes an additional parameter  $\alpha$  denoting the ratio between two continuum light curves (one off and one on the line flux), on top of the DRW model amplitude and timescale, top-hat width, top-hat scale, and time lag parameters in the previous `Rmap_Model` model. As before, the  $g$  light curve was fitted with DRW model to constrain the continuum variability and used that as prior information in the `Pmap_Model` step. The same delay range and MCMC runs were adopted.

The summary of the lag posterior distributions from these two methods is given in Table 5.6. The lag estimates from the two methods are consistent. Although, the latter method has quite large uncertainty estimates on the lags, the reverberation lag uncertainties are rela-

tively small and almost symmetric. The photometric delays, especially the  $g$  lag relative to itself has surprisingly large uncertainties. The  $i$  photometric lag is almost twice its reverberation counterpart, but consistent nonetheless. The delays from both methods do increase with wavelength except for the  $z_s$  lag, possibly due to contribution from the HI bound-free continuum emission from the BLR. This contribution has been a source of discussion (e.g., [Korista & Goad 2001; 2019](#)) and is quite hard to model and quantify.

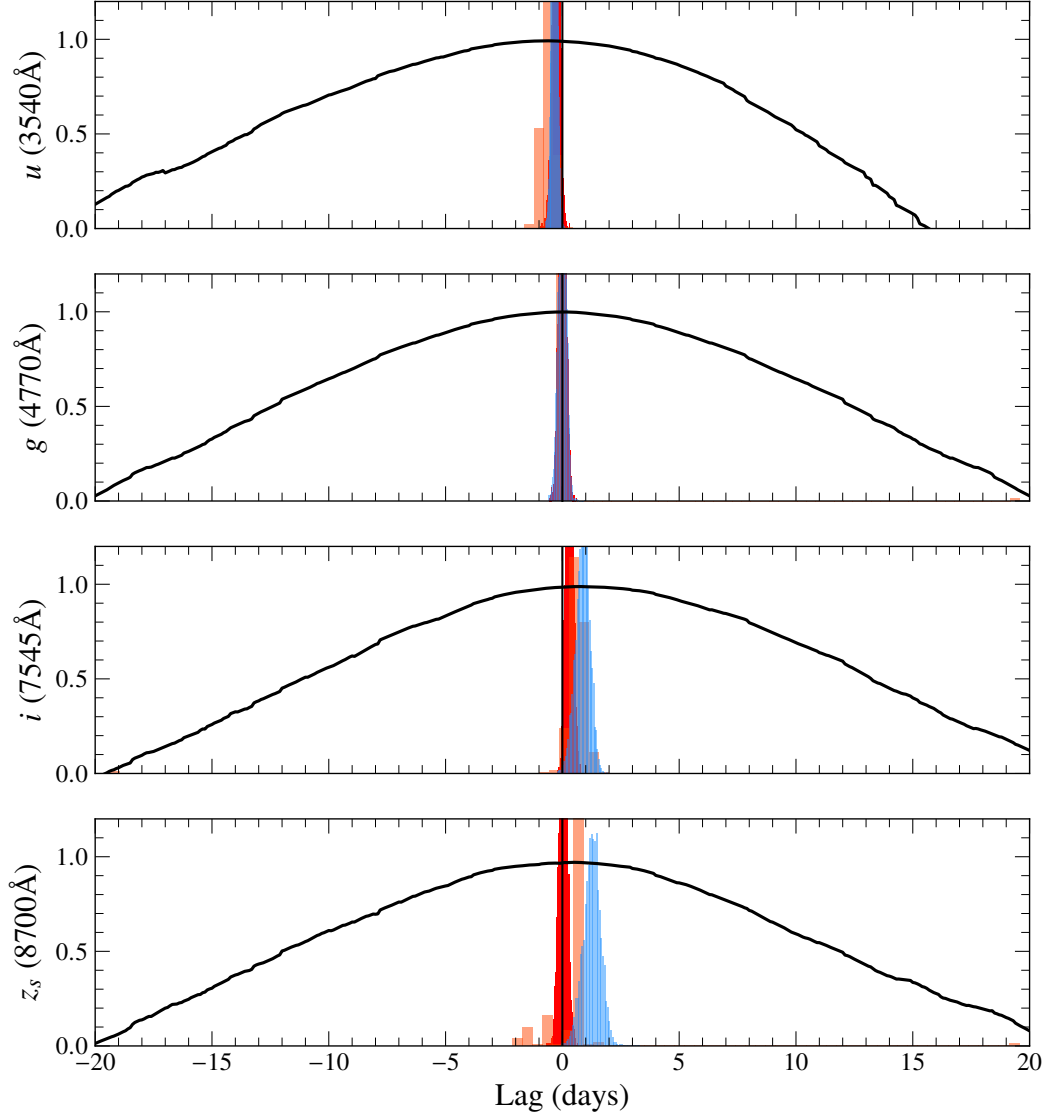


Figure 5.11: The solid black line shows the cross-correlation functions for each of the continuum light curves, ordered by wavelength. The zero lag is indicated by the vertical black solid line. The cross-correlation centroid distributions from FR/RSS method are shown in red. The translucent histograms correspond to posterior delay distributions from CREAM (blue) and JAVELIN lags from `Rmap_Model` (orange).

### 5.3.3 CREAM Modeling

Starkey et al. (2016; 2017) developed a model-dependent Continuum REprocessed AGN Markov Chain code called CREAM (Section 2.2.5). CREAM’s main application is to measure the inter-band continuum mean delays along with other accretion disc parameters, such as the temperature profile,  $T(r)$ , of the disc and mass accretion rate,  $\dot{M}$ , onto the disc, for a given black hole mass,  $M$ . Here, a CREAM model with an inclination set to  $i = 0$  (face-on), the power-law index  $\alpha = 3/4$  for a thin-disc and published SE black hole mass  $M = (3.98 \pm 0.92) \times 10^8 M_\odot$  (Table 5.1) was adopted. The lag range was set to  $-20$  to  $+20$  days, together with  $10^5$  MCMC runs, in inferring the driving light curve,  $X(t)$ , posterior probability distribution for  $T_1$ , mass accretion rate,  $\dot{M}$ , and time delay distributions.

Figure 5.12 shows the inferred driving light curve,  $X(t)$ , and fits to the response functions of the individual light curves. As expected, CREAM mean delays are scaled according to the  $\langle \tau \rangle \propto (M\dot{M})^{1/3} \lambda^{4/3}$  relation using CREAM’s noise model (Eqn 2.15). The measured mean delays range from 0.7 to 2.3 days relative to  $X(t)$ . CREAM accounts for most of the observed features with few outliers in the  $z_s$  light curve around HJD - 2450000 = 8380.

The CREAM inferred disc parameters are shown in Figure 5.13 for the adopted model. The CREAM fit resulted in  $\log(M\dot{M}/M_\odot^2/\text{yr}) = 7.07 \pm 0.23$ , a temperature at  $r_1$  of  $T_1 = (1.12 \pm 0.14) \times 10^4$  K and the Eddington fraction  $\dot{m}_{\text{Edd}} = L_{\text{Bol}}/L_{\text{Edd}} = 0.003$ . This Eddington ratio estimate is the same as that derived by Silpa et al. (2020). Approximating the bolometric luminosity as  $L_{\text{Bol}} = \eta \dot{M} c^2$  yields  $L_{\text{Bol}} = (1.65 \pm 0.78) \times 10^{44}$  erg/s for  $\eta = 0.1$  (assumed radiative efficiency of the disc). It implies an Eddington luminosity  $L_{\text{Edd}} = (6 \pm 4) \times 10^{46}$  erg/s. This estimate of  $L_{\text{Bol}}$  implies that during the campaign, the black hole was accreting at a lower rate compared to  $(1.26 \pm 0.29) \times 10^{45}$  erg/s derived by Vestergaard & Peterson (2006).

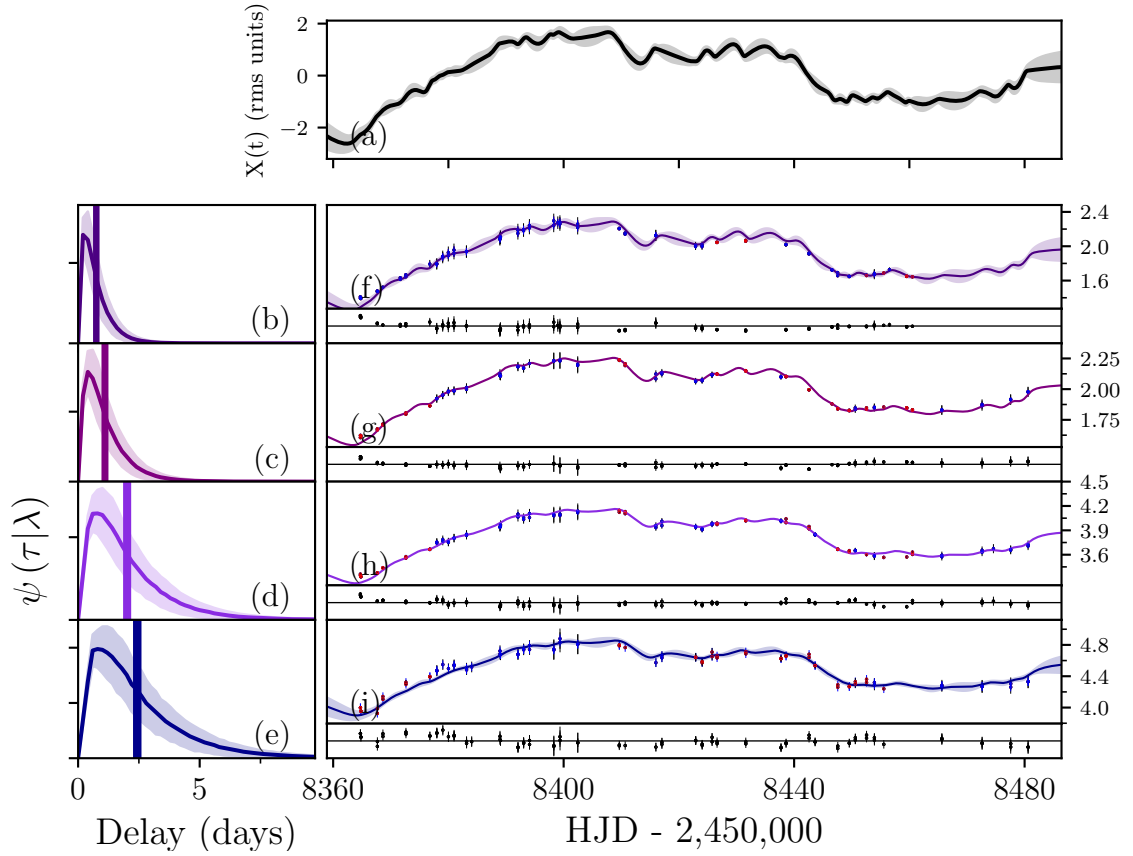


Figure 5.12: CREAM fits to the continuum light curves from PG 2304+043. Panels b - e show the inferred mean response functions assuming standard disc model. Panels f - i show the inferred echo light curves with residuals underneath each light curve for the  $u$ ,  $g$ ,  $i$ ,  $z_s$  bands accordingly. Panel a shows the deduced driving light curve.

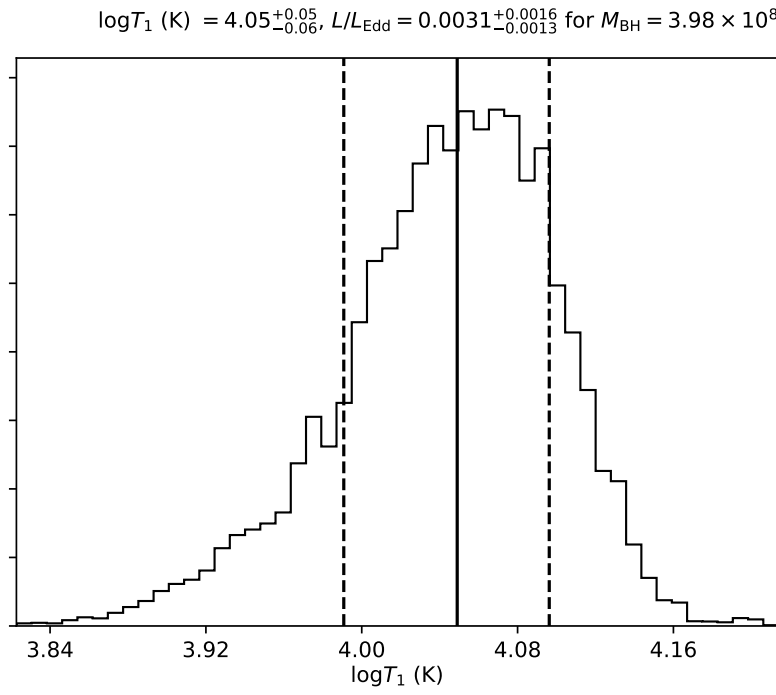


Figure 5.13: CREAM derived posterior probability histogram for  $T_1$  for a model with  $\alpha = 3/4$  and  $i = 0$ .

## 5.4 Lag Spectrum

The inter-band delays from the three approaches are displayed in Table 5.6. They are all in agreement in terms of the  $u$  lag, all detect a negative lag relative to  $g$  which is reassuring. The shorter  $z_s$  lag (i.e., smaller than the  $i$  lag) is present in both the JAVELIN and ICCF analysis, also reassuring (i.e., it means this lag result is independent on the method used). JAVELIN reverberation lags have smaller uncertainties compared to ICCF. This is expected as javelin will tend to have smaller uncertainty estimates than ICCF (Yu et al. 2020c). Even with that, the lags are generally consistent with each other to within the error margins. The lag spectrum  $\tau(\lambda)$  is characterized by the power-law equation

$$\tau(\lambda) = \tau_0 [(\lambda/\lambda_0)^\beta - 1] + \tau_g. \quad (5.1)$$

As before, the addition of the parameter  $\tau_g$  ensures the fit is not forced to pass through zero. This Eqn. 5.1 is fitted to both JAVELIN and ICCF delays to test the  $\tau \propto \lambda^{4/3}$  lag dependence, predicted by the standard thin-disc model of SS73. For JAVELIN, only the reverberation lags are considered (column 4 of Table 5.6) instead of the photometric lags, due to better error estimates. The reference wavelength is set to  $\lambda_0 = 4770 \text{ \AA}$ , corresponding to the  $g$ -band central wavelength. Initially, the power-law index  $\beta$  is fixed at  $4/3$  for comparison with the standard thin-disc scaling prediction  $\tau \propto \lambda^{4/3}$ . All the wavelengths or bands are considered in the fit, resulting in the best-fit value  $\tau_0 = 0.55 \pm 0.11$  days (from JAVELIN with  $\chi^2/2 = 2.13$ ) and  $\tau_0 = 0.84 \pm 0.41$  days (from ICCF with  $\chi^2/2 = 1.75$ ). Varying  $\beta$  led to an unconstrained normalization factor  $\tau_0$ .

The respective power-law fits are shown in Figure 5.14. The CREAM derived, blackbody standard accretion thin-disc model with  $L/L_{\text{Edd}} = 0.003$  is shown by the dotted line. The smaller uncertainty on the JAVELIN  $g$  lag is the reason for a larger  $\chi^2/N_{\text{dof}}$  value compared to the ICCF fit, as the fit appears to pass through zero. The parameter  $\tau_0$  is well-constrained in the case of JAVELIN (i.e., inconsistent with zero to  $3\sigma$ ), whereas the ICCF fit is consistent with zero to  $> 1\sigma$ . Both estimates of  $\tau_0$  are consistent with each other to within  $1\sigma$ . Generally, the delays obey the  $\tau \propto \lambda^{4/3}$  relation, despite the lower detected  $z_s$  lag possibly due to HI bound-free continuum emission from BLR, as evidenced by a Paschen jump at  $8200 \text{ \AA}$  ( $i$  to  $z_s$ ) in both spectra.

To constrain the accretion-disc size, the CREAM measured  $g$  lag ( $= 1.04 \pm 0.17$  days) is compared to the  $\tau_0$  values from JAVELIN and ICCF. This implies that the CREAM predicted disc size at  $\lambda_0$  is larger by factor  $1.9 \pm 0.5$  compared to JAVELIN and  $1.2 \pm 0.6$  compared to ICCF. The two factors are consistent as expected. This outcome, although consistent in terms of the discrepancy between model-predicted and observed disc size (e.g., Fausnaugh et al. 2018, Hlabathe et al. 2020), predicted delays from the CREAM model are uncharacteristically larger than those observed. This is perhaps due to the black-hole mass,  $M$ , from SE (Table 5.1) used in the CREAM modeling. CREAM delays are generally scaled according to  $\tau \propto (M\dot{M})^{1/3} \lambda^{4/3}$ , which means larger  $M$  would result in larger delays. Generally, any un-

certainty in  $M$  would contribute to the discrepancy. The  $M$  used here from SE is uncertain by 0.43 dex.

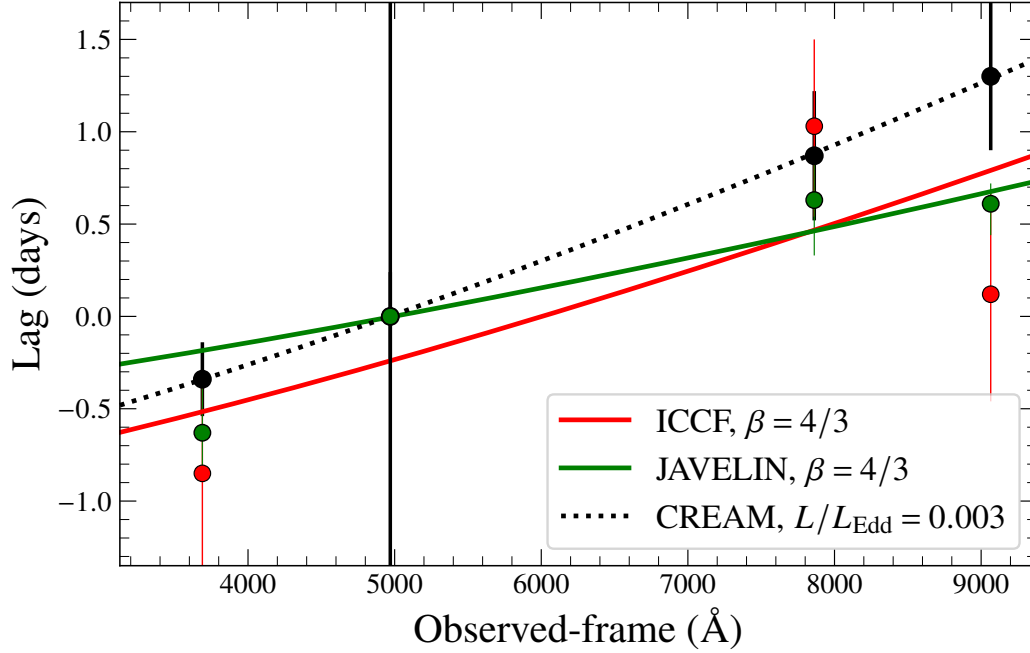


Figure 5.14: The ICCF (red) and JAVELIN (green) delays as a function of wavelength compared with CREAM (black) standard thin-disc model with  $L/L_{\text{Edd}} = 0.003$ . The red and green solid lines are the best-fit lines with power-law index fixed to  $\beta = 4/3$ .

## 5.5 Spectral Analysis

To derive the SED of PG 2304+043, a similar approach as outlined in Section 2.2.5 is used. A linear correlation is shown in Figure 5.15, where fluxes taken at different epochs for each wavelength  $f_\nu(\lambda, t)$  are plotted relative to the CREAM derived driving light curve,  $X(t - \tau)$ , summed over the delay distribution,  $\psi(\tau)$ . Figure 5.16 shows the derived variable spectrum,  $\Delta F(\lambda)$ , and the average spectrum,  $\bar{F}(\lambda)$ , after correcting for reddening (Schlegel et al. 1998). The observed variable spectrum or SED is consistent with  $f_\nu \propto \lambda^{-1/3}$  for a standard thin-disc model.

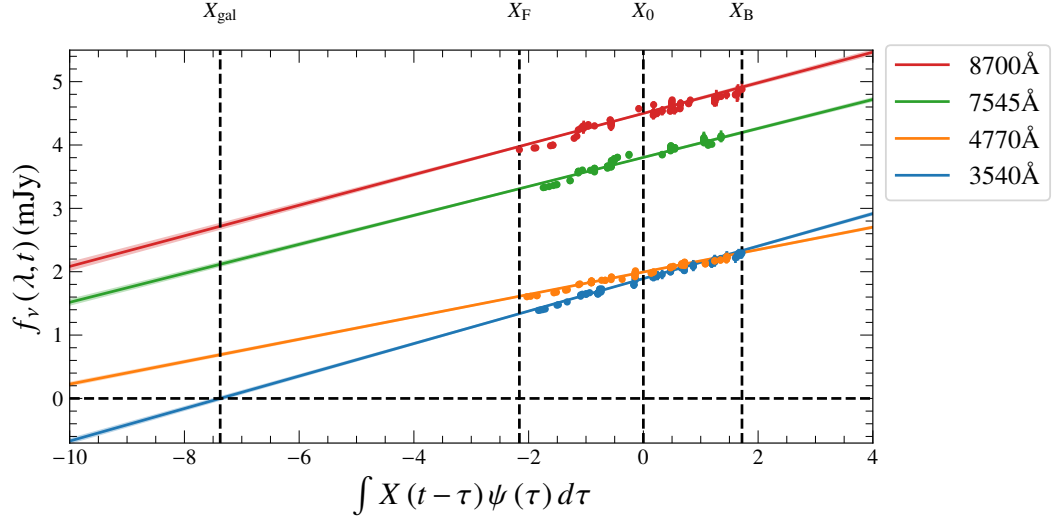


Figure 5.15:  $f_\nu(\lambda, t)$  versus  $\int X(t - \tau) \psi(\tau) d\tau$  following Eqn. 2.14 for each wavelength, where the vertical lines,  $X_F = -2.16$ ,  $X_B = 1.72$  and  $X_{gal} = -7.38$ , correspond to the points used to evaluate the faint-state, bright-state and galaxy-state spectra respectively.

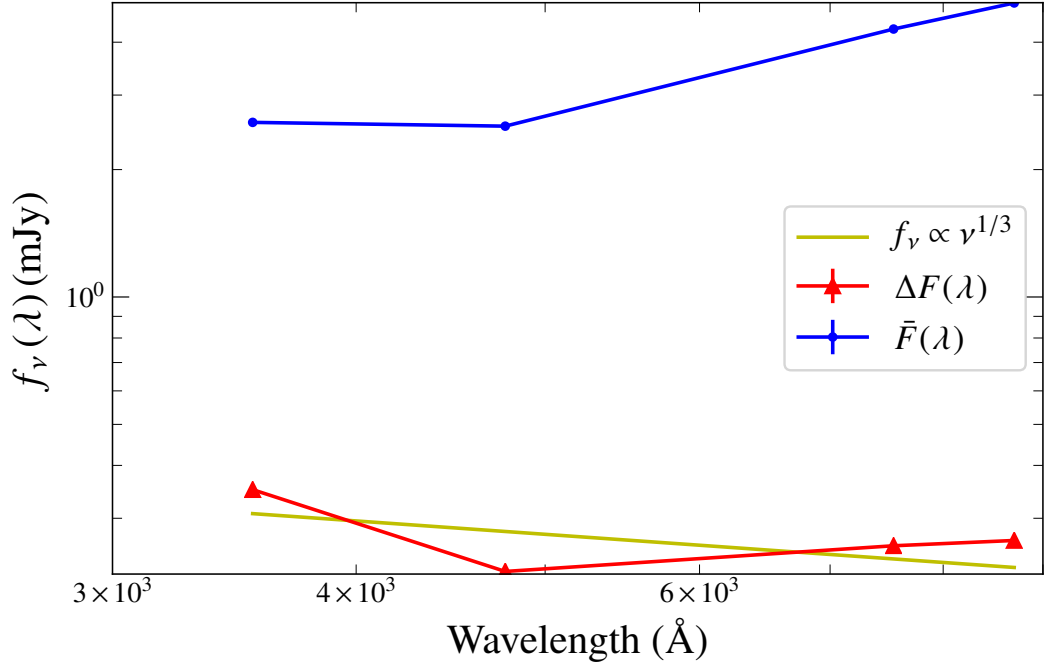


Figure 5.16: The derived variable spectrum,  $\Delta F(\lambda)$ , is shown in red and the average spectrum,  $\bar{F}(\lambda)$ , shown in blue after correcting for reddening using  $E(B - V) = 0.07$ . The model-predicted power-law slope  $f_\nu \propto \nu^{1/3}$  line is shown in yellow.

Table 5.7: Host-galaxy and disc spectra for each wavelength.

| $\lambda$<br>(Å) | $f_{\text{gal}}(\lambda)$<br>(mJy) | $\bar{F}_{\text{disc}}(\lambda)$<br>(mJy) |
|------------------|------------------------------------|-------------------------------------------|
| 3540             | $0.000 \pm 0.035$                  | $2.586 \pm 0.036$                         |
| 4770             | $0.876 \pm 0.023$                  | $1.657 \pm 0.024$                         |
| 7545             | $2.391 \pm 0.037$                  | $1.905 \pm 0.037$                         |
| 8700             | $2.991 \pm 0.053$                  | $1.961 \pm 0.054$                         |

Extinction-corrected values.

## 5.6 Luminosity at 5100 Å

The multi-wavelength photometric observations obtained here allows for AGN optical luminosity at 5100 Å to be determined following Section 5.5. The host-galaxy,  $f_{\text{gal}}(\lambda)$ , and disc,  $\bar{F}_{\text{disc}}(\lambda)$ , spectra are derived from Eqn 2.24 and Eqn. 2.25, respectively (Table 5.7). The host-galaxy contribution at 5100 Å equates to  $f_{\text{gal}}((1+z) 5100 \text{ Å}) = 1.057 \pm 0.025 \text{ mJy}$ , obtained through linear interpolation. There is no host-galaxy contribution estimate for this target in the literature to compare with. With this, the host-galaxy subtracted AGN flux at 5100 Å becomes  $1.686 \pm 0.025 \text{ mJy}$ . Using the redshift distance, 178 Mpc, the monochromatic luminosity at 5100 Å corresponding to this campaign is  $\log \lambda L_{5100 \text{ Å}} = 43.58 \pm 0.06 \text{ erg s}^{-1}$ . This value represents a significant decrease from  $\log \lambda L_{5100 \text{ Å}} = 44.1 \pm 0.1 \text{ erg s}^{-1}$  in Table 5.1, but similar to the value measured by Sani et al. (2010) of  $\log \lambda L_{5100 \text{ Å}} = 43.59 \text{ erg s}^{-1}$ . The value in Table 5.1 is not host-galaxy corrected, thus it may be overestimated.

## 5.7 Black Hole Mass

Assuming the H $\beta$  delay measured in Section 5.2 reflects realistic measurement, then the reverberation-based black hole mass of PG 2304+043 can be estimated and compared with SE mass estimate. This comparison is vital a for better understanding of the biases associated with each method.

Measurement of RM-based mass using Eqn. 1.23, requires measurements of velocity width,  $\Delta V$ , and time delay,  $\tau$ . Given the complex structure of the H $\beta$  profile in the rms spectrum and potential blending with other lines (Figure 5.6), a virial factor  $f_{\text{FWHM}} = 1.17$ , as recommended by Collin et al. (2006) when measuring the black hole mass from the FWHM of the broad emission line measured from the mean spectrum, was adopted to limit biases from spectral modeling and deblending of the contaminants. The results from the RM-based  $M$  is  $(1.14 \pm 0.16) \times 10^8 \text{ M}_{\odot}$ , consistent with SE mass measurement to  $3\sigma$ .

The above measured black hole mass do not take into account the uncertainty in the adopted virial factor,  $f$ , due to systematic errors associated with measuring  $f$ .



## Chapter 6

# Reverberation mapping of SDSS J132447.65+032432.6, a high-redshift active galactic nucleus

This study is one of the several efforts aimed at contributing to the sample of AGNs with lag measurements, using, either SE spectroscopy or reverberation mapping (RM) based observations. For distant sample ( $z > 0.3$ ), especially, these include measurements from (e.g., [Grier et al. 2017a](#), [Czerny et al. 2019a](#), [Grier et al. 2019](#), [Hoormann et al. 2019](#), [Homayouni et al. 2020](#), [Zajaček et al. 2020](#), [Yu et al. 2021](#)).

SDSS J132447.65+032432.6 (Table [6.1](#)) is classified as a quasi-stellar object (QSO) located at  $\alpha = 13:24:47.652$  (J2000),  $\delta = +03:24:32.65$  (J2000), with redshift  $z = 0.305$  and V-band magnitude of 17.01. At this redshift,  $H\beta$  emission line observations can still be made with optical telescopes such as SALT (Section [3.1](#)). Thus, providing the opportunity to measure the black-hole mass in this object. Currently, there are no existing RM measurements of this object, and this chapter aims to provide such measurements through combining LCO photometric observations (Section [3.2.1](#)) with SALT spectroscopic observations (Section [3.1.1](#)).

Section [6.1](#) describes the observations and data analysis. Sections [6.2](#), [6.3](#) and [6.4](#) discusses continuum-line and continuum-continuum time delays between SDSS J132447.65+032432.6 light curves. Section [6.5](#) uses the derived continuum-continuum time delays to derive the lag spectrum and Section [6.6](#) presents the optical luminosity derived from the disc spectrum. Section [6.7](#) presents black-hole mass measurement for SDSS J132447.65+032432.6. Section [6.8](#) compares this mass with the SE mass measurement.

Table 6.1: Object properties from NED

| Object name              | RA<br>(J2000) | DEC<br>(J2000) | z     | V<br>(mag) |
|--------------------------|---------------|----------------|-------|------------|
| SDSS J132447.65+032432.6 | 13:24:47.652  | +03:24:32.65   | 0.305 | 17.01      |

## 6.1 Observations and Data Analysis

### 6.1.1 Photometry

The photometric observations of SDSS J132447.65+032432.6 were obtained through the use of the LCO 1 m robotic telescopes (Section 3.2.1). The time span of the monitoring campaign is from 2014 to 2016. The observations were taken in four filters ( $g'$ ,  $r'$ ,  $i'$ ,  $z_s$ ), with each observing site (SAAO, McD, SSO, CTIO) contributing a certain number of observations. Here, only observations taken in the second year (2015) of the campaign are considered, in which variability is seen. Table 6.2 gives the summary of the observations.

As with the preceding chapters, about 10 comparison stars were selected using the criteria

Table 6.2: Summary of observations for SDSS J132447.65+032432.6.

| Filter <sup>(1)</sup> | $\lambda_{\text{pivot}}^{(2)}$ | Site <sup>(3)</sup> | Date range <sup>(4)</sup> | $t_{\text{exp}}$ (s) | No. of Epochs <sup>(5)</sup> | Total <sup>(6)</sup> |
|-----------------------|--------------------------------|---------------------|---------------------------|----------------------|------------------------------|----------------------|
| $g'$                  | 4770Å                          | SAAO                | 20150124-20150819         | 300                  | 42                           | 73                   |
|                       |                                | McD                 | 20150407-20150407         |                      | 2                            |                      |
|                       |                                | SSO                 | 20150215-20150821         |                      | 14                           |                      |
|                       |                                | CTIO                | 20150201-20150815         |                      | 15                           |                      |
| $r'$                  | 6231Å                          | SAAO                | 20150314-20150819         | 300                  | 38                           | 61                   |
|                       |                                | McD                 | 20150407-20150407         |                      | 2                            |                      |
|                       |                                | SSO                 | 20150409-20150821         |                      | 10                           |                      |
|                       |                                | CTIO                | 20150307-20150815         |                      | 11                           |                      |
| $i'$                  | 7625Å                          | SAAO                | 20150314-20150819         | 300                  | 37                           | 58                   |
|                       |                                | McD                 | 20150407-20150407         |                      | 2                            |                      |
|                       |                                | SSO                 | 20150409-20150821         |                      | 10                           |                      |
|                       |                                | CTIO                | 20150307-20150815         |                      | 9                            |                      |
| $z_s$                 | 8660Å                          | SAAO                | 20150314-20150808         | 300                  | 29                           | 47                   |
|                       |                                | SSO                 | 20150409-20150731         |                      | 9                            |                      |
|                       |                                | CTIO                | 20150307-20150815         |                      | 9                            |                      |

<sup>1</sup> The filter through which the data was taken.

<sup>2</sup> Filter centroid wavelength.

<sup>3</sup> SAAO (South African Astronomical Observatory), McD (McDonald Observatory), SSO (Siding Spring Observatory), CTIO (Cerro Tololo Interamerican Observatory).

<sup>4</sup> Starting date and end date of observations.

<sup>5</sup> The number of observations taken in that date range per filter.

<sup>6</sup> The total number of observations taken in that filter from all telescopes combined.

that they are within 5 arcminutes from the target, are unsaturated and appear brighter than the surrounding stars. Using the AstroImageJ (AIJ, Collins et al. 2017) task, `Plot seeing profile`, a seeing profile (Figure 6.1) is constructed for each of the selected comparison stars

with the aim of deriving an optimum aperture radius. An optimum aperture radius is taken as the average of the 10 estimates from AIJ. In this case, the average aperture radius was measured to be 8 pixels (or 3.74 arcseconds). The same aperture radius is used for all filters despite the relatively fainter field in  $z_s$ .

Aperture photometry was performed with SExtractor (SEx, Bertin & Arnouts 1996; 2010).

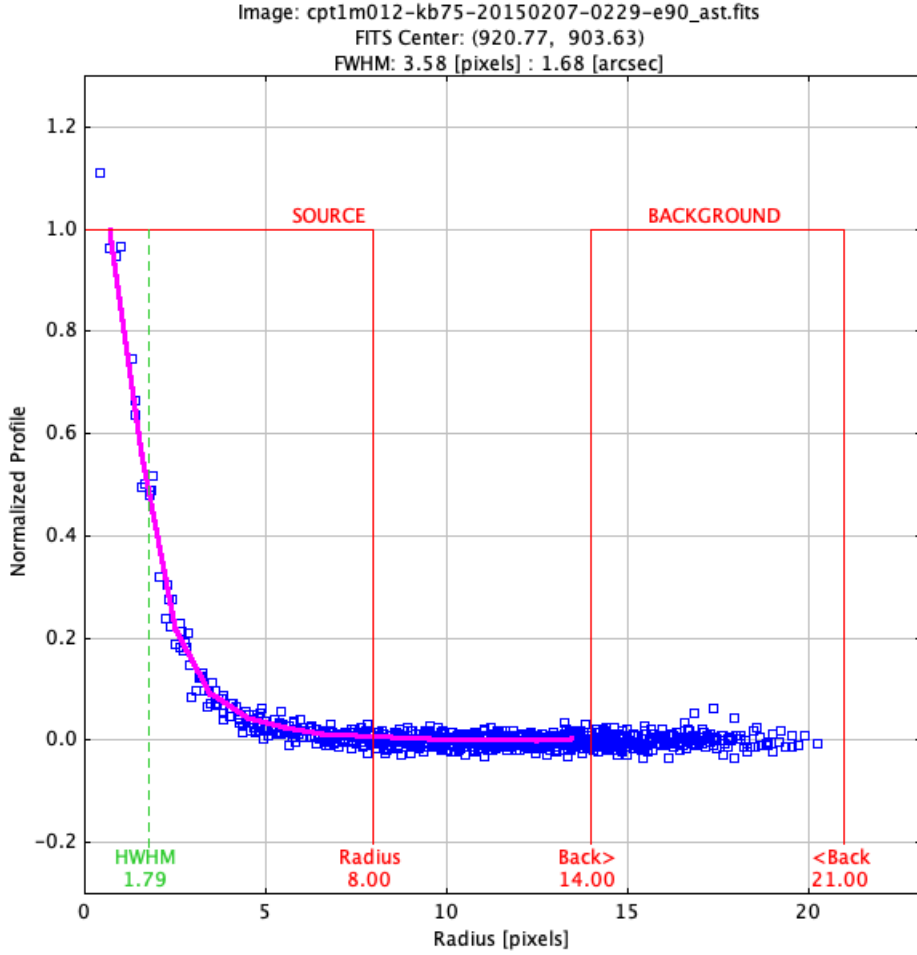


Figure 6.1: The seeing profile for one of the comparison stars. The suggested aperture and sky annuli sizes are as indicated.

After trying out different detection parameter values, the values 5, 3, 3 were set for the parameters detect minarea, detect analysis and detect threshold respectively. These were generally found to yield good results. Using the SEx output catalogs, differential photometry was performed as outlined in Section 3.3.1. For inter-calibrating the light curves, the SAAO data set was used as reference (Section 3.3.3). The final inter-calibrated light curves are shown in Figure 6.2 for each filter.

The two very broad peaks at  $\text{HJD} - 2450000 = 7090$  and 7180 characterise the variability in the  $g'$  light curve. The increase in flux from 7050 to 7090 is not present in the  $r'$  or  $i'$

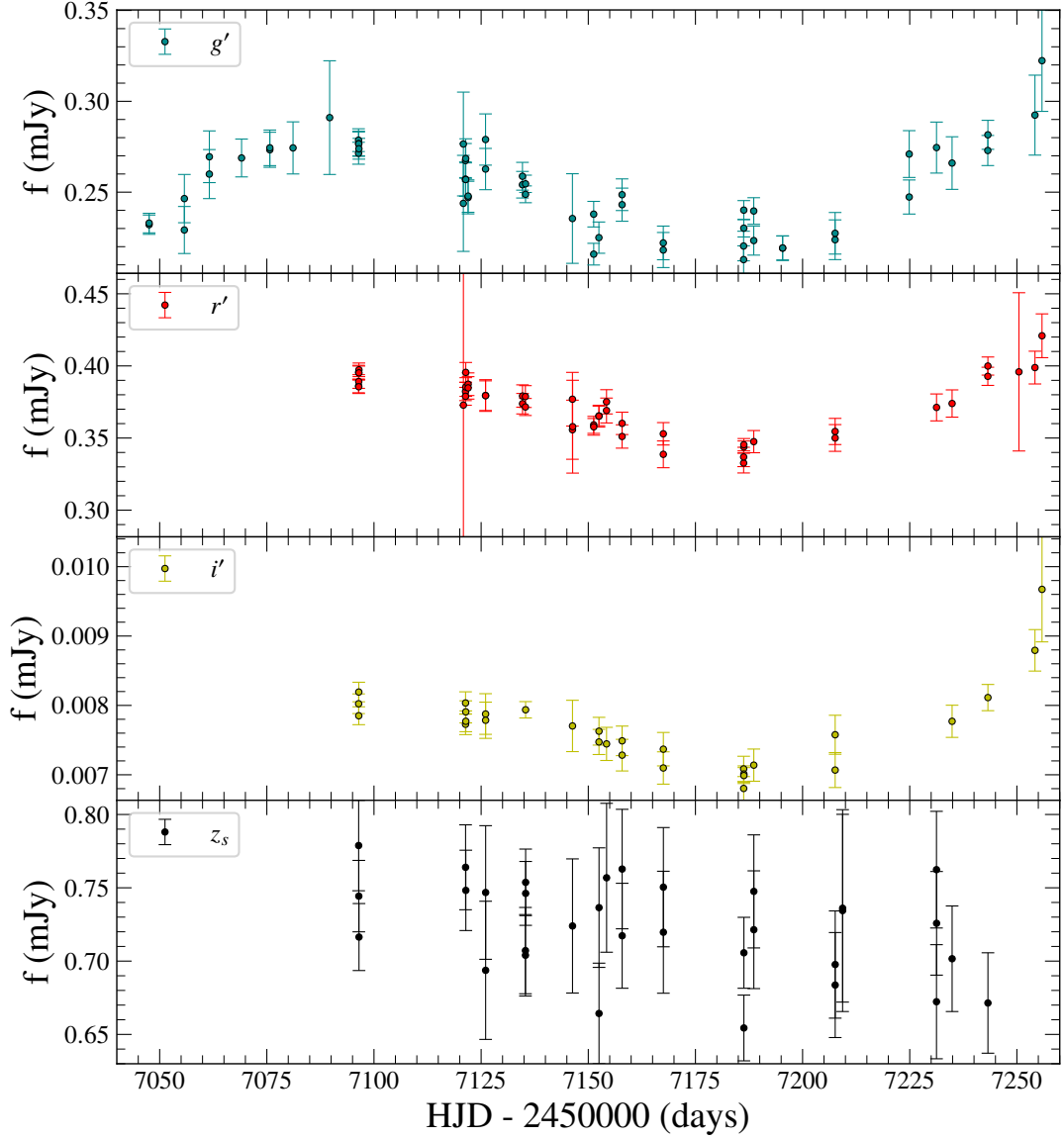


Figure 6.2: The  $g'$ ,  $r'$ ,  $i'$ ,  $z_s$  light curves of SDSS J132447.65+032432.6 from LCO 1 m robotic telescopes, ordered according to wavelength.

light curves due to the observations being triggered later (i.e., upon realising the target is undergoing some variability). The flux decreases slowly to about 7180 and increases again until 7260. In the same vein, the  $r'$ ,  $i'$  light curves appear to be correlated with  $g'$ . There are apparent gaps in the light curves that might lead to overestimation of the inter-band continuum delays. This, and the fact that the light curves generally exhibit weak variability ( $< 0.1$ ) could lessen the quality of the lag measurements. Note that there may be significant contamination by the host galaxy to the light curves, contributing to the quality of the light curves. As can be seen, the  $z_s$  light curve quality is too poor for further consideration in

this analysis.

### 6.1.2 Spectroscopy

The spectra of the central region of SDSS J132447.65+032432.6 were acquired with SALT RSS long-slit spectrograph (Section 3.1.1) between 2015 May and 2015 July, yielding only 7 spectra at a cadence of  $\sim 11$  days. The spectra covered a wavelength range from  $\sim 4700$  -  $7800 \text{ \AA}$  with a spectral resolution  $R \sim 1118$ , and the exposure time of 450 seconds per observation.

The individual 1-D spectra were vetted by eye and the spectrum from 20150520 was deemed to be bad, due to significantly poor S/N and was excluded from the subsequent analysis. The remaining spectra were modeled with PrepSpec (Section 3.4.1). The PrepSpec fit was constrained to the wavelength range  $4740 - 5050 \text{ \AA}$  to avoid the SALT chip gaps, but to include the  $H\beta$  line and the oxygen [O III] $\lambda\lambda 4959, 5007$  lines. Figure 6.3 shows PrepSpec fit to the SDSS J132447.65+032432.6 spectra.

The  $H\beta$  line in Figure 6.3a exhibits an extreme red asymmetric profile, typical of quasars. The rms residual spectrum (Figure 6.3c) shows that  $H\beta$  is varying (although weakly), but also exhibits residual spikes at wavelengths  $\sim 4827 \text{ \AA}$  and  $\sim 4882 \text{ \AA}$ . The spikes at  $\sim 4827 \text{ \AA}$  are probably due to telluric absorption which was not accounted for, and those at  $\sim 4882 \text{ \AA}$  are probably due to uncorrected cosmic ray or detector artifact. This is because it is extremely difficult to correct for telluric absorption that is sitting directly on the broad emission line that is expected to be varying over the course of the RM campaign. This limits the accuracy of the  $H\beta$  flux measurements. The broad component of the [O III]  $\lambda 4959$  narrow emission line is blended with the red-wing of the broad  $H\beta$  line in Figure 6.3a. This blending could potentially bias the line velocity dispersion  $\sigma_{\text{line}}$  (or second moment of the line), since it is sensitive to blending with other lines (Peterson et al. 2004). Table 6.3 lists linewidth measurements from the mean and rms spectra.

The FWHM values from the rms spectra of SDSS J132447.65+032432.6 seem underestimated, perhaps due to deblending. Linewidths measurements from the mean spectra are larger than those from the rms profile. The FWHM and  $\sigma_{\text{line}}$  in the rms will tend to have larger error bars due to the rms being noisy. These linewidths may be under/over estimated due to difficulty disentangling narrow and broad components.

Figure 6.4 presents light curves of variations of broad  $H\beta$  and  $g'$  band for SDSS J132447.65+032432.6.

Table 6.3:  $H\beta$  linewidths and windows.

| FWHM(mean)             | FWHM(rms)              | $\sigma_{\text{line}}$ (mean) | $\sigma_{\text{line}}$ (rms) | Window           |
|------------------------|------------------------|-------------------------------|------------------------------|------------------|
| ( $\text{km s}^{-1}$ ) | ( $\text{km s}^{-1}$ ) | ( $\text{km s}^{-1}$ )        | ( $\text{km s}^{-1}$ )       | ( $\text{\AA}$ ) |
| $3047 \pm 24$          | $2934 \pm 132$         | $1732 \pm 13$                 | $1710 \pm 58$                | 4758 - 4969      |

During the monitoring program, SDSS J132447.65+032432.6 came out of visibility range of

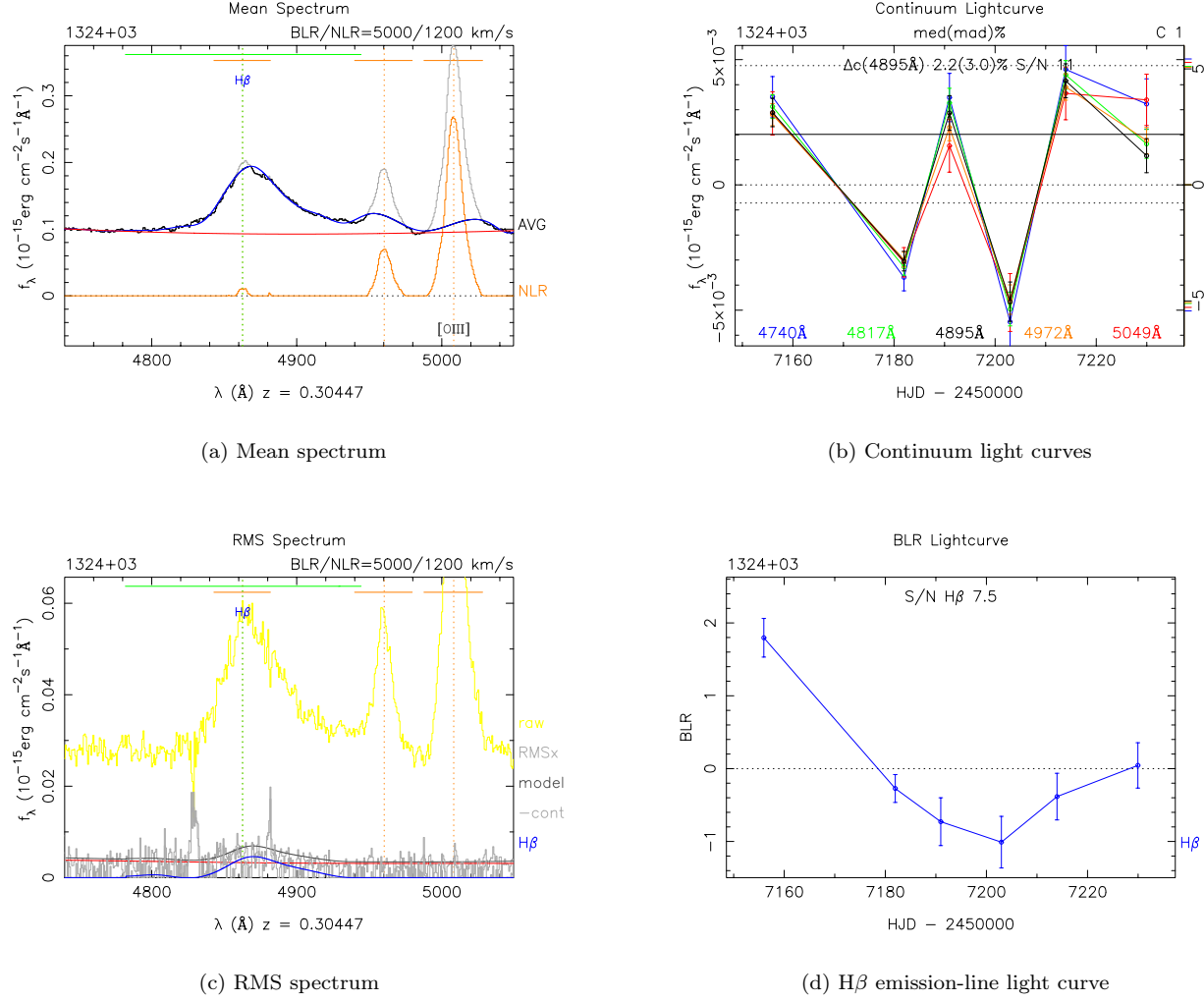
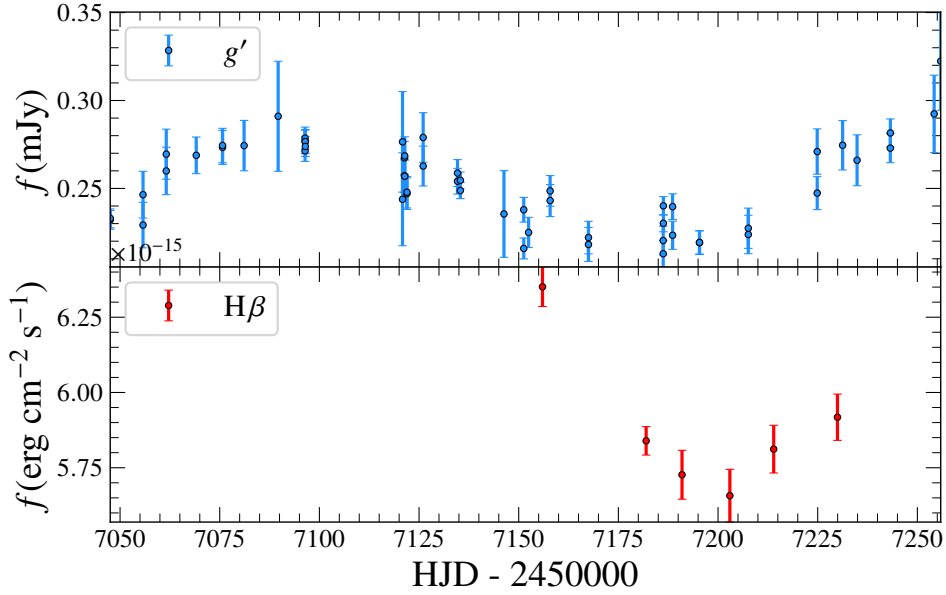


Figure 6.3: PrepSpec fit to the SDSS J132447.65+032432.6 SALT spectra.

the telescope, which led to fewer observations. A few more observations would have been enough to fully cover the turnover at  $\text{HJD} - 2450000 = 7201$ . This lack of observations could really hamper the lag estimate for this target (Section 6.2).

Figure 6.4: Variations of the  $g'$  and  $H\beta$  light curves.

## 6.2 Spectroscopic Lag Measurements

The time delay of the  $H\beta$  light curve relative to the  $g'$  light curve was measured with the ICCF method (Section 2.2.1). It is common to interpolate both light curves in the determination of the time delay with ICCF, as suggested by [White & Peterson \(1994\)](#). In this case, only the  $g'$  light curve was linearly interpolated and the  $H\beta$  light curve kept original. The latter light curve is undersampled, and interpolation would bias the resulting delay leading to large uncertainties. For this, a delay grid  $[-20, +60]$  with spacing of 2 days was considered. The CCF, and CCD are shown in Figure 6.5 for  $n = 3000$  simulations. The measured centroid delay is  $22.97^{+10.99}_{-12.93}$  days with conservative errorbars. This delay seems plausible, despite lack of sampling for the emission-line light curve, and appears strongly correlated,  $r_{\max} = 0.83$ , with the continuum light curve.

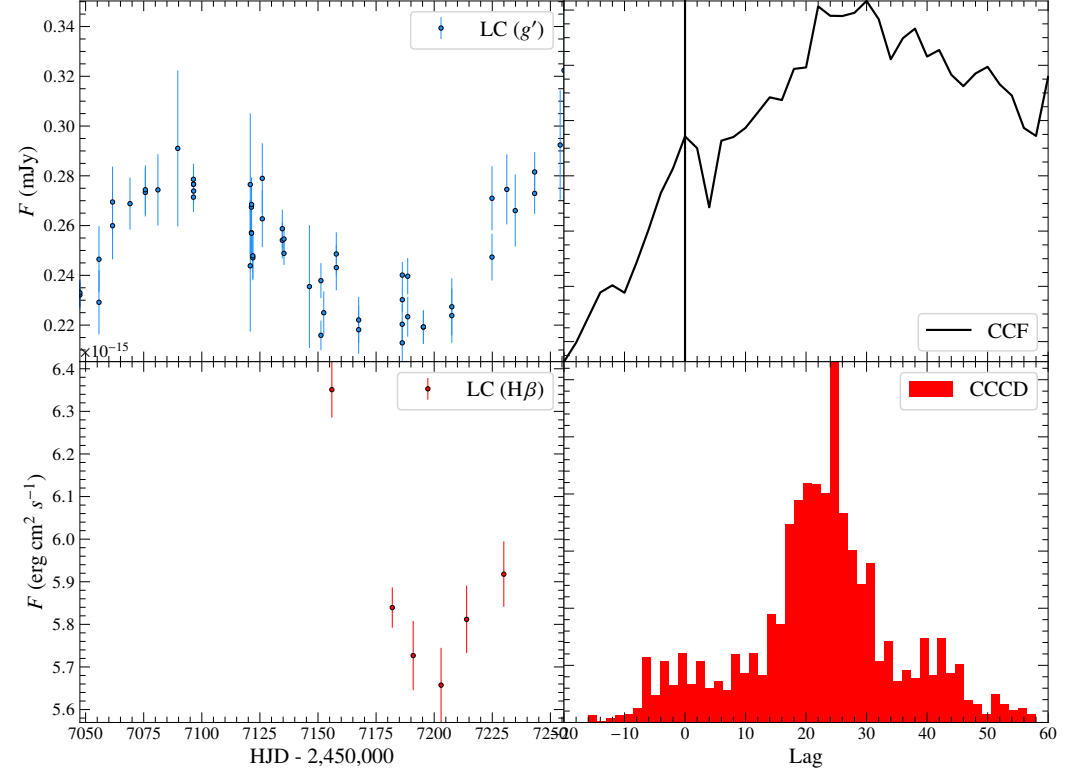


Figure 6.5: The ICCF results for  $H\beta$  line against  $g'$  light curve.

### 6.3 Continuum Lag Measurements

The inter-band time delays are also derived with the ICCF method (Section 2.2.1), relative to the  $g'$  light curve. This allows us to investigate the extent of the correlation between the continuum light curves. On average, the continuum light curves have a sampling rate of  $\sim 4$  days which implies an interpolation grid spacing of 2 days in the delay interval  $[-50, +50]$  days. Figure 6.6 shows the measured delays for the continuum light curves. Despite a lack of sharp peaks in Figure 6.2, the light curves are strongly correlated. The CCCDs are broad (Figure 6.6b), hence the larger uncertainties on the lags perhaps due to gaps in the light curves. The measured centroid time lag for each light curve or band is listed in Table 6.4 together with the corresponding correlation coefficient  $r_{\max}$ .

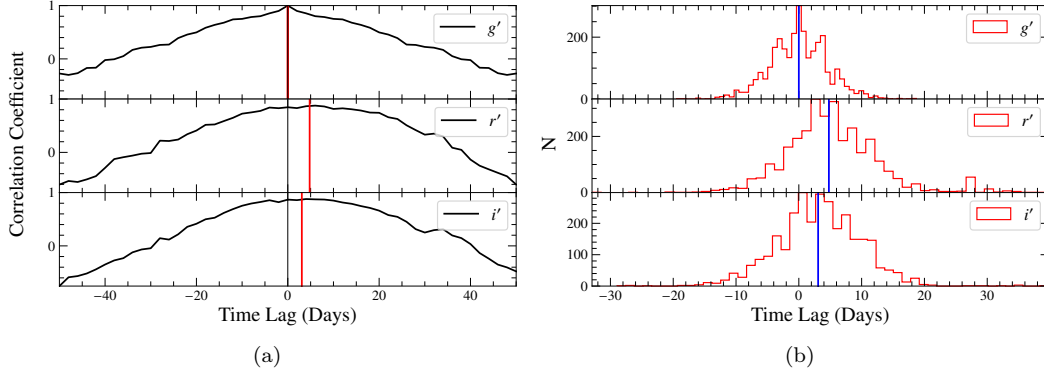


Figure 6.6: The CCF (a) for each light curve measured against  $g'$  and the corresponding CCCD (b) computed using 3000 Monte Carlo runs.

Table 6.4: ICCF time lags relative to  $g'$

| Light curve | Lag<br>(Days)             | $r_{\max}$ |
|-------------|---------------------------|------------|
| $g'$        | $0.00^{+4.09}_{-4.13}$    | 1.00       |
| $r'$        | $4.79^{+7.06}_{-5.95}$    | 0.88       |
| $i'$        | $3.08^{+6.77}_{-6.12}$    | 0.88       |
| $H\beta$    | $22.97^{+10.99}_{-12.93}$ | 0.83       |

## 6.4 CREAM Modeling

Rather than using CREAM (Section 2.2.5) to constrain the temperature profile of the disc,  $T_1$ , and hence  $\dot{M}$ , CREAM is used to only derive the posterior delay distribution for each light curve. The reason is that the variations are not sampled well enough to properly constrain both  $T_1$  and  $\dot{M}$ . Therefore, a model of a face-on disc ( $i = 0$ ), scaling relation  $\langle \tau \rangle \propto \lambda^{4/3}$ , fixed Eddington fraction  $L/L_{\text{Edd}} = 0.1$ , and  $M = 10^8 M_{\odot}$  was assumed. The maximum Fourier frequency was set to  $\nu_{\max} = 2\pi/\Delta t_{\text{mean}} = 2.0$  cycles/day, adopting  $10^5$  MCMC runs.

In the top row of Figure 6.7, is the CREAM-derived driver which approximates the data reasonably well. The  $1\sigma$  error envelopes are shown on each of the light curves (panels f-i) and the fitted residuals underneath the light curve allow us to judge the quality of the fit. The response transfer functions are shown (panels b-d), with the vertical lines denoting the mean delays  $\langle \tau \rangle$ . For the  $H\beta$  line, CREAM estimates the best-fit lag of  $22.19^{+1.60}_{-2.97}$  days from the posterior lag distribution (panel-e). Both the ICCF and CREAM result in consistent  $H\beta$  lags, the latter with smaller uncertainties on the lag.

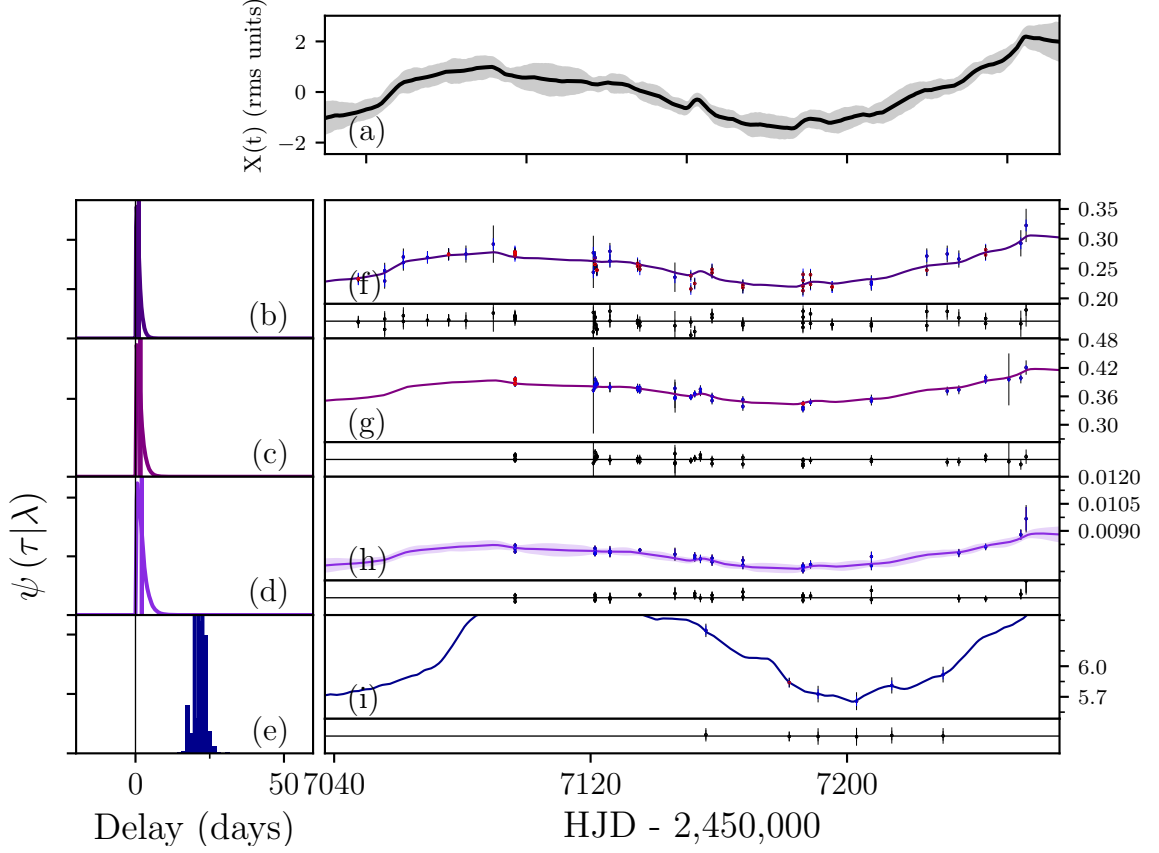


Figure 6.7: Panel-a shows the CREAM-derived driving light curve along with fits to the  $g'$ ,  $r'$ ,  $i'$  and  $H\beta$  light curves. Panels b-d shows the response transfer functions with the vertical line indicating the measured delay. Panel-f is the posterior delay distribution for  $H\beta$  light curve's top-hat response function. Panels f-h are in units of mJy, and i in units of  $\text{erg cm}^{-2} \text{s}^{-1}$ .

## 6.5 Lag Spectrum

In terms of the lag spectrum,  $\tau(\lambda)$ , defined as

$$\tau(\lambda) = \tau_0 \left[ \left( \frac{\lambda}{\lambda_0} \right)^\beta - 1 \right] + \tau_{g'}, \quad (6.1)$$

where the inclusion of the parameter  $\tau_{g'}$  means the fit is not forced to pass through zero. The large uncertainties on the  $g'$ ,  $r'$ ,  $i'$  inter-band lags (Table 6.4) also mean the wavelength dependence of the lags cannot be well-constrained. This is the case when performing the fit with  $\beta = 4/3$  (Figure 6.8). It results in the best-fit parameter  $\tau_0 = 4.33 \pm 3.74$  days and  $\tau_{g'} = 0.47 \pm 1.72$  days ( $\chi^2/N_{\text{dof}} = 0.19$ ,  $N_{\text{dof}} = 1$ ). The large uncertainties on the best-fit parameters and lack of degrees of freedom implies the lag spectrum is not well-constrained

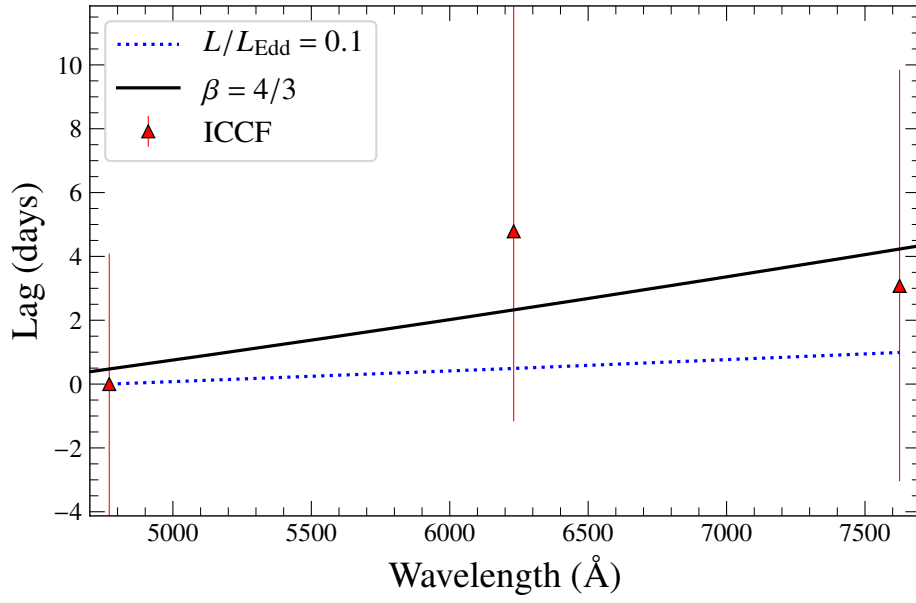


Figure 6.8: The ICCF time lags as a function of wavelength. The black line is the best-fit line for  $\beta = 4/3$ . The dotted blue line is the standard disc model assuming  $L/L_{\text{Edd}} = 0.1$ .

in terms of expectations from the thin-disc reprocessing model.

## 6.6 Luminosity at 5100 Å

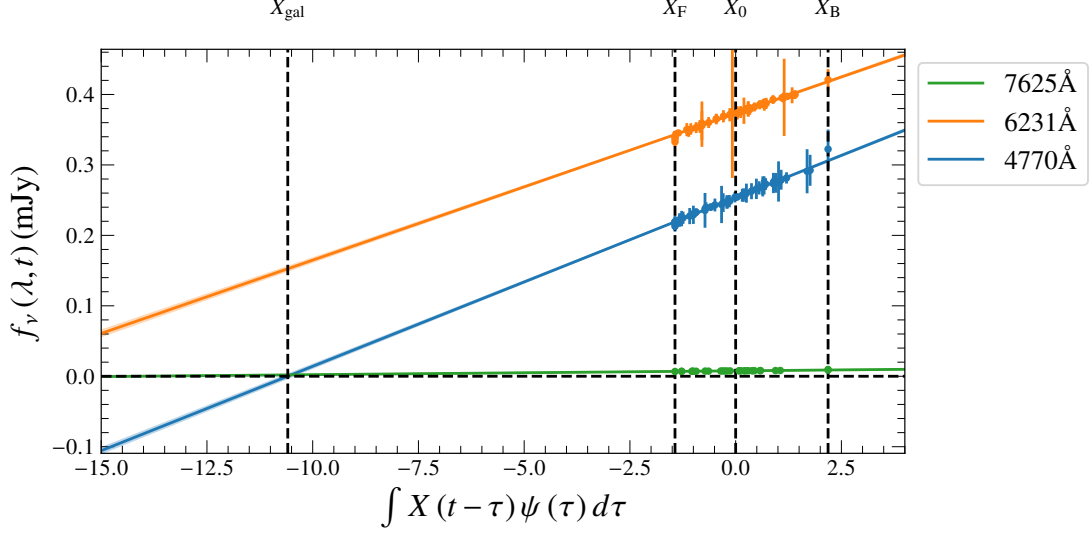


Figure 6.9: The flux-flux analysis from CREAM. The linear response of the light curves to the driving light curve is shown by the linear fits.

To obtain the AGN continuum luminosity at 5100 Å matching this campaign, the host-galaxy contribution must be accounted for (Section 2.2.5). The host-galaxy contribution at each wavelength or band is evaluated at  $X_{\text{gal}}$  following Eqn. 2.24. This occurs at point  $X_{\text{gal}} = -10.59$  in Figure 6.9. The very different slope in the  $i$ -band compared to  $g$  and  $r$  is not clear in terms of the cause. To obtain the AGN fluxes in each filter, the host-galaxy contribution has to be subtracted and this is done following Eqn. 2.25. The fluxes are listed in Table 6.5 for  $g'$  and  $r'$  filters. The observed AGN flux at 5100 Å was obtained by linear interpolation of the disc spectrum or SED (Eqn. 2.25), assuming the SED is consistent with  $f_\nu \propto \nu^{1/3}$  for a thin steady-state blackbody disc. Similarly, the host-galaxy contribution at 5100 Å was obtained by linear interpolation of the host-galaxy spectrum (Eqn. 2.24) as  $0.036 \pm 0.003$  mJy. It resulted in the host-galaxy subtracted AGN flux at 5100 Å of  $f_{\text{AGN}}((1+z) 5100 \text{ Å}) = 0.229 \pm 0.004$  mJy. Using the luminosity distance  $D_L = 1527.8$  Mpc, equates to the luminosity during the campaign of  $\log(\lambda L_{5100 \text{ Å}}) = 44.58 \pm 0.07$  erg s $^{-1}$ .

Table 6.5: Host galaxy and disc spectra.

| $\lambda$<br>(Å) | $F_{\text{gal}}(\lambda)$<br>(mJy) | $F_{\text{disc}}(\lambda)$<br>(mJy) |
|------------------|------------------------------------|-------------------------------------|
| 4770             | $0.000 \pm 0.003$                  | $0.275 \pm 0.003$                   |
| 6231             | $0.161 \pm 0.003$                  | $0.233 \pm 0.003$                   |

Fluxes for each filter or wavelength.

## 6.7 Black Hole Mass

No black-hole mass of SDSS J132447.65+032432.6 currently exists in the literature, so this serves as a first estimate of the black-hole mass in this AGN. The black hole mass is estimated using Eqn. 1.23. Here, the  $\sigma_{\text{line}}$  is used instead of the FWHM for the line dispersion  $\Delta V$ . Because of the noise and the residual spikes in the rms spectrum in Figure 6.3c, the measurement of  $\sigma_{\text{line}}$  may be biased due to blending with contaminants. Instead, the  $\sigma_{\text{line}}$  from the mean spectrum is adopted in the calculation of the black-hole mass. The virial factor is taken to be  $f_{\sigma} = 3.85$  (Collin et al. 2006) when measuring from the mean spectrum rather than the rms spectrum. Substituting the centroid delay  $\tau_{\text{H}\beta} = 22.97^{+10.99}_{-12.93}$  days from Section 6.2 and  $\sigma_{\text{mean}} = 1732 \pm 13 \text{ km s}^{-1}$ , gives an estimated black-hole mass for SDSS J132447.65+032432.6 as  $M = (5.18^{+2.48}_{-2.91}) \times 10^7 M_{\odot}$ . The validity of this mass estimate will need to be investigated, given the uncertainty surrounding the H $\beta$  delay (due to its under-sampled light curve).

## 6.8 Single-epoch Measurement

Having an estimate of the AGN continuum luminosity,  $\lambda L_{\lambda, \text{AGN}}$ , as derived above, allows for the black-hole mass to be measured from SE spectroscopy and to compare with the mass measured from RM-based observations. The former method requires a single (ideally high S/N) spectrum to carry out the measurements (e.g., Wandel et al. 1999a, Vestergaard & Peterson 2006). For this purpose, the SDSS spectrum of the same object was used noting that the SDSS spectra are absolute flux calibrated and corrected for telluric lines. The sought after parameter from this single spectrum is the measure of the FWHM of the broad H $\beta$  emission line. Vestergaard & Peterson (2006) proposed a calibrated mass scaling relationship taking into consideration the FWHM of H $\beta$  and the monochromatic luminosity at 5100 Å, to give an estimate of the black-hole mass from SE,

$$\log M_{\text{BH}}(\text{H}\beta) = \log \left( \left[ \frac{\text{FWHM}}{1000 \text{ km s}^{-1}} \right]^2 \left[ \frac{\lambda L_{\lambda}(5100 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right]^{0.50} \right) + (6.91 \pm 0.02). \quad (6.2)$$

This relation has been estimated to have the weighted zero-point offset of  $\pm 0.43$  dex. The FWHM of the H $\beta$  line was measured using Python QSO fitting code (PYQSOFIT, Guo et al. 2018). The downloaded SDSS spectrum with spectral wavelength coverage 3800 - 9200 Å was simultaneously fitted with the continuum model plus a Fe II template (Boroson & Green 1992, Vestergaard & Wilkes 2001), and a model with multiple Gaussians for H $\beta$ , the oxygen doublet [O III]  $\lambda\lambda 4959, 5007$  and the H $\alpha$  emission lines. Figure 6.10 shows the fit to the SDSS spectrum. The continuum model, which is a combination of a power-law, polynomial and Balmer continuum models approximates the blue bump well and flattens to the red side. As part of the output, PYQSOFIT includes estimates for parameters FWHM, equivalent width (EW), second moment of the line ( $\sigma_{\text{line}}$ ), central wavelength of the line. The FWHM and  $\sigma_{\text{line}}$  are derived in a similar manner as Peterson et al. (2004). For H $\beta$ , it resulted in a

$\text{FWHM} = 3683 \text{ km s}^{-1}$  with no statistical error. For the statistical error, a 10% error was assumed on the FWHM as in Vestergaard & Peterson (2006). Eqn. 6.2 gives an estimate of the black hole mass from SE as  $\log(M_{\text{BH}}) = 8.38 \pm 0.09 \text{ M}_{\odot}$  or  $M_{\text{BH}} = (2.4 \pm 0.5) \times 10^8 \text{ M}_{\odot}$ , using luminosity obtained in Section 6.6. The two mass estimates from SE and RM-based  $((1.0 \pm 0.3) \times 10^8 \text{ M}_{\odot})$  are consistent with each other to  $3\sigma$ .

It is worth mentioning that the measured RM-based mass did not factor the uncertainty in the adopted virial factor,  $f$ , due to systematic errors associated with measuring  $f$ .

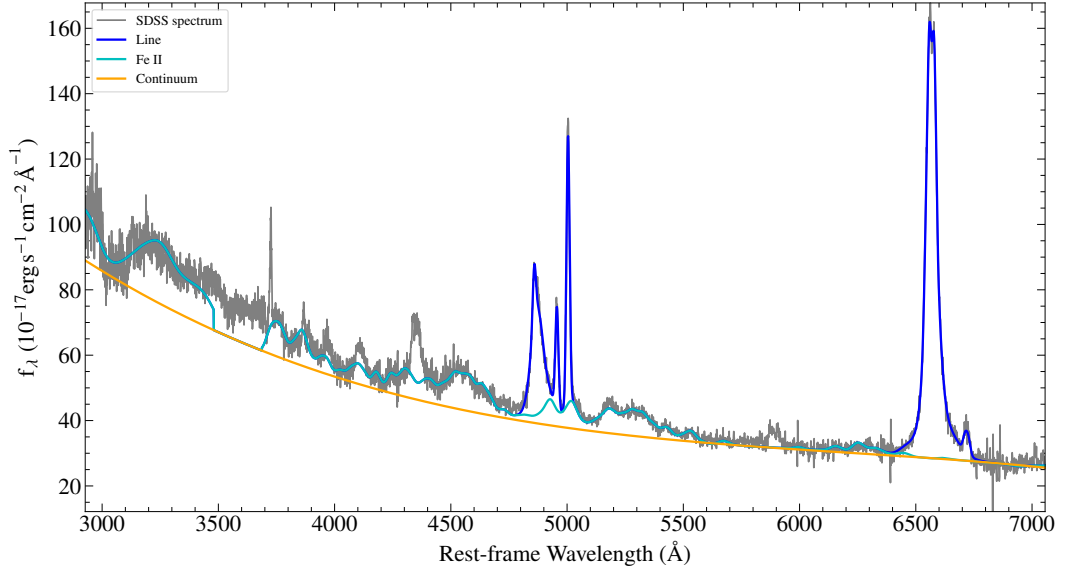


Figure 6.10: The SDSS spectrum (grey) overplotted with best-fitting models for the continuum (orange), Fe II template (cyan) and emission lines (blue) in units of  $10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$ .

# Chapter 7

## Discussion

In this chapter, the results obtained in this study are put into perspective, in line with the motivation outlined in Section 1.9 and in consideration with other similar studies. This chapter is organized as follows: Section 7.1 gives the summary of the AGN measurements; Section 7.2 covers the key considerations influencing the final black-hole mass estimate using Eqn. 1.23; Section 7.3 puts the results in context with existing scaling relationships; Section 7.4 discusses the measurements of the Eddington ratio and accretion rate for each AGN. The multi-wavelength photometric coverage of each AGN allows us to compare with predictions from the standard thin-disc model of (SS73, Shakura & Sunyaev 1973) in Section 7.5. In this Section, we further discuss some of the limitations on the standard model that may introduce systematic errors to our calculations. These were discussed in Section 2.7

Throughout this thesis, we have given all results and errors while using the assumption of the standard model of (SS73, Shakura & Sunyaev 1973). As discussed in Section 2.6 and 2.7, there are a range of reasons that this model may be incorrect, and some of these may introduce significant errors into these calculations. We touch on some of these limitations and weaknesses of this model throughout this Chapter, but detailed analysis of these effects are beyond the scope of this thesis.

### 7.1 Summary of Results

Table 7.1 summarizes the responsive lags for the broad  $H\beta$  line, determined black-hole masses, optical luminosities, Eddington ratios and dimensionless accretion rates for the sample of AGNs analysed in this study. Several campaigns have monitored 3C 120 (Table 4.11) prior to this one, including dynamical modeling (Pancoast et al. 2014a;b) of its broad-line region (BLR) by Grier et al. (2017a). Prior to this campaign, only Kollatschny et al. (2014) obtained multiple-line lag measurements of 3C 120, but with large errorbars due to the poorer quality of their light curves. This study offers an improvement in terms of better S/N and sampling rate of the emission-line data, allowing for testing of the virial assumption (e.g., Peterson & Wandel 1999, Onken & Peterson 2002) and BLR stratifica-

Table 7.1: Summary of AGN measurements in this work.

| Object                   | $\tau_{\text{H}\beta}$<br>(days) | $\langle f \rangle^{(a)}$ | $M_{\text{BH}}$<br>( $10^7 M_{\odot}$ ) | $\log \lambda L_{5100 \text{ \AA}}$<br>( $\text{erg s}^{-1}$ ) | $L_{\text{Bol}}/L_{\text{Edd}}$ | $\dot{\mathcal{M}}$    |
|--------------------------|----------------------------------|---------------------------|-----------------------------------------|----------------------------------------------------------------|---------------------------------|------------------------|
| 3C 120                   | $21.2^{+1.6}_{-1.0}$             | 5.5                       | $6.3^{+0.5}_{-0.3}$                     | $43.99 \pm 0.01$                                               | $0.114^{+0.009}_{-0.006}$       | $1.14^{+0.9}_{-0.6}$   |
| PG 2304+043              | $16.2^{+3.4}_{-2.3}$             | 1.17                      | $11.4^{+1.6}_{-1.6}$                    | $43.58 \pm 0.06$                                               | $0.025^{+0.005}_{-0.005}$       | $0.25^{+0.05}_{-0.05}$ |
| SDSS J132447.65+032432.6 | $22.97^{+10.99}_{-12.93}$        | 3.85                      | $5.18^{+2.48}_{-2.91}$                  | $44.64 \pm 0.05$                                               | $0.62^{+0.30}_{-0.40}$          | $6.2^{+3.0}_{-4.0}$    |

<sup>a</sup> Virial factor adopted in the calculation of  $M_{\text{BH}}$ . The adopted factor is based on the method for determining  $\sigma_{\text{line}}$ . This is described in each Chapter in the section on black hole masses and further discussed in Section 7.2

tion (Kollatschny 2003), see Figure 4.17. PG 2304+043 was the study of single-epoch (SE) spectroscopy by Vestergaard & Peterson (2006), but no prior RM-based measurements had been made. Therefore, the RM-based measurements are presented for the first time here. For SDSS J132447.65+032432.6, this serves as the first statistical RM measurements, as no prior similar undertakings have been made on this object.

### 7.1.1 Lookback Time

Figure 7.1 shows the AGN optical luminosity at 5100 Å as a function of redshift. This places the distribution of AGNs in this study in the redshift-luminosity parameter space, relative to other samples.

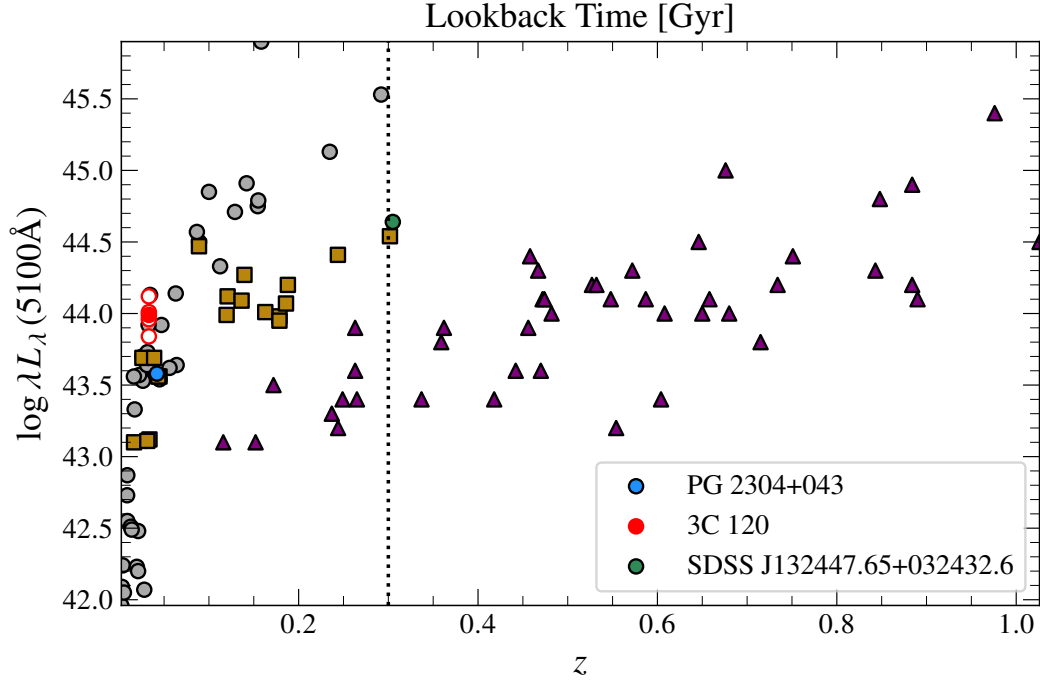


Figure 7.1: The distribution of objects with measured lags in the redshift-luminosity plane. The round grey points represent the sample of Bentz et al. (2013) while the square and triangular points represent the samples of Du et al. (2014; 2015; 2016b; 2018b) and Grier et al. (2017b), respectively. Measurements from this work are shown in color, the open circles are the previous 3C 120 measurements. The vertical dotted line marks the  $z = 0.3$  redshift.

## 7.2 Limitations on Mass Measurements

Revisiting the black hole mass  $M$  equation

$$M = f \frac{c\tau(\Delta V)^2}{G}, \quad (7.1)$$

where the parameters  $\tau$  and  $\Delta V$  are the primary focus of discussion in Section 7.2.1 and 7.2.2, respectively, in terms of their influence on the resulting black hole mass for each AGN in this work.

### 7.2.1 Lag Measurements

One of the parameters that help provide confidence in line lag ( $\tau$ ) measurements is the variability of the amplitude ( $F_{\text{var}}$ , Rodríguez-Pascual et al. 1997, Edelson et al. 2002, Vaughan et al. 2003) of the light curve during the campaign. For the lag to be reliable,  $F_{\text{var}}$  must be  $\geq 0.1$  (Peterson 2014) to indicate that the variations are sampled adequately. Factors affecting the measurement of  $F_{\text{var}}$ , are the scatter and temporal gaps in the light curve. The maximum cross-correlation coefficient ( $r_{\text{max}}$ , Section 2.2.1) is an important parameter that

provides confidence in the measurement of the lag, which reveals how strongly correlated two light curves are. The scatter and long-term trends (Welsh 1999) can affect the measurements of both  $\tau_{\text{line}}$  and  $r_{\text{max}}$  (e.g., Zhang et al. 2019). Then, there is a question of what makes  $\tau_{\text{line}}$  significant, a  $r_{\text{max}} \geq 0.35$  must be met (Peterson 2001) otherwise the  $\tau$  measurement may be unreliable. For  $\tau$  to be plausible, it should pass visual inspection. In other words, the lag should be discernible by eye, through shifting one light curve with respect to the other by the perceived lag. Grier et al. (2017b; 2018) devised a number of steps to consider the lag a significant detection, which include the following:

1. The lag,  $\tau$ , must be inconsistent with zero to  $\geq 2\sigma$ .
2. The maximum cross-correlation coefficient,  $r_{\text{max}}$ , must be  $\geq 0.45$ , to ensure the two light curves are well correlated.
3. The rms variability S/N is greater than 7.5 for the continuum and greater than 0.5 for line light curve.

The continuum light curves in each filter for each individual AGN were fitted with CREAM's thin steady-state blackbody accretion-disc model (Section 2.2.5) in order to test against predictions from SS73 model and to derive the temperature of the disc,  $T_1$ , at  $r_1$  (radius at 1 light-day away), mass accretion rate,  $\dot{M}$ , and Eddington ratio,  $\dot{m}_{\text{Edd}}$ , for black-hole mass,  $M$ .

The continuum light curves in each filter for each individual AGN were fitted with CREAM's thin steady-state blackbody accretion-disc model (Section 2.2.5) in order to test against predictions from SS73 model and to derive the temperature of the disc,  $T_1$ , at  $r_1$  (radius at 1 light-day away), mass accretion rate,  $\dot{M}$ , and Eddington ratio,  $\dot{m}_{\text{Edd}}$ , for black-hole mass,  $M$ .

For 3C 120, the broad-line light curve variabilities are well-detected with the high-ionization line, He II 4686, exhibiting the highest variability (Table 4.6). The measured  $\text{H}\beta$  variability suggests it has not changed much (increasing or decreasing) since the first campaign (Peterson et al. 1998a), with average variability of  $F_{\text{var}} = 0.076$ . The ensuing line lags are all inconsistent with zero to  $2\sigma$ . However, as mentioned before, the derived lag uncertainties seem underestimated. The scatter in the line light-curves of  $\text{H}\gamma$  and  $\text{H}\beta$  is not reflected in the corresponding lag uncertainties. For this case, CREAM becomes important as it can expand the light curve errors by using Monte Carlo Markov Chain (MCMC) method. The same scatter did affect the measurement of  $r_{\text{max}}$  leading to values below the 0.45 threshold. The corresponding peaks, however, are so well-detected that the  $\tau$  measurements passes the visual inspection. Overall, line lags from this object are well detected.

On the other hand, the PG 2304+043 emission-line light curve has a measured variability of amplitude of 0.03 (i.e., below the limit for RM studies). In terms of the above lag-significance criteria, the line light curve is strongly correlated with the continuum light curve with  $r_{\text{max}} = 0.87$ . The measured lag is inconsistent with zero up to  $3\sigma$ . However,

upon close examination, the lag does not pass the visual inspection. In other words, the determined lag is still open to question owing to lack of structure in the line light curve and evidence for matching structures in the continuum curve.

The SDSS J132447.65+032432.6 line lag measurement, even though it passes the visual inspection, is a perfect example of the effects of under-sampling. Temporal gaps and limited monitoring duration lead to a low variability amplitude,  $F_{\text{var}} = 0.04$ , and large lag uncertainties (consistent with zero at  $2\sigma$ ). The light curve is strongly correlated with the continuum with  $r_{\text{max}} = 0.83$  despite the lack of observations. The lag and its uncertainties will need to be investigated with more observations.

Currently, there are no standard criteria as to what makes a lag a significant detection. This is different from study to study (e.g., [Shen et al. 2015](#), [Homayouni et al. 2019](#), [Li et al. 2019](#)) and should be standardised. In this work, the focus was on two aspects of lag reliability. These include visual inspection and checking if the measured lag is inconsistent with zero to  $2\sigma$ .

In summary, only line lag measurements from 3C 120 can be trusted. While lags from PG 2304+043 and SDSS J132447.65+032432.6, owing to reasons given above, are not reliable.

### 7.2.2 Line-width Measurements

Ideally, each individual AGN should have its own virial factor,  $f$ , (e.g., [Horne 1994](#), [Horne et al. 2004](#), [Bentz et al. 2010](#), [Grier et al. 2013b](#), [Pancoast et al. 2014a;b](#), [Grier et al. 2017a](#)). Due to the scarcity of high quality data, an average  $\langle f \rangle$  is often assumed ([Onken et al. 2004](#), [Woo et al. 2015](#)). The choice ( $\sigma_{\text{line}}$  or FWHM) of the line-width measure,  $\Delta V$ , and therefore  $f$ , has a direct impact on the black-hole mass measurement. [Peterson et al. \(2004\)](#) and [Peterson \(2011\)](#) suggested the use of  $\sigma_{\text{line}}$  (instead of FWHM of the line) measured from the rms spectrum, as a better characterization of the broad-line width ( $\Delta V$ ) in the measurement of the black-hole mass,  $M$ , (Eqn. 7.1), noting that it gives consistent results in terms of the virial relationship. As a result, most RM measurements (e.g., [Bentz & Katz 2015](#)) have opted for the use of  $\sigma_{\text{line}}$  measured from the rms spectrum.

3C 120 exhibits a clear symmetric  $\text{H}\beta$  profile in the mean spectrum (Figure 4.4). This is further validated through velocity-resolved lag measurements, showing a clear symmetric pattern (Figure 4.18). The rms spectrum also shows a well-detected symmetric profile of the  $\text{H}\beta$  line (Figure 4.4). A dimensionless factor,  $\langle f_{\sigma} \rangle = 5.5 \pm 1.8$  ([Onken et al. 2004](#)), corresponding to  $\sigma_{\text{line}}$ , measured from the rms spectrum was adopted for 3C 120.

However, in some individual AGNs, characterizing  $\Delta V$  is not a straight-forward task. PG 2304+043 displays a complex double-peaked profile of the  $\text{H}\beta$  emission line in the rms spectrum (Figure 5.6). To limit biases that may be introduced (under/overestimating the line width),  $\Delta V$  is estimated from the FWHM measured from the mean spectrum,  $\langle f_{\text{FWHM}} \rangle = 1.17 \pm 0.50$  ([Collin et al. 2006](#)).

SDSS J132447.65+032432.6 has a noisy rms spectrum and its  $H\beta$  profile is contaminated by the telluric absorption lines. Collin et al. (2006) proposed the use of  $\sigma_{\text{line}}$  measured from the mean spectrum in the case of a noisy rms spectrum, which corresponds to  $\langle f_{\sigma} \rangle = 3.85 \pm 1.15$ .

### 7.2.3 Implications for the Black Hole Masses

The wrong characterization of  $\Delta V$  and unreliable  $\tau$ , can lead to misleading or inconsistent results. For 3C 120, the assumed mean factor  $\langle f \rangle$  and measured  $H\beta$  lag led to a black-hole mass that is generally consistent with previous campaigns (top panel of Figure 4.17), except for Du et al. (2018a) due to the asymmetric  $H\beta$  profile in their rms spectrum leading to small  $\sigma_{\text{line}}$  measurement. Overall, the  $H\beta$  results from campaign to campaign are consistent with the virial assumption (bottom panel of Figure 4.17) in which the line width decreases as the  $H\beta$  lag increases. 3C 120 is also one of the few objects to have their black hole masses determined via dynamical modeling (Grier et al. 2017a), which is also consistent with the mass determined in this work. The study from Grier et al. (2017a) resulted in virial factor specific to 3C 120 of  $f_{\sigma} = 5.75 \pm 2.25$ , making this object one of the few to have such measurement.

Prior to this campaign, the mass of PG 2304+043 was estimated via SE (Table 5.1). The systematic offset,  $\Delta \log M$ , or accuracy between the SE and RM-based masses is quantified as  $\Delta \log M = \log M_{\text{SE}} - \log M_{\text{RM}}$  (Denney et al. 2009a), resulting in a significant systematic offset of 0.5. Denney et al. (2009a) and Park et al. (2012) found that not properly accounting for host-galaxy contribution can overestimate the SE mass. This may explain the larger black-hole mass found by Vestergaard & Peterson (2006) for PG 2304+043. However, since the host-galaxy contribution is constrained in this work and using the assumption that its contribution is not expected to vary significantly over the years, it leads to new luminosity of Vestergaard & Peterson (2006) corrected for starlight as  $\log \lambda L_{5100 \text{ \AA}} = 43.97 \pm 0.14 \text{ erg s}^{-1}$ . This results in a recalculated SE mass of  $\log M_{\text{BH}} = 8.5 \pm 0.1$  compared to  $\log M_{\text{BH}} = 8.6 \pm 0.1$  from before, implying no change in mass. Another possible factor for the discrepancy between SE and RM-based masses is the improper removal of the narrow component for the FWHM measurement. However, the systematic difference due to failure to properly account for the narrow component is insignificant compared to host-galaxy starlight especially for low-luminosity AGNs, since host-galaxy contribution at 5100 Å is significant (Park et al. 2012). Therefore, host-galaxy contribution is likely the main contributor to the systematic offset between SE and RM-based masses. The lack of reliability of the  $H\beta$  lag measurement for this target also adds to the offset.

The assumed  $\langle f \rangle = 3.85$  led to the mass measurement for SDSS J132447.65+032432.6 in Table 7.1. Assuming the lag for this object holds, then the measured black hole mass serves as the  $2\sigma$  upper limit. For comparison, its SE mass was also estimated using continuum luminosity at 5100 Å and  $H\beta$  FWHM measured from the SDSS spectrum. The SE mass is larger than RM-based mass perhaps due to the uncertainty in the host-galaxy starlight contribution (i.e., under/over estimated) to the continuum luminosity, being that its contri-

bution is an interpolated measure in the wide wavelength range between  $g$  and  $r$ .

The above measured black hole masses do not take into account the uncertainty on the chosen virial factors due to systematic errors that may be introduced. This systematic factor may increase the uncertainty by up to a factor of 2 (Section 2.6).

Throughout the thesis, we sought to measure the black hole mass for each of the individual AGNs. At the same time, acknowledging some of the assumptions in this field and their effect on the resulting black hole mass. For example, the assumptions in the measurement of the virial factor,  $f$ , and the characterization of the broad emission-line width can introduce errors into the measurement of the black hole mass by several factors.

## 7.3 Context with other Samples

One of the important relationships to emerge from RM of AGNs is the relationship between black hole mass and stellar velocity ( $M - \sigma_*$ , Section 1.5.1), and the relationship between the BLR size and luminosity ( $R_{\text{BLR}} - L$ , Section 1.6). Even though  $M - \sigma_*$  represents the tighter of the two relationships, adding more data points will help improve the calibration of these relationships at low and high redshifts. The  $R_{\text{BLR}} - L$  relation is extremely important as it enables SE mass estimates, and  $M - \sigma_*$  helps constrain the evolution of AGNs and their host galaxies. Here, the AGN measurements (Table 7.1) are discussed in comparison to other samples in the context of these two important relationships.

### 7.3.1 Size and Luminosity

A relation exists between the delays measured through reverberation mapping of the broad emission lines and the level of the continuum luminosity at the time of the campaign (Section 1.6). Figure 7.2 shows this for several AGNs (Bentz et al. 2013, Du et al. 2014; 2015; 2016b; 2018b, Grier et al. 2017b) along with AGNs from this work.

For 3C 120, there have been several measurements of the  $H\beta$  time-lag and the optical luminosity from literature. Generally, the  $H\beta$  delay is correlated with the optical luminosity for this object. Since the original observations, the  $H\beta$  delay has decreased from  $\sim 40$  days (Table 4.11) measured by Peterson et al. (1998a) to 20.2 days (Du et al. 2018a). Although, it stands to reason that the Peterson et al. (1998a) measurement has quite large error bars, so this decrement may not be as clear. Otherwise, this would imply that over the span of 22 years, its BLR has changed significantly. In the process, the light curve quality improved, leading to smaller uncertainties. However, the continuum luminosity at 5100 Å has not changed significantly since the Grier et al. (2012) campaign, i.e., the BLR is seemingly shrinking while the continuum level stays almost unchanged. This behaviour can be explained in terms of “intrinsic Baldwin effect” (Pogge & Peterson 1992) where  $H\beta$  response to continuum variations decreases with increasing level of the continuum luminosity. More measurements of size and luminosity are needed following this campaign to confirm this

effect.

Of the AGN sample considered here, the PG 2304+043  $H\beta$  lag shows the tightest correlation with the luminosity (Figure 7.2). The estimated luminosity is very similar to that measured by Sani et al. (2010), suggesting it has not changed much since. Its position on the  $R_{\text{BLR}} - L$  may reflect true lag measurement or measurement arising due to spurious features.

The position of SDSS J132447.65+032432.6 (which has a redshift significantly higher than the other two AGNs considered here) is offset from the best-fit line by an amount  $\Delta R_{H\beta} = \log(\tau_{\text{obs}}/\tau_{R-L}) = -1.15$ . However, the luminosity is measured between  $g$  and  $r$ , which may suffer from systematics due to significant host-galaxy contribution. Even with this, the position of SDSS J132447.65+032432.6 agrees with the distributions from Du et al. (2016b), Grier et al. (2017b) samples. There is now an accepted reason for the apparent deviation of some luminous AGNs from the  $R_{\text{BLR}} - L$  relation (Section 1.6.1). This has to do with high accretion rates ( $\dot{M} > 3$ ) in these objects, including SDSS J132447.65+032432.6 (Section 7.4 for evidence of high accretion rate in this object).

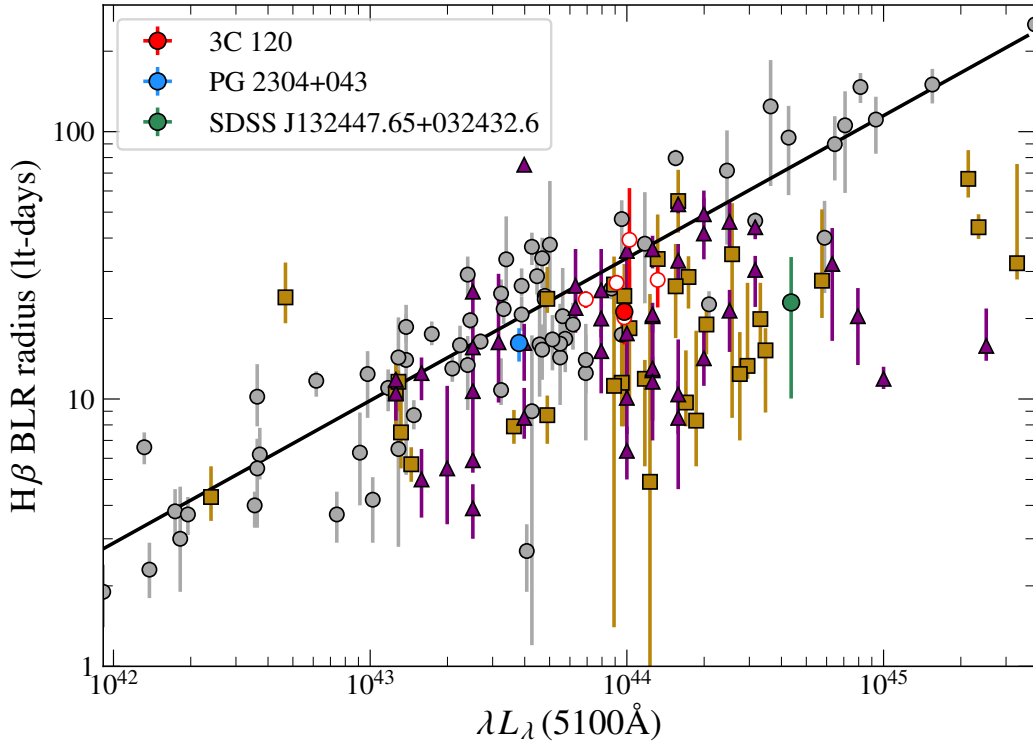


Figure 7.2: The  $R_{\text{BLR}} - L$  relation for several individual AGNs. The symbols are the same as Figure 7.1.

### 7.3.2 Black Hole Mass and Stellar Velocity

This work also seeks to place the measured black-hole masses on the  $M_{\text{BH}} - \sigma_*$  relation using samples of [McConnell & Ma \(2013\)](#) and [Woo et al. \(2010\)](#) (Figure 7.3). The former study is for quiescent galaxies while the latter is for RM-based masses. For 3C 120, [Nelson & Whittle \(1995\)](#) reports the stellar velocity dispersion as  $\sigma_* = 162 \pm 20 \text{ km s}^{-1}$ . The 3C 120 measurement in this work is also shown in Figure 7.3. The best-fit lines for both samples are shown as solid grey and dashed blue lines, for inactive and active samples, respectively. The equation characterizing the best-fit lines is as follows:

$$\log(M_{\text{BH}}/M_{\odot}) = \alpha + \beta \log(\sigma_*/200 \text{ km s}^{-1}) \quad (7.2)$$

where  $\alpha = 8.32$  and  $\beta = 5.64$  for quiescent and  $\alpha = 8.00$  and  $\beta = 3.55$  for active galaxies. The position of 3C 120 is well-approximated by both best-fit trends from the respective samples. Unfortunately, for PG 2304+043 and SDSS J132447.65+032432.6, there are no measurements of the stellar velocity dispersions in the literature. Having an estimate of the stellar velocity dispersion ( $\sigma_*$ ) for SDSS J132447.65+032432.6, would mean a contribution to the sample of [Li et al. \(2021\)](#) for high-redshift ( $z > 0.3$ ) objects, whose measurements appear to follow the same correlation as local RM AGNs and quiescent galaxies. It is difficult to reliably measure  $\sigma_*$ , especially in high- $z$  AGNs. This is because high- $z$  AGNs are the most luminous, hence they can be detectable at large distances. As such, their strong emission dilutes the host-galaxy starlight leading to a lack of strong absorption line features in the host-galaxy spectrum. Also, high spatial resolution is required for high- $z$  objects to carefully decompose nuclear and host-galaxy starlight (i.e., in the case of imaging), which is not always easy to achieve due to limitations in observing capabilities.

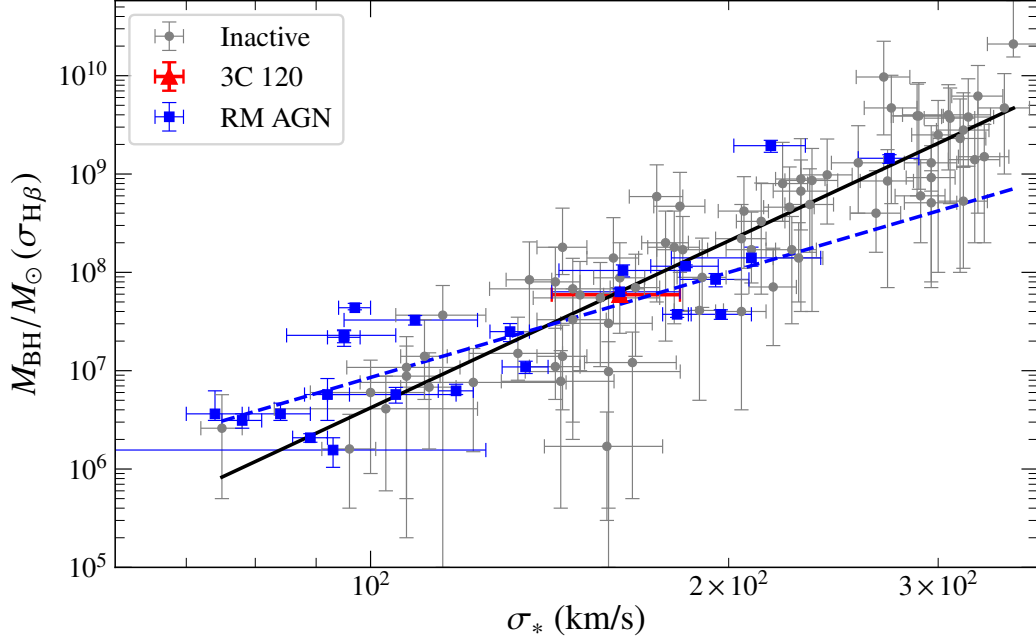


Figure 7.3:  $M - \sigma_*$  relation for quiescent galaxies (grey, [McConnell & Ma 2013](#)) against active galaxies with RM-based masses (blue, [Woo et al. 2010](#)). The RM-based masses were normalized with  $f = 5.2$ . The best-fit lines are shown in solid grey for quiescent galaxies ( $\alpha = 8.32$  and  $\beta = 5.64$ ) and dashed blue for active galaxies ( $\alpha = 8.00$  and  $\beta = 3.55$ ).

## 7.4 Eddington Ratio and Accretion Rate

It is believed that black holes in AGNs are powered by accretion of matter onto them ([Rees 1984](#)). To get an idea of the energy output in these sources requires an estimate of the Eddington ratio,  $\dot{m}_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$ . Through the flux variation gradient (FVG, [Choloniewski 1981](#)) method, the optical luminosities at  $5100 \text{ \AA}$  for each AGN have been host-galaxy subtracted (Section 2.2.5). Consequently the bolometric luminosity can be estimated, adopting the bolometric correction (BC) factor from [Richards et al. \(2006\)](#) as  $L_{\text{bol}} = 9.26 (\lambda L_{5100 \text{ \AA}})$ . With this correction, the Eddington ratio for each AGN is listed in Table 7.1, where  $L_{\text{Edd}}$  is calculated using Eqn. 1.3 and the errors obtained through propagation. The  $\dot{m}_{\text{Edd}}$  for 3C 120 in this work ( $0.114^{+0.009}_{-0.006}$ ) is similar to the value of  $\dot{m}_{\text{Edd}} = 0.122$  (without errors) determined by [Czerny et al. \(2019b\)](#). Both 3C 120 and PG 2304+043 have  $\dot{m}_{\text{Edd}} \leq 0.3$ . The observed SED of AGNs with  $\dot{m}_{\text{Edd}} \leq 0.3$  can be understood in terms of the optically-thick and geometrically-thin accretion disc ([Castelló-Mor et al. 2016](#), and references therein). The estimated ratios from the three AGNs imply they are accreting below the Eddington rate,  $\dot{m}_{\text{Edd}} < 1$ . This is almost expected as most AGNs accrete below this limit (e.g., [Woo & Urry 2002](#), [Bian & Zhao 2003](#)). It is worth noting that uncertainty in the luminosity  $\lambda L_{5100 \text{ \AA}}$  increases the uncertainty in bolometric luminosity,  $L_{\text{bol}}$ . The host-galaxy contribution can lead to an overestimate of  $L_{\text{bol}}$ , and consequently an increase in  $\dot{m}_{\text{Edd}}$ . On the other hand, the choice of BC has little influence on  $\dot{m}_{\text{Edd}}$ , perhaps because the adopted values of BC are

fairly similar. Similarly, uncertainty in the black-hole mass  $M$  would increase uncertainty in  $L_{\text{Edd}}$ . So, for accurate  $\dot{m}_{\text{Edd}}$ , accurate black-hole masses must be estimated, and the host-galaxy contribution properly accounted for.

#### 7.4.1 Accretion Rate

The Eddington ratio is related to the dimensionless accretion rate  $\dot{\mathcal{M}}$  according to Eqn. 1.5. Having an estimate of  $\dot{\mathcal{M}}$  allows us to categorize the AGNs into sub-Eddington and super-Eddington accretors, with  $\dot{\mathcal{M}} < 3$  implying the former and  $\dot{\mathcal{M}} > 3$  the latter. The value of the accretion efficiency is generally assumed to be  $\eta = 0.1$  for the standard thin-disc model (Frank et al. 2002, Shankar et al. 2009). This results in the measured accretion rates listed in Table 7.1. For 3C 120, Du et al. (2018a) gives an upper limit on the accretion rate as  $\dot{\mathcal{M}} \leq 2$ , so the value estimated here ( $1.14^{+0.9}_{-0.6}$ ) is consistent. PG 2304+043 has the lowest  $\dot{\mathcal{M}}$  ( $= 0.25^{+0.05}_{-0.05}$ ), followed by 3C 120. SDSS J132447.65+032432.6 may be a super-Eddington accretor  $\dot{\mathcal{M}} (= 6.2^{+3.0}_{-4.0})$ , explaining its deviation on the  $R_{\text{BLR}} - L$  relation (Wang et al. 2014). High-redshift objects (i.e., quasars) tend to have high accretion rates and bolometric luminosities, this is why they can be observed at high redshifts. Accretion in systems like SDSS J132447.65+032432.6 may also be fueled by slim disc (Abramowicz et al. 1988). In a slim disc, the shadowing effect explained by Wang et al. (2014) becomes strong, causing the ionizing photons to diminish leading to shortened lags.

#### 7.4.2 Effect of Inclination

Eqn. 1.5 can be rewritten in terms of the disc inclination,  $i$ , the optical luminosity at 5100 Å and the black-hole mass,  $M$ , via

$$\dot{\mathcal{M}} = 20.1 \left( \frac{l_{44}}{\cos i} \right)^{(3/2)} M_7^{-2}, \quad (7.3)$$

where  $l_{44} = L_{5100}/10^{44} \text{ erg s}^{-1}$  and  $M_7 = M/10^7 M_{\odot}$  (Du et al. 2015). The inclination of the disc to the line of sight takes into account the geometry and dynamics of the BLR. For type-1 AGNs,  $\cos i \sim 0.75$  (which represents mean disc inclination, Du et al. (2015)). For  $\cos i < 0.75$   $\dot{\mathcal{M}}$  would increase slightly. For  $\cos i > 0.75$   $\dot{\mathcal{M}}$  would decrease slightly. So changing the inclination has approximately 30% change on the resulting  $L_{\text{bol}}/L_{\text{Edd}}$  and hence on  $\dot{\mathcal{M}}$ .

### 7.5 Accretion-disc Mapping

Accretion-disc variability in AGNs is crucial, as it helps to infer the physical properties of the disc, such as the temperature profile and the accretion-disc size at some reference wavelength. It also helps us to understand the origin of the continuum variability and behaviour in these objects. The model of SS73, which consists of a geometrically-thin, optically-thick disc, is often assumed in investigating the observed accretion-disc variability. In this model, the

observed UV/optical continuum variations are correlated with X-ray variations. The inter-band delays are predicted to scale as  $\tau(\lambda) \propto \lambda^{4/3}$  and the temperature profile of the disc as  $T(r) \propto r^{-3/4}$  ( $r$  is the radius from the central black hole).

The continuum light curves in each filter for each individual AGN were fitted with CREAM's thin steady-state blackbody accretion-disc model (Section 2.2.5) in order to test against predictions from SS73 model and to derive the temperature of the disc,  $T_1$ , at  $r_1$  (radius at 1 light-day away), mass accretion rate,  $\dot{M}$ , and Eddington ratio,  $\dot{m}_{\text{Edd}}$ , for black-hole mass,  $M$ .

For the 3C 120 disc modeling, the measured black hole mass in Table 7.1 was used for consistency. For PG 2304+043, the SE virial mass in Table 5.1 was used rather than the derived mass in Table 7.1. This is to compare CREAM-derived disc parameters ( $\dot{M}$  and  $\dot{m}_{\text{Edd}}$ ) to the published values, for the same SE mass, to see if over the years they have changed since Vestergaard & Peterson (2006). For SDSS J132447.65+032432.6, the mass of  $M = (1 \times 10^8) M_\odot$  was assumed. The choice of mass,  $M$ , for this object did not really matter as we are only interested in the continuum and line delays. This is because the quality of the light curves for this target are not good enough to constrain the disc parameters.

The derived accretion-disc parameters for 3C 120 are  $T_1 = (1.51 \pm 0.10) \times 10^4$  K, mass accretion rate  $\dot{M} = 0.60 \pm 0.15 M_\odot/\text{yr}$ ,  $\dot{m}_{\text{Edd}} = 0.42^{+0.10}_{-0.09}$  and  $i = 0^\circ$  corresponding to model 1 (Table 4.7). Model 2 yielded the same parameter values except for a disc inclination relative to the observer of  $i = (52 \pm 9)^\circ$ ,  $1\sigma$  above the mean inclination of  $40^\circ$  for Type 1 AGNs. The measured inclination  $i > 40^\circ$  contradicts a face-on disc inclination ( $i = 0$ ) and is  $5\times$  larger than the inclination measured by Pozo Nuñez et al. (2014) of  $10^\circ \pm 4^\circ$  (which is close to a face-on disc inclination). The difference may be due to the different underlying assumptions between CREAM and the model used by Pozo Nuñez et al. (2014).

For PG 2304+043, these were derived as  $T_1 = (1.12 \pm 0.14) \times 10^4$  K,  $\dot{M} = 0.029 \pm 0.014 M_\odot/\text{yr}$ ,  $\dot{m}_{\text{Edd}} = 0.0031^{+0.0016}_{-0.0013}$  and  $i = 0^\circ$ . These values are statistically significant up to  $2\sigma$  for 3C 120, suggesting its parameters are well-constrained. The PG 2304+043 values are only significant to  $1\sigma$ . The estimates for  $\dot{m}_{\text{Edd}}$  and consequently that for bolometric luminosities, are not corrected for host-galaxy contribution and hence, they are different from those in Section 7.4.

For SDSS J132447.65+032432.6, the disc parameters ( $T_1$  and  $\dot{M}$ ) could not be constrained due to relatively poor sampling and S/N of the continuum light curves, i.e., there is not enough information in the light curves to constrain the disc parameters. However, CREAM does yield a good fit to the data for the model in which the above parameters are kept fixed.

### 7.5.1 Context to other Accretion-disc Mapping Results

The observed lags in 3C 120, utilizing six wavebands, reveal they are consistent or follow the expected lag-wavelength dependence (Figure 4.13). However, comparing the observed disc radius,  $\tau_0$  (Eqn. 4.1) with CREAM's thin-disc model reveals a disc size 1.6 times larger

than predicted at the reference wavelength,  $\lambda_0 = 5477 \text{ \AA}$ . Other studies employing CREAM’s accretion-disc fitting model include [Troyer et al. \(2016\)](#) and [Starkey et al. \(2017\)](#). The former study did not constrain the wavelength dependence of the lags in NGC 6814 due to large uncertainties on their B and V-band lags, with the latter study also finding a discrepancy between observed and predicted disc sizes in NGC 5548. [Fausnaugh et al. \(2016\)](#) quantified this discrepancy in NGC 5548 as 3 times larger than predicted. The [Fausnaugh et al. \(2016\)](#) study is considered the most comprehensive, not only in terms of broad wavelength coverage, but also in terms of better constraining the measured inter-band lags. [Hernández Santisteban et al. \(2020\)](#), also using CREAM, again found evidence for a larger disc than predicted in Fairall 9. This problem of larger disc than predicted has been reported in several other studies (e.g., [McHardy et al. 2014](#), [Shappee et al. 2014](#), [Edelson et al. 2015](#), [Lira et al. 2015](#), [Edelson et al. 2017](#), [Cackett et al. 2018](#), [Kokubo 2018](#), [McHardy et al. 2018](#), [Pozo Nuñez et al. 2019](#), [Cackett et al. 2020](#)). The discrepancy is generally constrained to be 2 - 3 $\times$  more than predicted, using the realistic values of the black hole mass and accretion rate. This discrepancy is discussed further in Section 7.5.2.

For PG 2304+043 (Figure 5.14), however, using the observed JAVELIN lags results in a disc size *smaller* than the model by a factor of 1.9. This is perhaps because the assumed black-hole mass,  $M$ , and therefore accretion rate,  $\dot{M}$ , may not represent realistic values for this object. If, instead of using the SE mass we use the RM-based mass (Table 7.1), the observed disc size based on JAVELIN lags would be larger by 1.3 times than predicted.

### Re-calculating Accretion-disc Size

The accretion-disc size can be re-measured using the host-galaxy-corrected bolometric luminosity and therefore  $\dot{m}_{\text{Edd}}$  (Table 7.1), via

$$\tau_0 = \frac{1}{c} \left( X \frac{k\lambda_0}{hc} \right)^{4/3} \left[ \left( \frac{GM}{8\pi\sigma} \right) \left( \frac{L_{\text{Edd}}}{\eta c^2} \right) (3 + \kappa) \dot{m}_{\text{E}} \right]^{1/3}, \quad (7.4)$$

where the accretion efficiency  $\eta = 0.1$ ,  $X$  is the conversion factor from  $\lambda$  to  $T$  and  $\kappa = 1$  (ratio of external to internal heating) ([Fausnaugh et al. 2016](#)). Assuming the  $X$  factor is given by Wien’s law, this change results in an increased discrepancy, from 1.6 to 2.5, between the observed and predicted disc size for 3C 120. Again supporting the observation that realistic values of  $M$  and  $\dot{M}$  result in larger observed sizes than predicted.

### 7.5.2 Discrepancy with Theory

The above observed discrepancies are generally attributed to contamination by the Balmer continuum emission from the BLR. This effect is often evidenced by the measured excess U/u lags or lags that are comparable to Balmer emission-line lags such as He II  $\lambda 4686$  (Figure 4.13). This effect is particularly pronounced, as in the case of NGC 5548 ([Edelson et al. 2015](#), [Fausnaugh et al. 2016](#)) and NGC 4593 ([Cackett et al. 2018](#), [McHardy et al. 2018](#)). In addition to an excess U/u lag, there is evidence of discontinuity around the Balmer jump

at 3646 Å, where the lags experience a sharp drop, and a discontinuity around the Paschen jump at 8204 Å, as seen in NGC 4593 (Cackett et al. 2018). These suggest a contribution by the diffuse continuum (DC, Korista & Goad 2001, Lawther et al. 2018, Chelouche et al. 2019, Korista & Goad 2019) from the BLR to the inter-band lags. Figure 4.13 shows both of these effects for 3C 120: the Balmer jump at 3640 Å (U to *g*) and the Paschen jump at 8200 Å (*i* to *z<sub>s</sub>*). For PG 2304+043, there is only evidence of the Paschen jump at 8200 Å (*i* to *z<sub>s</sub>*) in Figure 5.14. However, neither of these components show up in the variable (rms) disc spectrum of 3C 120 or PG 2304+043 (Figure 4.15 and 5.16).

Korista & Goad (2001) put forward the physical conditions that produce this DC emission. They showed in their photoionization model that DC is likely to arise in an environment where the hydrogen gas density is high,  $n_{\text{H}} \geq 10^7 \text{ cm}^{-3}$ , (at low densities the gas is highly ionized), incident ionizing hydrogen photon flux is  $\Phi_{\text{H}} \geq 10^{17} \text{ cm}^{-2} \text{ s}^{-1}$  and a fixed hydrogen column density is  $N_{\text{H}} = 10^{23} \text{ cm}^{-2}$ . This is the same environmental conditions that produces the observed broad emission lines in AGN spectra (i.e., the BLR). This DC is generally in the form of a bound-free and free-free continuum emission. It produces a delay spectrum with lags that increase with increasing wavelength. In particular, it produces lags that lie above and below the disc reprocessing inter-band delays in the case of Balmer and Paschen jumps, respectively.

Quantifying the DC contribution to the measured delays requires high quality modeling of the AGN spectra, such as spectral decomposition. This contribution is often not accounted for, including in this study (for the case of 3C 120 and PG 2304+043) as it is not a straightforward task to do, i.e., modeling accurately the different components of the spectrum. Ideally, one would want to adopt an AGN continuum model that is inclusive of both Balmer and DC continua as part of the decomposition (e.g., Barth et al. 2015). This, combined with synthetic photometry, estimates the contribution of the individual model components to the observed flux in each filter. Fausnaugh et al. (2016) did spectral modeling of the NGC 5548 spectra to estimate the fraction of the BLR emission in each filter. They found that the largest bias introduced by the BLR contribution is in the *u* and U bands. This bias also confirms the reason for the enhanced U-lag measured for 3C 120 in this work. However, the bias is not as large to warrant excluding the U-lag in the lag spectrum fit.

There is also a question of whether the lamp-post model is an adequate descriptor of the nature of continuum variability observed in AGNs. In several AGNs, this model seems adequate with evidence of X-ray variations leading the UV/optical variations as predicted (Buisson et al. 2017). In NGC 4151 (Edelson et al. 2017), however, the X-ray/UV lags are longer than the UV/optical lags, suggesting that the picture provided by the lamp-post model may be too simple. Gardner & Done (2017) also show that UV/optical lags in NGC 5548 are not consistent with X-ray reprocessing of the disc. Chelouche et al. (2019) finds evidence of the time lags between adjacent optical bands as being due to photoionized material from the outer accretion disc, as oppose to disc reprocessing.

For both 3C 120 and PG 2304+043, the model seems adequate in that is able to reproduce

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the observed variability and underlying SED. However, there is still discrepancy between predicted and observed delays.



## Chapter 8

# Summary and Conclusion

This work focuses on three AGNs (3C 120, PG 2304+043 and SDSS J132447.65+032432.6), each with its own chapter and implications for the AGN RM field. Chapter 4 focuses on 3C 120 and its inclusion in this work is motivated by the good S/N and temporal sampling of both spectroscopic and photometric observations from LCO (Section 3.2). The black-hole mass for 3C 120 is determined using multi-line lag measurements, and the kinematics of its BLR clouds are determined via velocity-resolved lag measurements. Additionally, the inter-band delays in this object are measured and compared with predictions from the standard thin-disc model (SS73, [Shakura & Sunyaev 1973](#)). The main results from the 3C 120 analysis are as follows:

- The broad emission-line lag measurements yielded  $18.8_{-1.0}^{+1.3}$ ,  $2.7_{-0.8}^{+0.7}$ ,  $21.2_{-1.0}^{+1.6}$  and  $16.9_{-1.1}^{+0.9}$  days for  $H\gamma$ , He II  $\lambda 4686$ ,  $H\beta$  and He I  $\lambda 5876$  emission lines, respectively. When compared with the values from [Kollatschny et al. \(2014\)](#), being the other study where multi-line lag measurements were carried out, they are consistent but with smaller uncertainties.
- The black-hole mass,  $(6.3_{-0.3}^{+0.5}) \times 10^7 (f/5.5) M_{\odot}$ , combining  $H\beta$  line-width and time-lag is consistent with previous similar studies on 3C 120 (Table 4.11).
- The velocity-resolved lag measurements reveal a clear symmetric pattern (Figure 4.18) consistent with the virialized motions of the gas clouds in 3C 120. This is consistent with [Grier et al. \(2013b\)](#) from an earlier campaign but inconsistent with [Du et al. \(2018a\)](#) from an overlapping campaign.
- Multi-band lag measurements in 3C 120 are consistent with X-ray reprocessing in which longer wavelengths lag behind shorter wavelengths according to  $\tau \propto \lambda^{4/3}$ , but with an excess U-band lag encountered in other similar studies (e.g., [Edelson et al. 2019](#)).
- Adopting a face-on model, CREAM determines the accretion-disc parameters as  $T_1 = (1.5 \pm 0.1) \times 10^4$  K,  $\log(M\dot{M}/M_{\odot}^2 \text{yr}^{-1}) = 7.58 \pm 0.11$  and  $\dot{m}_{\text{Edd}} = 0.42_{-0.1}^{+0.1}$ , which are

well-constrained.

- The observed disc size is a factor  $1.6\times$  larger than predicted by the model with  $\dot{m}_{\text{Edd}} = 0.42$ , consistent with similar previous studies (e.g., [Fausnaugh et al. 2016](#)).
- The SED of the disc spectrum is compatible with predicted power-law ( $F_\nu \propto \nu^{1/3}$ ) from thin-disc theory.

PG 2304+043 (Chapter 5) is one of the quasars from the sample of [Boroson & Green \(1992\)](#) and its inclusion in this work was stimulated by the absence of an RM-based mass estimate of its black hole, to compare with its SE mass estimate from [Vestergaard & Peterson \(2006\)](#). Combining spectroscopic observations from SALT (Section 3.1) and photometric observations from LCO (Section 3.2) enables its RM-based mass to be determined here for the first time. The quality of the photometric observations also allows for the inter-band delays to be determined for the first time in this object. The summary of the results emanating from this chapter are as follows:

- The  $\text{H}\beta$  delay,  $16.2^{+3.4}_{-2.3}$  days, from ICCF is consistent with measurements from zDCF and JAVELIN.
- The RM-based black hole mass,  $(11.4^{+1.6}_{-1.6}) \times 10^7 (f/1.17) \text{ M}_\odot$ , is a factor 3.5 smaller than the SE mass, consistent with previous studies where SE masses are larger than the RM-based masses.
- The position of PG 2304+043 on the  $R - L$  relation is consistent with the expected trend from [Bentz et al. \(2013\)](#).
- The inter-band delays follow the  $\tau \propto \lambda^{4/3}$  relation, but with evidence of a Paschen jump due to diffused continuum emission from the BLR ([Cackett et al. 2018](#), [Hlabathe et al. 2020](#)).
- The CREAM model with  $\dot{m}_{\text{Edd}} = 0.003$  predicts a disc size a factor  $1.9\times$  larger than observed. This discrepancy is consistent with previous studies (e.g., [Fausnaugh et al. 2016](#)).
- The SED of the disc spectrum is consistent with  $F_\nu \propto \nu^{1/3}$  from thin-disc theory.

SDSS J132447.65+032432.6 is included as a high-redshift AGN just beyond the local universe  $z > 0.3$ . There is currently a lack of robust RM measurements at high redshifts due to lack of quality data in terms of temporal sampling and high S/N. The more AGNs with RM measurements at high  $z$ , the better their evolution can be understood and constrained (e.g., [Li et al. 2021](#)). Chapter 6 presents the first RM measurements on this object, summarized as follows:

- The ICCF  $\text{H}\beta$  lag relative to the  $g$ -band is determined as  $22.97^{+10.99}_{-12.93}$  days, consistent with  $22.19^{+1.60}_{-2.97}$  days measured by CREAM.

- The black-hole mass is determined to be  $(5.18^{+2.48}_{-2.91}) \times 10^7 (f/3.85) M_{\odot}$  using the ICCF lag.
- Its position on the  $R_{H\beta} - L$  relation is offset from the main trend line, consistent with high accreting objects (Du et al. 2018b).

These results demonstrate how good S/N photometric observations can be used to derive the luminosity and host-galaxy contribution via the flux-flux analysis based on the flux variation gradient (FVG) method (Haas et al. 2011). This is validated when comparing the 3C 120 derived luminosity with previous results (Pozo Nuñez et al. 2012), with which it is consistent. It is also the case with PG 2304+043, whose luminosity is consistent with Sani et al. (2010). From the flux-flux analysis, the color profile (or SED) of the AGN (e.g., Cackett et al. 2020, Hernández Santisteban et al. 2020) was constrained and found to be consistent with a predicted power-law for a Shakura & Sunyaev (1973) thin-disc model. Although in the case of 3C 120, the observed SED is orders of magnitude fainter than predicted; a similar outcome was found by Starkey et al. (2017), Hernández Santisteban et al. (2020). Using optical-optical lags, the problem of the observed disc normalization being larger than predicted (e.g., Fausnaugh et al. 2016) is also encountered here. The different choices of the broad-line width measure are adopted in this thesis and their influence on the resulting black-hole mass is ascertained. For PG 2304+043 and SDSS J132447.65+032432.6, single-epoch and reverberation-based masses are estimated in an effort to constrain the discrepancy (e.g., Dalla Bontà et al. 2020). In the case of SDSS J132447.65+032432.6, it is shown how poorer sampling results in increased errors (Yu et al. 2020c). The position of SDSS J132447.65+032432.6 on the  $R_{BLR} - L$  (Bentz et al. 2013) relation confirms the idea that high-accreting objects ( $\dot{M} > 3$ ) are scattered below the relation (Du et al. 2016a).

Throughout the thesis, the observed light curve variability is assumed as being explained by the lamp-post model. Now, there have been some noticeable studies challenging the validity of the model. In this study, we also concur with some of the concerns raised in some of these studies. Typically, that the observed lags do not match the predicted lags from the model. Also, in studies with X-ray observations, there is a perceived lack of correlation between observed X-ray and UV/optical variability. With that, the AGN models are always evolving as we try to understand the relation between X-ray and UV/optical variability. Recently, Alston et al. (2020), Caballero-García et al. (2020), Panagiotou et al. (2022b) explored a system in which the configuration of the X-ray source is not static as in the lamp-post model, but dynamic (i.e., the height,  $h_X$ , of the X-ray corona varies). Panagiotou et al. (2022a) showed how adopting this configuration can account for the moderate correlation between the X-ray and UV/optical variability. In the case of Fairall 9 observations, Hagen & Done (2023) showed that X-ray reprocessing alone as predicted by the lamp-post model, cannot fully explain the UV variability, but that the majority of the variability comes from the process intrinsic to the disc. In some studies (e.g., Fausnaugh et al. 2016), it has been noted that some observed continuum lags are as a result of contribution from the variable diffuse BLR gas. This is further supported by the findings from Netzer (2022). Although, models

involving time-dependent variability from the diffuse BLR gas are yet to be tested in relation to reproducing the observed X-ray variability. If the above is an indication of the lamp-post model being completely wrong, then it completely invalidates the results obtained in this study.

Overall, the results obtained in this thesis contribute in the broader understanding of the AGN RM field as a whole.

## 8.1 Future Work

This section importantly, also covers lessons learned as part of this RM experiment, particularly, in the cases of PG 2304+043 and SDSS J132447.65+032432.6. In both campaigns, the SALT spectroscopic observations were triggered much later than the photometry and as a result missed the corresponding varying structures or patterns present in the continuum light curve. Ideally the spectroscopic monitoring campaign should be at least twice the expected delay. To address this, future observations will involve closely monitoring the photometric observations such that as soon as significant variability is detected in the photometry, an alert is created for immediate follow-up with spectroscopy. This ties well with the South African Astronomical Observatory plans to introduce Artificial Intelligence into the scheduling in the near future. Otherwise, as shown in this work, the lag measurements can be of limited use.

More observations of PG 2304+043 and SDSS J132447.65+032432.6 are required to improve the reliability of the lag measurements and therefore, to obtain better black-hole masses. This will also afford us the opportunity to constrain better the discrepancy between RM and SE-based masses, to investigate the role of the Eddington ratio in SE mass estimation. Future observations of SDSS J132447.65+032432.6 will also include the Mg II emission line for calibration with the  $H\beta$ -based mass and to add to the  $R_{\text{MgII}} - L$  sample.

Beyond the AGN sample presented here, there is a need to extend the sample to include high- $z$  AGNs. It is because the co-evolution of black-hole mass with its host-galaxy properties at large distances is least constrained. This is encouraged by the Rubin's observatory Legacy Survey of Space and Time (LSST) which is expected to generate large volumes of data per observation. It marks the new era of Astronomy which promises to answer some of the outstanding questions in the field of AGNs, including those highlighted in this thesis. The LSST will utilize six photometric bands (*ugrizy*) to produce high-quality photometric observations with precision of  $< 1\%$ , high cadence of  $\sim 2$  days over a multi-year period (Panda et al. 2019), suitable for photometric reverberation mapping. In the case of detected variability, there will be follow-up spectroscopic observations with SDSS-V Black Hole Mapper (Kollmeier et al. 2017), with the aim of determining the BLR size and black-hole mass. This will also help improve reverberation mapping measurements in terms of the uncertainty in the time-lag determination, stellar velocity dispersion measurements.

There is also an ongoing AGN Key project with Las Cumbres Observatory (LCO)(Valenti

[et al. 2015](#)), whose aims are highlighted in Section 1.9. There includes plans to publish previously collected data of AGNs spanning a wide redshift range. This is of importance in that it also includes Mg II observations to measure time delays, which currently are scarce.

AGN STORM (Space Telescope and Optical Reverberation Mapping) has an ongoing campaign called AGN STORM 2, a successor of AGN STORM 1. Its aim is to do intensive, multi-wavelength monitoring of a single AGN via observations emanating from HST, Swift and ground-based telescopes. Each telescope will probe different regions of the AGN structure (e.g., [Kara et al. 2021b](#)), thus broadening the wavelength coverage. This will help constrain the disc structure and provide better understanding of the origin of the X-ray variability and its correlation (if any) with UV/optical variability.

Noted in this thesis is the need to standardize lag reliability. Currently, each campaign has its own way of standardizing or determining lag significance. There is no level of consistency from campaign to campaign. This is important to settle especially considering the case of low S/N, poor sampling, or large temporal gaps in the light curves.



# Appendix A

## Equations

### A.1 Measuring the mass of a central body

From Newton's law of gravitation, the force of gravity between two bodies of mass  $M$  and  $m$  is

$$F = G \frac{Mm}{R^2}, \quad (\text{A.1})$$

where  $G$  is the gravitational constant and  $R$  is the separation between the two bodies. The centripetal force acting on the body  $m$  in orbit is

$$F = \frac{mV^2}{R}. \quad (\text{A.2})$$

Equating the two forces gives the mass  $M$  of the central body

$$M = \frac{V^2 R}{G}. \quad (\text{A.3})$$

In other words, knowing the distance and the velocity of the orbiting body, one can measure the mass of the central body.



# Appendix B

## Plots

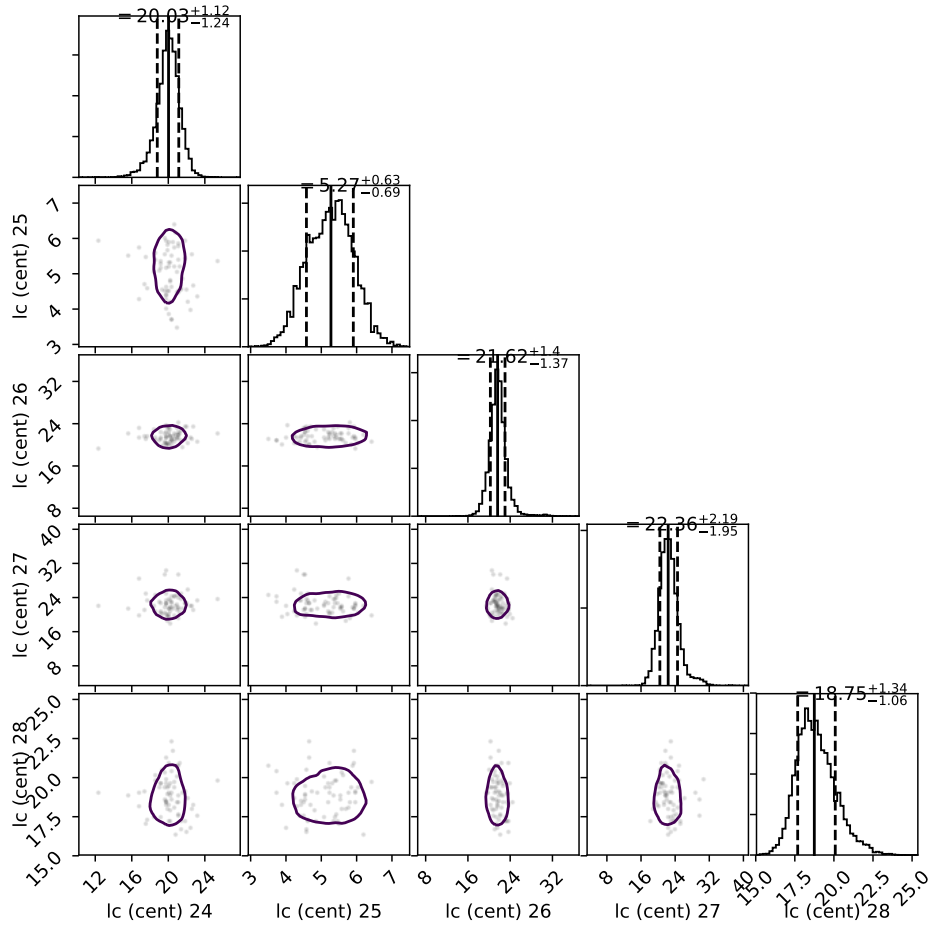


Figure B.1: Posterior probability histograms for BLR top-hat light curves, from top to bottom  $H\gamma$ , He II  $\lambda 4686$ ,  $H\beta$  (blue),  $H\beta$  (red) and He I  $\lambda 5876$ .

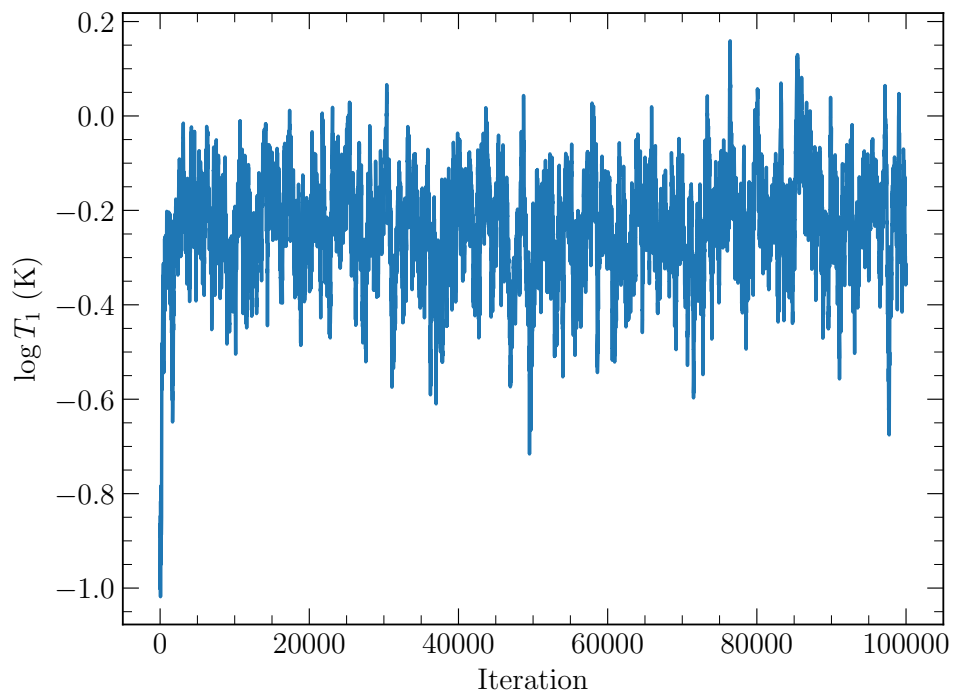


Figure B.2: Samples for temperature  $T_1$ .

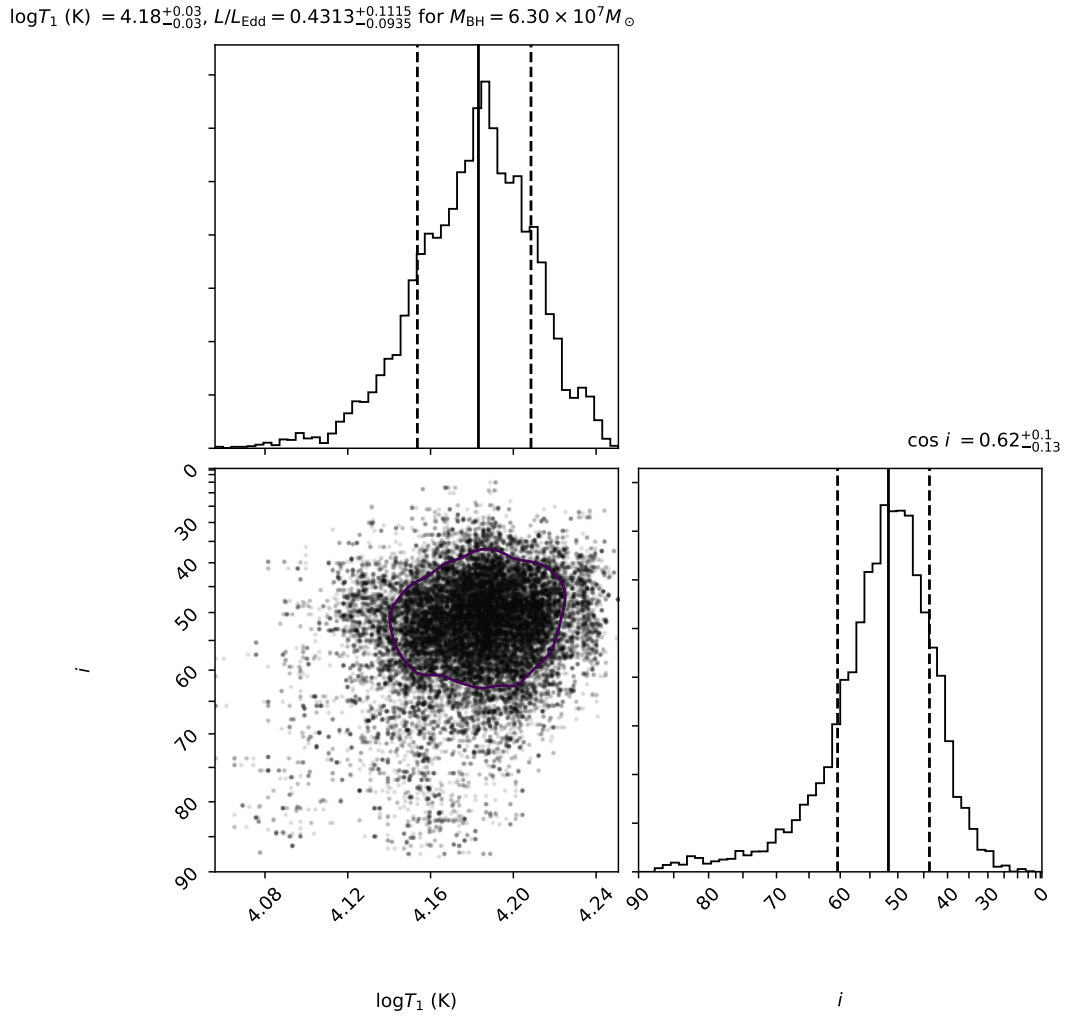


Figure B.3: Posterior probability distribution for  $T_1$  and inclination  $i$ .

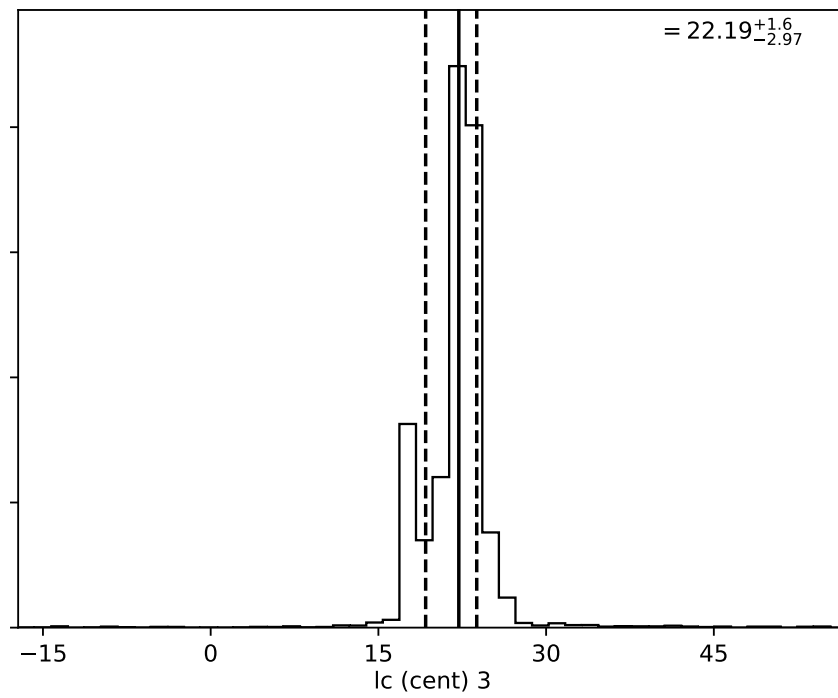


Figure B.4: Posterior probability histogram for  $H\beta$ .

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