

Reverberation Mapping Analysis of the 2016 HST Campaign on NGC 4593

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Abstract

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1. Introduction

Active galactic nuclei (AGNs) are among the most luminous objects in the universe, emitting radiation across the entire electromagnetic spectrum (Netzer 2013) and exhibiting strong variability on timescales ranging from hours to days (Ulrich et al. 1997). In contrast to inactive galaxies such as the Milky Way, the supermassive black hole (SMBH) in an active galaxy accretes matter from the central region. This process generates thermal emission from the accretion flow (Peterson 1997) and drives line emission through photoionization and subsequent recombination in the surrounding gas (Netzer 2013). These ionized line-emitting regions are commonly divided into the broad-line region (BLR) and the narrow-line region (NLR) (Peterson 1997). The BLR is located at close distances of light-days to a few light-years from the central SMBH (Goad et al. 2012) and rotates at high velocities of several thousand km, s^{-1} , which leads to strong Doppler broadening of the emission lines (Peterson 1997). In contrast, the NLR extends out to several hundred parsecs from the central region (Peterson 1997) with velocities of only a few hundred km, s^{-1} , resulting in comparatively narrow line profiles.

An interesting example of this class of objects is the barred spiral galaxy NGC 4593. It shows pronounced variability from the X-ray to the optical bands (McHardy et al. 2017; Cackett et al. 2018) and exhibits several prominent broad emission lines, including Balmer and helium lines, as well as low-ionization lines like $\text{O I } \lambda 8446$ (Kollatschny & Dietrich 1997; Cackett et al. 2018; Ochmann et al. 2025). Several studies on NGC 4593 have analyzed the structure and kinematics of its broad-line region (e.g. Kollatschny & Dietrich 1997; Denney et al. 2006; Cackett et al. 2018) using reverberation mapping (RM) of the broad emission lines. This method uses measurable time delays between variations in the ionizing continuum and the response of the line-emitting gas to infer the characteristic size and geometry of the broad-line region (Peterson 1993).

In a recent study, Cackett et al. 2018 carried out an observation campaign using the Hubble Space Telescope (HST) with the Space Telescope Imaging Spectrograph (STIS), between 12 July and 6 August 2016, on NGC 4593 covering wavelength

ranges of approximately $1100 \text{ \AA} - 1700 \text{ \AA}$ and $3900 \text{ \AA} - 9000 \text{ \AA}$. This campaign focused on the reverberation of the accretion disk of NGC 4593 by analyzing the UV and optical continua (Cackett et al. 2018). However, a RM analysis of the BLR has not been attempted with this dataset. As a HST dataset, it is ideally suited for a RM analysis, thanks to its daily cadence and broad wavelength coverage. It allows a more detailed structural analysis of the BLR of NGC 4593 compared to earlier campaigns (Kollatschny & Dietrich 1997; Denney et al. 2006; Williams et al. 2018) by including broad emission lines to the analysis, which have not been monitored for NGC 4593 yet (e.g. UV emission lines).

Furthermore, NGC 4593 shows variability in the low-ionization $\text{O I } \lambda 8446$ line and the $\text{Ca II } \lambda 8498 \lambda 8542 \lambda 8662$ triplet (Ochmann et al. 2025), which have not been included in RM campaigns so far. The $\text{O I } \lambda 8446$ line is particularly interesting because its strength can be enhanced by Bowen fluorescence (Bowen 1947; Grandi 1980). Since it is covered by the Cackett et al. 2018 campaign, its variability and time lag to can be measured from a HST/STIS RM campaign for the first time.

2. Scientific Background

2.1 Active Galactic Nuclei

Active Galactic Nuclei (AGNs) refer to the central region of active galaxies. These objects are among the most luminous in the universe, with bolometric luminosities ranging from 10^{41} to 10^{48} erg s $^{-1}$ that can outshine entire galaxies by several orders of magnitude (Peterson 1997). Historically, several stellar-based models were proposed for AGNs, such as dense star clusters or supermassive stars. However, these scenarios were discarded, as they are expected to collapse into black holes themselves, and they cannot provide the required energy output. Today, it is understood that the enormous luminosities of AGN are powered by accretion of matter onto a supermassive black hole (SMBH) at the centers of galaxies (Rees 1984). The most widely accepted model for this accretion is a hot, rotating accretion disk surrounding the SMBH, which produces most of the observed radiation (Shakura & Sunyaev 1973). The following sections will outline the key components of AGNs and their variability, which is central to reverberation mapping analysis.

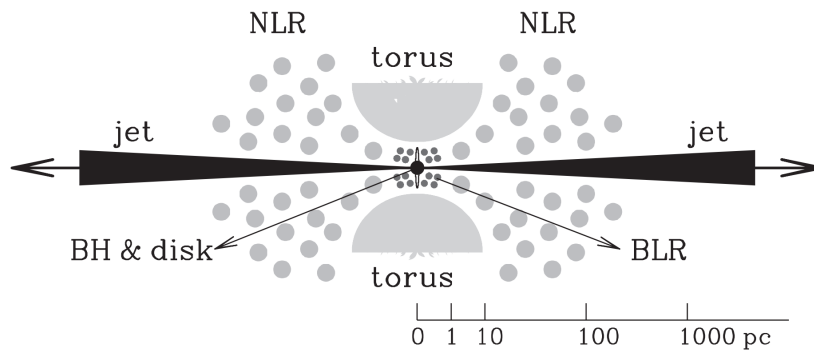


Figure 2.1: Different components of an AGN. Adopted from (Mo et al. 2010). Their Figure 14.3.

2.1.1 Geometric and Spectral Features of AGNs

According to the unified model, AGNs consists of a central supermassive black hole (SMBH), a surrounding accretion disk, a dusty torus and ionized gas regions known as the broad-line region (BLR) and narrow-line region (NLR) (Antonucci 1993). In some cases, relativistic jets are launched perpendicular to the plane of the accretion disk (Urry & Padovani 1995). A schematic illustration is shown in Figure 2.1. The following sections describe the physical components of AGN and the spectral features associated with them.

Supermassive Black Hole and Accretion Disk

The center of an AGN is defined by a supermassive black hole (SMBH), with typical masses between $10^6 M_\odot$ and $10^9 M_\odot$ (Peterson et al. 2004). It does not contribute to the AGN spectrum directly, but acts as the central engine driving observed spectral features of the AGN. It dominates the gravitational potential and, unlike inactive galaxies such as the Milky Way, it is surrounded by an accretion disk. Through viscous processes within the disk, such as turbulent friction and magneto-rotational instability, the angular momentum of the matter is transported outward, which leads to a spiraling inflow of matter toward the SMBH (Shakura & Sunyaev 1973). Several models have been proposed to describe the accretion process. The most widely used model is the geometrically thin and optically thick accretion disk, which consists of ionized gas in differential rotation around the SMBH (Shakura & Sunyaev 1973; Netzer 2013). The disk is composed primarily of ionized hydrogen and helium, with trace amounts of heavier elements (Netzer 2013). The radial extent of the disk is relatively small compared to galactic scales and typically ranges from a few light-hours to a few light-days, corresponding to about 10^{-3} to 10^{-2} pc (Shakura & Sunyaev 1973; Netzer 2013).

During the accretion process a substantial fraction of the gravitational energy of the matter is transformed into thermal radiation, which accounts for the enormous luminosity observed in AGNs and heats the accretion disk to high temperatures that depend on the mass of the SMBH (Netzer 2013). For example, the maximum effective temperature for an accretion disk around a SMBH with $M = 10^8 M_\odot$ is on the order of several $\times 10^5$ K, leading to UV and optical emission (Shakura & Sunyaev 1973; Netzer 2013). By contrast, disks around stellar-mass black holes reach much higher temperatures (up to a few $\times 10^6$ K), and therefore emit mostly in X-rays (Shakura & Sunyaev 1973; Netzer 2013). Due to the radial temperature gradient, the emitted spectrum cannot be described as a single blackbody. Instead, it results

from a superposition of many blackbody-like components at different temperatures, often referred to as a multicolour black-body (Netzer 2013). This produces a broad optical–UV continuum of ionizing photons, which interact with gas clouds near the nucleus and play a crucial role in shaping the spectral features of the broad-line and narrow-line region. These photons cause photoionization followed by recombination, which gives rise to the strong emission lines that are characteristic of AGN spectra (Netzer 2013).

Broad-Line and Narrow-Line Region

The ionized line-emitting gas clouds can be divided into the broad-line region (BLR) and the narrow-line region (NLR). Both regions differ in density, distance from the SMBH, and the observed line widths (Urry & Padovani 1995). The BLR is located close to the nucleus, at distances ranging from a few light-days to a few light-years from the central SMBH (Goad et al. 2012; see Figure 2.1). It consists of dense gas clouds with electron densities of $n_e \approx 10^{11} \text{ cm}^{-3}$, moving at velocities of several thousand km s^{-1} due to the strong gravitational influence of the SMBH. These velocities lead to significant Doppler broadening of permitted emission lines, with widths of $(500\text{--}10,000) \text{ km s}^{-1}$ (Peterson 1997). As described earlier, the BLR is photoionized by the continuum radiation emitted from the accretion disk. Consequently, the line emission from this region responds to changes in the continuum, leading to a strong correlation between the two, and strong variability (Netzer 2013). This relationship is particularly relevant for reverberation mapping, which will be discussed later in Section 2.2.

Modeling the geometry of the BLR is challenging because several emission lines have to be considered and their intensities vary in response to changes in the continuum radiation (Netzer 2013). A current basic concept locates the BLR just above the accretion disc, between the disc’s outer edge and the dusty torus (Gaskell 2009; Goad et al. 2012), with inflowing and outflowing gas (Czerny & Hryniewicz 2011) and a disc-like distribution (e.g. Williams et al. 2018). It also shows radial ionization stratification (Collin-Souffrin & Lasota 1988; Gaskell & Sparke 1986; Kollatschny et al. 2001), with higher-ionization lines found closer to the SMBH than lower-ionization lines. Typical broad emission lines include the Balmer, Lyman, and helium lines (Netzer 2013).

The narrow-line region (NLR) extends out to several hundred parsecs from the central region (Peterson 1997). The gas in this region moves at much lower velocities, resulting in emission lines with widths typically of order $(350\text{--}400) \text{ km s}^{-1}$

(Peterson 1997). In contrast to the BLR, the NLR exhibits both permitted and forbidden transitions. Forbidden lines, such as [O III] $\lambda 5007$, are prominent in the NLR because at its low densities ($n_e \sim 10^2\text{--}10^4\text{ cm}^{-3}$) collisional de-excitation is rare, allowing radiative decay from metastable levels (Peterson 1997). Due to its much larger extent compared to the BLR, the NLR responds only very slowly to variations in the ionizing continuum. Therefore, the flux of the narrow emission lines can be treated as constant over timescales of several years (Peterson 1993).

Because permitted emission lines can originate in both the BLR and the NLR, they often exhibit a multi-component line profile consisting of a broad and a narrow component (Peterson 1997). The relative strength of the broad and narrow components depends on the fractional contribution of emission from the BLR and the NLR, respectively (Peterson 1997).

Dusty Torus

Surrounding the accretion disk and the broad-line region is the dusty torus, a geometrically thick, optically dense structure composed of gas and dust. It extends from the radius at which dust can survive the intense radiation from the accretion disk out to scales of a few parsecs (Netzer 2013). The torus likely has a clumpy distribution and plays a crucial role in the unified model of AGNs (Urry & Padovani 1995; Netzer 2013). The dust in the torus absorbs a significant fraction of the UV and optical radiation emitted by the accretion disk and re-emits it thermally in the infrared. As a result, AGNs typically exhibit strong infrared emission, with the peak wavelength depending on the dust temperature in the torus (Netzer 2013). Even when the central region is hidden from direct view by the torus, this reprocessed infrared emission remains observable. It therefore provides a characteristic signature of obscured AGN activity and enables indirect constraints on the otherwise hidden central engine (Netzer 2013).

2.1.2 Classification

AGNs are classified into subgroups based on their spectral features. The key parameters for this classification are luminosity, emission-line profiles and radio properties. Based on those parameters AGNs get grouped into Seyfert galaxies, quasars and radio galaxies (Peterson 1997). Seyfert galaxies are further subdivided, based on the presence of broad and narrow emission lines (Peterson 1997), as discussed in the following section. Examples of other subclasses are narrow-line Seyfert 1 galaxies

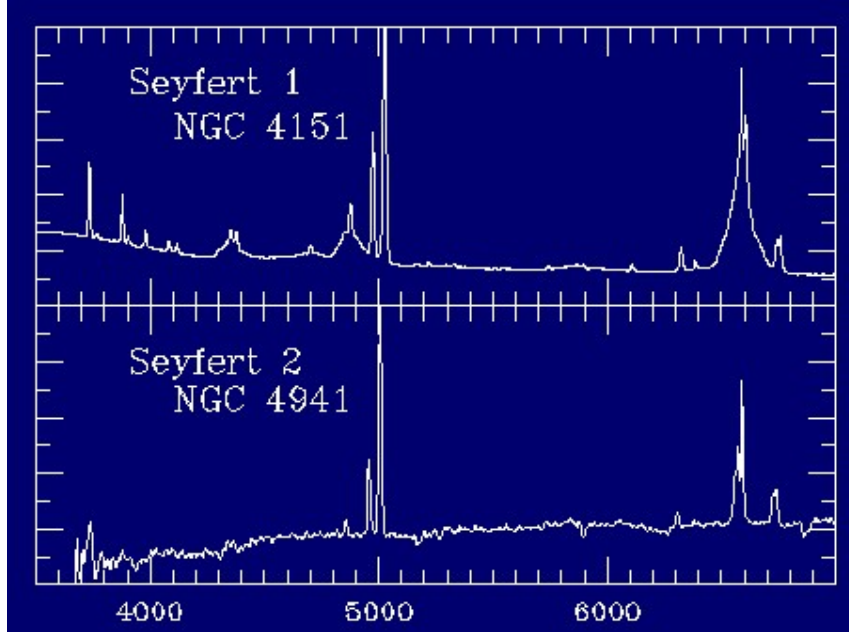


Figure 2.2: An example of Seyfert I and Seyfert II spectra illustrating their differences. Broad lines, such as $H\alpha$ and $H\beta$, are only present in the Seyfert I spectrum, whereas forbidden [O III] lines are visible in both cases. Adapted from Keel 2002.

(NLS1s), low-ionization nuclear emission-line regions (LINERs), and jet-dominated sources such as BL Lac objects or blazars (Antonucci 1993; Urry & Padovani 1995).

Seyfert Galaxies

Seyfert galaxies are named after Carl K. Seyfert, who in 1943 observed spiral galaxies characterized by exceptionally bright nuclei and strong emission lines in their optical spectra (Seyfert 1943). They are classified into the sub-classes Seyfert I and Seyfert II based on the presence of broad emission lines (Peterson 1997), which is demonstrated in Figure 2.2.

Seyfert I galaxies, show both broad and narrow emission lines in their optical spectra. Broad lines (e.g the Balmer line $H\alpha$) typically exhibit full widths at half maximum (FWHM) of several thousand kilometers per second and emerge from the fast-moving, high-density gas in the BLR (Peterson 1997). In contrast, narrow lines, including prominent forbidden transitions like [O III] $\lambda 5007$ or [N II] $\lambda 6584$, originate from the slow-moving, low-density gas in the NLR (Peterson 1997). An AGN showing both components in its spectrum is classified as a Seyfert I galaxy (Peterson 1997), as is the case which is the case for NGC 4593. Further details on NGC 4593 are provided in Section 3.1. Between the two main Seyfert classes, several intermediate subclasses (1.2, 1.5, 1.8, 1.9) are defined based on the relative strength of the broad and narrow Balmer-line components in the optical spectrum

(Osterbrock 1977; Osterbrock 1981; Peterson 1997). Seyfert 1.8 and 1.9 galaxies show very weak broad components. In Seyfert 1.9 objects, the broad component is visible only in the $H\alpha$ line, whereas in Seyfert 1.8 objects it is also detectable in $H\beta$. Furthermore, if the broad and narrow components in $H\beta$ are of equal strength, the AGN is classified as a Seyfert 1.5 (Peterson 1997). If the narrow component is even weaker than the broad component, it is classified as a Seyfert 1.2 (Osterbrock 1977).

Seyfert II galaxies lack broad-line emission in their optical spectra, most likely due to orientation-dependent obscuration by a dusty torus (Antonucci 1993; Peterson 1997). This implies that the classification of Seyfert galaxies depends strongly on the observer's viewing angle, which is a central element of the unified model of AGN (Antonucci 1993; Peterson 1997). The unified model is discussed in more detail in Section 2.1.3.

Another notable subclass of Seyfert galaxies is narrow-line Seyfert I galaxies (NLS1s). They are commonly defined by the comparatively small width of the typically broad $H\beta$ emission line ($\text{FWHM} < 2000 \text{ km s}^{-1}$) and weak $[\text{O III}] \lambda 5007$ emission relative to $H\beta$ (Osterbrock & Pogge 1985; Komossa 2007), and they typically show strong Fe II emission (Véron-Cetty et al. 2001). Strong Fe II emission often correlates with weak $[\text{O III}]$ emission and small Balmer-line widths, which provides strong constraints on the physical properties of the central region of an AGN and makes NLS1s of particular interest for study (Osterbrock & Pogge 1985; Komossa 2007).

Additional AGN Classes

In addition to Seyfert galaxies, there are several other classes of AGNs. Quasars (quasi-stellar objects) are more luminous than Seyfert galaxies, typically outshine their host galaxies, and are usually observed at higher redshifts (Netzer 2013). Because quasars show emission properties identical to those of Seyfert galaxies, the modern distinction is primarily based on luminosity: quasars are high-luminosity AGNs, whereas Seyfert galaxies occupy the lower-luminosity end (Netzer 2013).

Radio galaxies form another important AGN class, distinguished by their strong radio emission and prominent jets and are typically found in elliptical host galaxies (Netzer 2013). When their jets are aligned close to the observers line of sight, they are observed as blazars or BL Lac objects, which exhibit rapid variability and featureless optical spectra due to relativistic beaming (Netzer 2013).

Finally, LINERs are low-luminosity AGNs with spectra dominated by low-ionization emission lines. The physical origin of their ionization mechanism is still debated,

and in some cases, they may not be powered by accretion at all (Netzer 2013).

While these classifications are based primarily on spectral characteristics, many of the observed differences between AGN types can be attributed to orientation effects. The Unified Model of AGN provides a framework that explains this apparent diversity through a common internal structure, viewed from different angles.

2.1.3 Unification Model

Figure 2.3 illustrates the unified model of AGN proposed by Antonucci 1993. He argued that the observed differences among AGN spectra do not require fundamentally different intrinsic structures. Instead, they arise mainly from orientation of the central region towards the observer and from its obscuration by the dusty torus.

The figure shows how the same AGN would be classified depending on the observer's viewing angle. As mentioned above, the dusty torus plays a key role, as it surrounds the SMBH, the accretion disk and the fast-moving BLR. If the line of sight is blocked by the torus, the broad-line emission is obscured, resulting in a Seyfert II spectrum, exhibiting only narrow emission lines. In this geometry, the AGN is viewed at high inclination, with the torus intercepting the line of sight. If, on the other hand, the nucleus is viewed directly and is not obscured by the torus, both broad and narrow emission lines are observed in the spectrum, and the AGN is classified as a Seyfert I galaxy (Urry & Padovani 1995).

The same principle applies to other AGN classes. Quasars can be considered the high-luminosity counterparts of Seyfert galaxies, where orientation and torus obscuration likewise affect their observed properties. Blazars, are seen when the relativistic jet is aligned closely with the observer's line of sight, leading to strong Doppler boosting, which makes the radiation appear significantly brighter and shifted to higher frequencies than it intrinsically is (Urry & Padovani 1995).

Although the classical Unification Model treats AGN classification as fixed and purely geometry-driven, some AGNs have been observed to change their spectral type over time (e.g. Ricci & Trakhtenbrot 2023). These so-called "changing-look AGNs" demonstrate that a purely orientation-based interpretation, such as the Unification Model, cannot explain all observed phenomena. They suggest that intrinsic changes, such as variations in accretion rate or obscuring material, can also affect the classification (Ricci & Trakhtenbrot 2023).

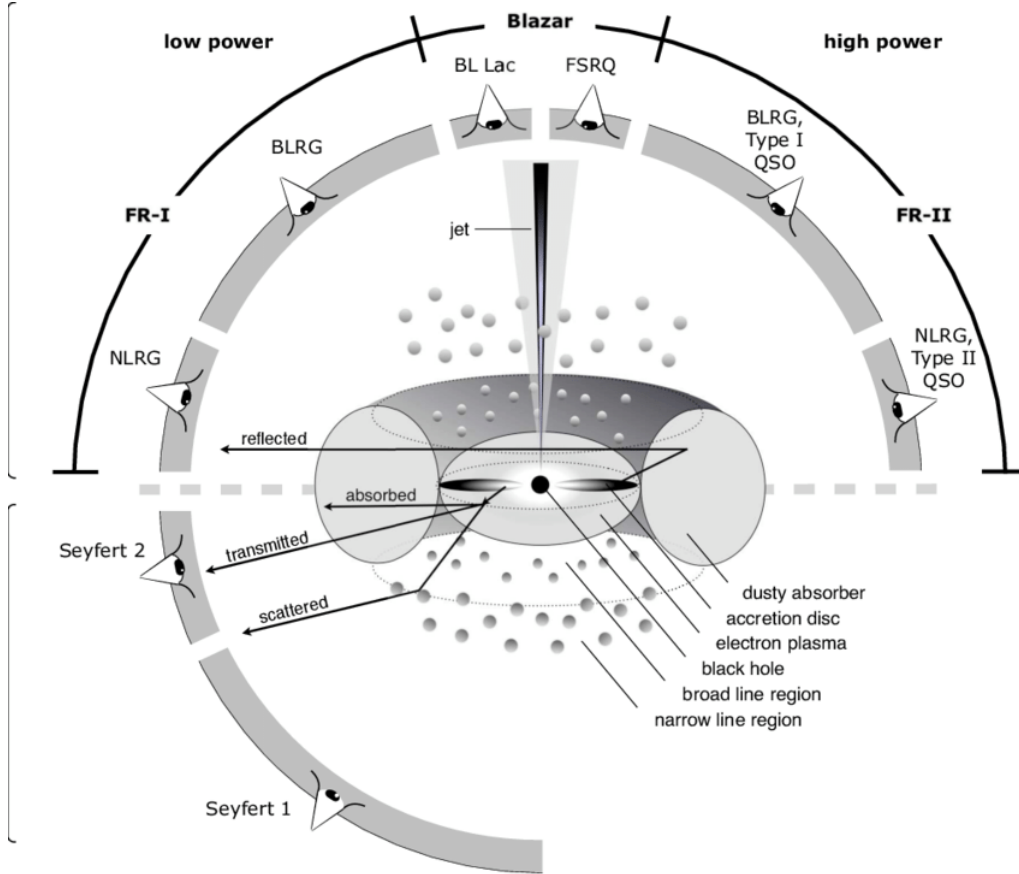


Figure 2.3: This graphic shows a schematic of the unification model of an AGN. The figure was adopted from Beckmann & Shrader 2013.

2.1.4 Variability

The variability of active galactic nuclei is one of the key aspects that enables the study of their central regions, which generally cannot be probed with conventional spatially resolved observations. Variability is observed on timescales ranging from hours to several years and is generally stochastic, resulting in flux variations of both emission lines and continuum emission of up to a few tens of percent in the UV and optical bands (Ulrich et al. 1997). Although the origin of this variability is not yet fully understood, the most widely accepted models attribute it to inhomogeneities and instabilities within the accretion disk (Ulrich et al. 1997; Dexter & Agol 2010). Depending on the underlying physical process, variations occur on different characteristic timescales. Processes such as thermal fluctuations or changes in the accretion flow happen on timescales of decades to centuries for typical SMBH masses and radii, and are therefore difficult to observe directly. In contrast, processes operating on shorter timescales are easier to study. Examples include gas motions and mechanical instabilities (e.g., sound waves) within the disk, which occur on timescales of weeks

to months (Ricci & Trakhtenbrot 2023). The shortest timescale is the light-crossing timescale, $t_{\text{lc}} = R/c$, which specifies how long light takes to traverse the emitting region (e.g. BLR) (Ricci & Trakhtenbrot 2023). Here, c denotes the speed of light, and R denotes the characteristic size or radius of the variable emitting region. Following Ricci & Trakhtenbrot 2023, assuming a SMBH of mass $\approx 10^8 M_{\odot}$, the light-crossing timescale can be written as

$$t_{\text{lc}} = \frac{R}{c} \simeq 0.87 \left(\frac{R}{150 r_g} \right) M_8 \text{ days}, \quad (2.1)$$

where $r_g = GM/c^2$ is the gravitational radius of the black hole. Thus, the light-crossing timescale of the variable emitting region is of order days, and t_{lc} scales linearly with the size of the emitting region (Ricci & Trakhtenbrot 2023).

Because variations in the ionizing continuum occur on such short timescales, it is possible to measure delayed responses from other regions within the AGN that are correlated with the continuum, using long-term monitoring campaigns (Peterson 1997). In particular, the BLR responds to changes in the photoionizing continuum radiation of the central source with a time delay (lag) that is longer than the light-crossing timescale of the emitting region (Peterson 1997). This lag forms the basis of classical reverberation mapping, which will be further elaborated in the next section.

2.2 Reverberation Mapping

The main focus of this work is a classical reverberation mapping analysis of the broad lines of NGC 4593. Reverberation mapping probes the structure of the BLR around the SMBH by measuring the time delay (lag) between continuum variations and the correlated response of the broad lines. This lag can be used to constrain the BLR geometry and to estimate the SMBH mass (Peterson 1993).

2.2.1 Principle of Reverberation Mapping

The fundamental assumption in reverberation mapping is that variations in the observed continuum flux are echoed by variations in the emission-line flux, with a measurable time delay (lag). When the continuum luminosity varies, the emission-line response follows with a measurable time lag (Peterson 1993). The time lag τ corresponds to the average light-travel time between the photo-ionizing continuum source and the line-emitting regions. Following the derivation of Peterson 1997, τ can be written as

$$\tau = (1 + \cos \theta) \cdot \frac{R_{\text{BLR}}}{c}, \quad (2.2)$$

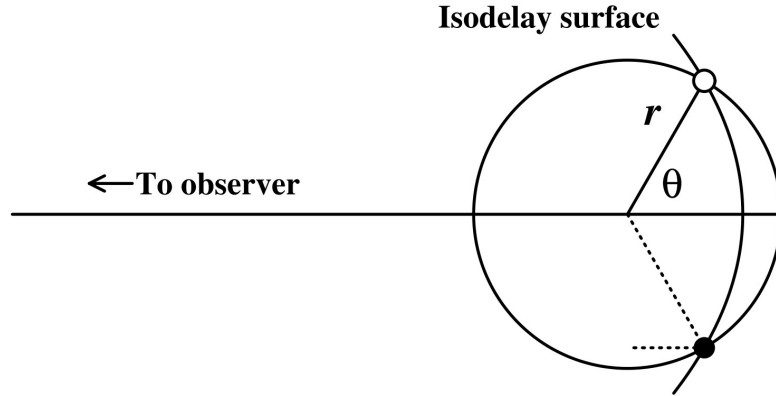


Figure 2.4: Spherical BLR model and an isodelay surface, adopted from (Peterson & Horne 2004).

where R_{BLR} is the characteristic BLR radius, c is the speed of light, and θ is the angle between the line of sight and the position vector of the emitting gas with respect to the central source (see Figure 2.4; Peterson 1997). The circle in Figure 2.4 represents the BLR modeled as spherical distribution of the clouds. For a fixed lag τ , the emitting regions that respond at that delay lie on a paraboloid aligned with the observer's line of sight, known as an isodelay surface. Therefore, emission observed at a given lag τ originates from the intersection of the BLR distribution with the corresponding isodelay surface (Peterson 1997). Thus, reverberation mapping can be used to "map" the BLR by inferring a characteristic BLR radius from the measured time lag (Peterson 1997). However, the observer receives emission from a range of delays (i.e., effectively from many isodelay surfaces), so the so-called transfer equation is required, which integrates over all delays (Peterson 1997):

$$L(t) = \int \Psi(\tau) C(t - \tau) d\tau. \quad (2.3)$$

Here, $\Psi(\tau)$ is the transfer function, which encodes the BLR geometry and kinematics, $C(t)$ is the continuum light curve, and $L(t)$ is the emission-line light curve (Peterson 1997). Although the BLR response is, in principle, fully described by the transfer function $\Psi(\tau)$, the lag is commonly estimated using cross-correlation techniques. In practice, recovering the full transfer function $\Psi(\tau)$ requires densely sampled, high signal-to-noise light curves spanning a duration much longer than the expected lag. Since real monitoring campaigns are often affected by observational gaps and noise, such reconstructions are rarely possible (Horne et al. 2004; Peterson 1993). For this reason, this project focuses on measuring the mean time lag between continuum and emission-line variations using the interpolated cross-correlation function (ICCF) method (Gaskell & Peterson 1987), which is well established in RM cam-

paigns (e.g. Kollatschny & Dietrich 1997; Denney et al. 2006; Williams et al. 2018; Probst et al. 2025).

2.2.2 Lag Measurement

Using the notation of Peterson 1997, the cross-correlation function between the ionizing continuum and an emission line is defined as

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

The auto-correlation function of the ionizing continuum is

$$F_{\text{ACF}}(\tau) = \int_{-\infty}^{\infty} C(t)C(t - \tau)dt. \quad (2.5)$$

Together with the transfer equation (Equation 2.3), the cross-correlation function can be written as the convolution of the transfer function and the auto-correlation function of the ionizing continuum:

$$F_{\text{CCF}}(\tau) = \int_{-\infty}^{\infty} \Psi(\tau')F_{\text{ACF}}(\tau - \tau')d\tau'. \quad (2.6)$$

The lag is commonly defined as either the peak location (τ_{peak}) or the centroid (τ_{centroid}) of the CCF (Peterson 1997). While τ_{peak} is defined as the location of the CCF maximum, τ_{centroid} is calculated over all CCF points above a selected threshold, typically 80% of the peak value. Because the CCF is closely related to the transfer function, it is possible to infer a characteristic BLR size associated with the emission-line response (Peterson 1997), which can be expressed as

$$R_{\text{BLR}} = c \cdot \tau_{\text{centroid}}. \quad (2.7)$$

This follows from the light-travel timescale (Peterson et al. 2004). Since the centroid lag is generally considered a more robust estimator of the mean BLR light-travel time of the BLR (Peterson et al. 2004), it is used in this project.

The uncertainty of the measured lag is estimated using a Monte Carlo approach combining flux randomization (FR) and random subset selection (RSS) (Peterson et al. 1998; Peterson et al. 2004). In the FR step, each flux value is randomly perturbed according to its measurement uncertainty. In the RSS step, N data points are drawn randomly with replacement, while duplicate selections are discarded, resulting in a new light curve with $M \leq N$ points. For each realization, the ICCF analysis is

repeated, yielding a distribution of centroid lags. The uncertainties are estimated from the distribution of centroid lags obtained from the simulations (Peterson et al. 2004). The 16th and 84th percentiles of this distribution are adopted as the bounds of the 1σ confidence interval (Peterson et al. 1998).

2.2.3 Black Hole Mass

The reverberation mapping method can be used not only to measure the characteristic size of the BLR, but also to estimate the mass of the central SMBH. Under the assumption that the gas dynamics in the BLR are dominated by the gravitational potential of the central SMBH, the black hole mass can be estimated using the virial theorem (Peterson et al. 2004).

The centroid time lag τ_{centroid} provides an estimate of the characteristic BLR radius via Equation 2.7. Together with the velocity dispersion ΔV of the BLR gas, the virial mass is given by

$$M_{\text{vir}} = \frac{R_{\text{BLR}} \Delta V^2}{G}. \quad (2.8)$$

The black hole mass is then given by

$$M_{\text{BH}} = f \cdot M_{\text{vir}}. \quad (2.9)$$

Here, G denotes the gravitational constant, and f is a scale factor that accounts for the unknown geometry, kinematics, and inclination of the BLR (Peterson et al. 2004). The velocity dispersion ΔV can be estimated from the widths of the broad emission lines (Peterson et al. 2004).

The scale factor f is calibrated by matching reverberation-based black hole masses to the empirical $M_{\text{BH}} - \sigma_*$ relation observed in inactive galaxies, where σ_* denotes the stellar velocity dispersion of the galactic bulge (Onken et al. 2004). Different studies have reported values of f based on various AGN samples, for example, $f = 5.5$ (Onken et al. 2004), $f = 4.31$ (Grier et al. 2013), and $f = 3.6$ (Graham et al. 2011). The calibration of the scale factor also depends on the measurement method used for the line width of the broad emission lines (Peterson et al. 2004). Two commonly used measures are the line dispersion σ_{line} (see Peterson et al. 2004) and the FWHM. As this work focuses on the FWHM measures and the previously named scale factories were estimated with the line dispersion measure, a average scale factor of $f = 1.8$ gets adopted, following Probst et al. 2025. This value bases on the average scale factor $f = 3.6$ reported by Graham et al. 2011 and takes the relation $\text{FWHM}/\sigma_{\text{line}} \approx 2$ Peterson et al. 2004 into account.

2.3 Bowen Fluorescence of O I λ 8446

Previous studies of NGC 4593 report strong emission in the low-ionization lines O I λ 8446 and the Ca II λ 8498 λ 8542 λ 8662 triplet (Ochmann et al. 2025). In particular, O I λ 8446 is of interest because it can be enhanced through a fluorescence mechanism referred to as Bowen fluorescence (Bowen 1947; Grandi 1980). The mechanism was first described by I.S. Bowen in 1934 to explain unexpected emission lines in nebular spectra. This mechanism describes a resonant line-pumping process in which photons emitted by one ion are absorbed by another ion of a different species via a permitted transition enabled by a near coincidence in wavelength between the pumping line and the absorbing transition. The resulting de-excitation leads to an enhancement of the emission lines (Bowen 1934).

One transition that can be enhanced by Bowen fluorescence is O I λ 8446, which can be pumped by Ly β photons (Bowen 1947; Netzer & Penston 1976). In this process, Ly β photons at λ 1025.72 Å are absorbed by neutral oxygen through the near-resonant transition $2p^4\ ^3P_2 \rightarrow 3d\ ^3D^0$ of O I at λ 1025.77 Å. The excited $3d\ ^3D^0$ level decays to $3p\ ^3P$, which then decays to $3s\ ^3S^o$, emitting the O I λ 8446 emission line (see Figure 2.5; Grandi 1980). This provides an additional excitation channel for O I λ 8446, in addition to recombination, continuum fluorescence or collisional excitation.

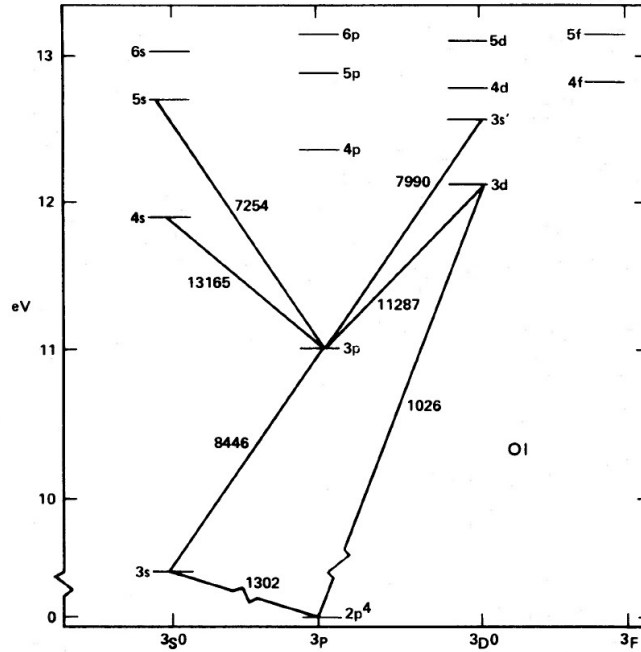


Figure 2.5: Energy level diagram displaying the process of Bowen fluorescence pumping of O I, adopted from (Grandi 1980).

3. Campaign and Data Preparation

The analysis of this campaign is based on the HST dataset of the observation campaign of NGC 4503 in 2016 (PI: Cackett, E.M, Prop ID 14121). This campaign took place between the 12th of July and the 6th of August with daily observations, which resulted in 26 successful out of 27 observations. It was performed with the Hubble Space Telescope (HST) using the Space Telescope Imaging Spectrograph (STIS) with the three different Gratings. The following section will cover an overview of the properties and specifications of NGC4593 and the campaign in 2016.

3.1 NGC4593

NGC 4593 is classified as a Seyfert 1 galaxy with a barred spiral morphology of type (R)SB(rs)b (Denney et al. 2006). It is located at RA = $12^{\text{h}}39^{\text{m}}39.44^{\text{s}}$, Dec = $-05^{\circ}20'39.03''$ (J2000) and has a redshift of $z = 0.0083 \pm 0.0005$, corresponding to a distance of ~ 35.9 Mpc (NED 2025) assuming a Λ CDM cosmology. The galaxy exhibits a prominent large-scale bar and nuclear dust ring connected to dust lanes along the bar, as seen in Figure 3.1.

The AGN in NGC 4593 exhibits strong broad emission lines, including Balmer and Lyman lines as well as He, O, and Ca lines among others (Kollatschny & Dietrich 1997; Denney et al. 2006; Cackett et al. 2018; Ochmann et al. 2025). Several variability and reverberation-mapping campaigns have monitored different broad emission lines(e.g. Dietrich et al. 1994; Kollatschny & Dietrich 1997; Denney et al. 2006. They reported FWHM values from the mean (AVG) and root-mean-square (RMS) spectra of their respective campaigns. The RMS spectrum is defined as the standard deviation of the flux at each wavelength across epochs:

$$F_{\text{RMS}}(\lambda) = \sqrt{\frac{1}{N-1} \sum_{i=1}^N [F_i(\lambda) - \bar{F}(\lambda)]^2}, \quad (3.1)$$

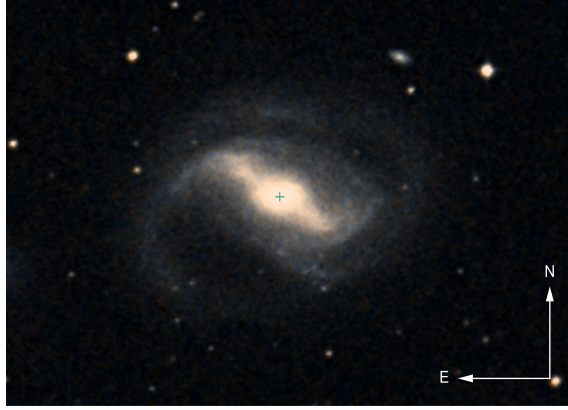


Figure 3.1: Screenshot of NGC 4593 visualized with Aladin Lite (*Aladin Lite* 2025) using DSS2 survey imagery (STScI 2025). The image is oriented with north up and east to the left. Right ascension increases to the left and declination increases upward.

with the mean spectrum at wavelength λ given by

$$\bar{F}(\lambda) = \frac{1}{N} \sum_{i=1}^N F_i(\lambda). \quad (3.2)$$

Kollatschny & Dietrich 1997 measured $\text{FWHM}_{\text{AVG/RMS}} = (3400 \pm 200) \text{ km s}^{-1}$ for $\text{H}\alpha$, while Denney et al. 2006 reported for $\text{H}\beta$ $\text{FWHM}_{\text{AVG}} = (5142 \pm 16) \text{ km s}^{-1}$ and $\text{FWHM}_{\text{RMS}} = (4141 \pm 416) \text{ km s}^{-1}$. Based on these broad-line widths, they estimated the SMBH mass to be $M \approx 1.4 \times 10^7 M_{\odot}$ (Kollatschny & Dietrich 1997) and $M = (9.8 \pm 2.1) \times 10^6 M_{\odot}$ (Denney et al. 2006). Overall, these results suggest that the SMBH mass is of order $10^7 M_{\odot}$.

Furthermore, NGC 4593 shows a rare double-peaked emission-line complex involving $\text{O I } \lambda 8446$ and the $\text{Ca II } \lambda 8498, \lambda 8542, \lambda 8662$ triplet (Ochmann et al. 2025). Ochmann et al. 2025 found that the Ca II triplet has an intensity ratio of 1:1:1 and line profiles that closely resemble those of $\text{O I } \lambda 8446$, exhibiting a red-to-blue peak ratio of 4:3 and a FWHM of $\approx 3700 \text{ km s}^{-1}$, suggesting that these lines originate in a similar high-density emission region. A fit of the asymmetric line profile of $\text{Ca II } \lambda 8662$ with an elliptic accretion disk model, shows an eccentric of $e \approx 0.22$ and a low-inclination of $i \approx 11^\circ$.

3.2 The 2016 HST Campaign

The HST campaign (PI: Cackett, E.M, Prop ID 14121) was designed to study wavelength-dependent continuum lags. It took place between the 12th of July and the 6th of August with daily observations, which resulted in 26 successful out of 27

observations. Observations were carried out with the Hubble Space Telescope (HST) using the Space Telescope Imaging Spectrograph (STIS) and three different gratings. The low-resolution STIS gratings provided continuous spectral coverage over a broad wavelength range of approximately $1100 \text{ \AA} - 1700 \text{ \AA}$ and $3900 \text{ \AA} - 9000 \text{ \AA}$. In each observation, spectra were obtained using the G140L, G430L, and G750L. All spectra were acquired with the $52'' \times 0.2''$ slit.

The characteristics of the STIS gratings used in this work are summarized in Table 3.1. After standard pipeline processing, charge-transfer inefficiency (CTI) corrections were applied using an algorithm based on (Anderson & Bedin 2010). The remaining hot pixels were removed manually by M. Ochmann.

We retrieved 27 spectra from the *Hubble Advanced Spectral Products (HASP)* 2025 archive using the HASP search form in *Mikulski Archive for Space Telescopes (MAST)* 2025. 26 of these spectra are usable for further analysis. The top panel of Figure 3.2 shows all spectra in the spectral range from 4000 \AA to 9000 \AA .

Table 3.1: Overview of STIS grating characteristics (STIS 2025).

| Grating | Range [\AA] | Exp. Time [s] | Res. Power | Dispersion [$\text{\AA}/\text{pixel}$] |
|---------|------------------------|---------------|-------------------|--|
| G140L | 1119–1715 | 1234 | ~ 1000 | 0.6 |
| G430L | 2888–5697 | 298 | $\sim 500 - 1000$ | 2.73 |
| G750L | 5245–10233 | 288 | $\sim 500 - 1000$ | 4.92 |

3.3 Intercalibration and Determination of AVG and RMS Spectra

For the subsequent analysis, the average spectrum (AVG) is obtained by averaging over all epochs, improving the signal-to-noise ratio (S/N). Furthermore it is essential for the reverberation mapping analysis to identify variability between the epochs, which can be assessed with the root-mean-square (RMS) spectrum, defined as the standard deviation of the flux at each wavelength across epochs (see. Equation 3.1). Constant features, such as narrow emission lines, vanish in the RMS spectrum, leaving only variable components such as broad emission lines. The top panel of Figure 3.2 shows the AVG and RMS spectra from the original retrieved data. Residual variability is still noticeable in nominally non-varying lines, particularly in the forbidden line $[\text{O III}] \lambda 5007$. This indicates small wavelength misalignment between epochs. Therefore, an intercalibration anchored to the narrow $[\text{O III}] \lambda 5007$ line was performed, which is common practice in RM campaign (e.g. Dietrich et al. 1994;

Denney et al. 2006). This was achieved by shifting the wavelengths of the individual spectra and scaling the [O III] $\lambda 5007$ line flux to a constant value. As a narrow line, the flux of [O III] $\lambda 5007$ can be assumed to remain constant over the timescale of the campaign. Based on this assumption, the [O III] flux in each spectrum was scaled to $(106 \pm 5) \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ and the wavelength was shifted by a maximum of 1 Å.

Figure 3.2 shows a comparison of the original and the intercalibrated epochs and the corresponding AVG and RMS spectra. The disappearance of narrow features in the calibrated RMS spectrum, especially the [O III] $\lambda 5007$ line, confirms that the apparent variability in the RMS of the original epochs was induced by the wavelength shifts between them, rather than intrinsic line variability. However the intercalibration was only applied to the optical part of the spectra, because a narrow-line flux calibration is only valid over a limited wavelength regime. In the following analysis, the intercalibrated AVG and RMS spectra are used for the optical range obtained with the G430L and G750L gratings, while the AVG and RMS spectra from the original epochs are used for the UV emission-line analysis, as these were acquired with the G140L grating.

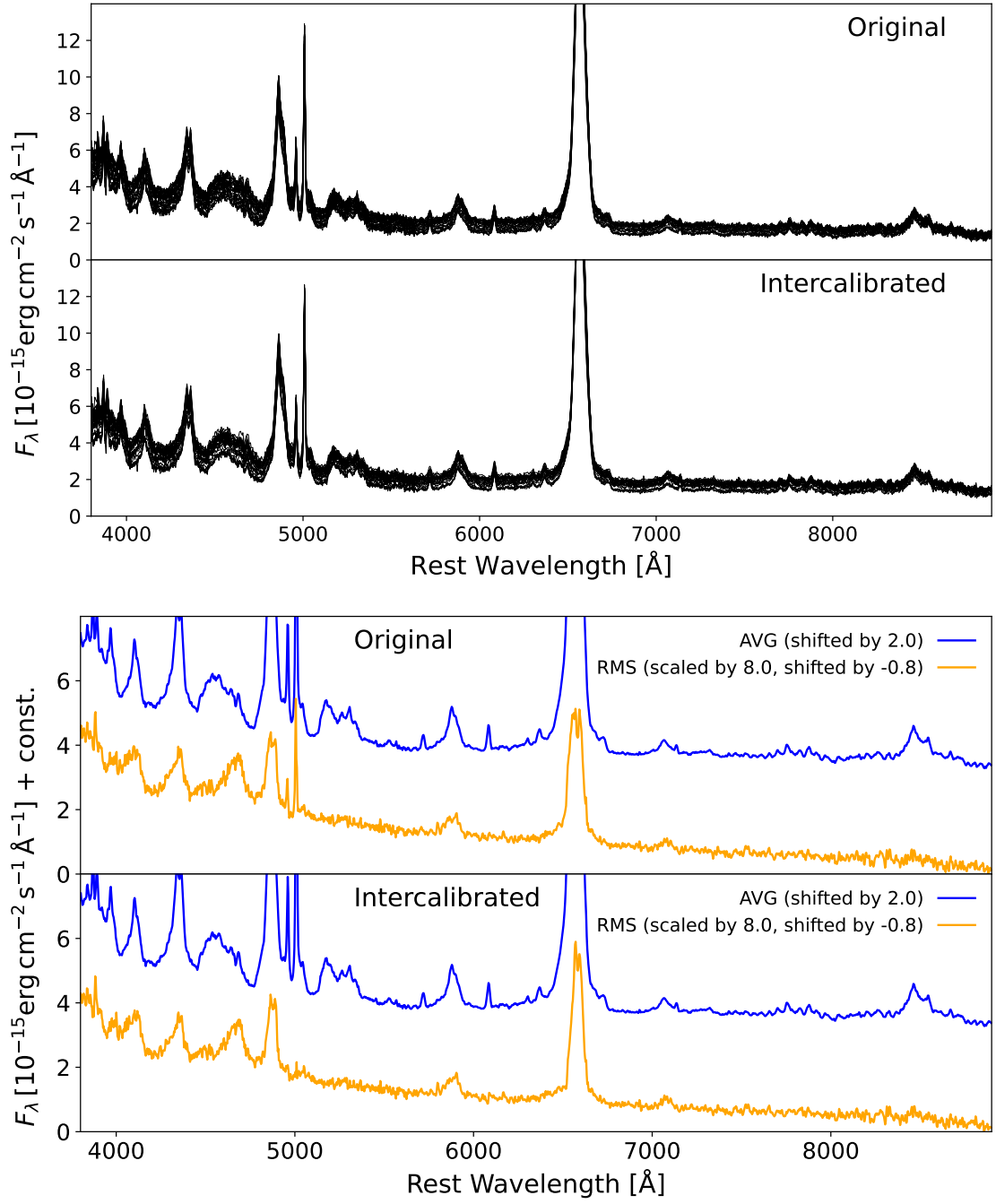


Figure 3.2: Comparison of the spectral range between 4000Å and 9000Å from the 2016 HST campaign of NGC 4593, showing the effects of [O III] λ 5007 intercalibration on both the individual spectra (top) and the derived average and rms spectra (bottom).

4. Reverberation Mapping Analysis of NGC4593

4.1 Line Identification

To begin the RM analysis, the emission lines in the AVG spectrum are identified. This is done for the optical–NIR range 3900 Å–9000 Å and for the UV range 1100 Å–1700 Å.

In the optical–NIR range (see Figure 4.1), several prominent broad emission lines are identified: Balmer lines from $H\alpha$ – $H\epsilon$; $\text{He I } \lambda 4471$, $\text{He I } \lambda 5016$, $\text{He I } \lambda 5876$ and $\text{He I } \lambda 7065$; $\text{He II } \lambda 4686$; and the low-ionization lines $\text{OI } \lambda 8446$ and the $\text{Ca II } \lambda 8498$ $\lambda 8542$ $\lambda 8662$ triplet. All of these lines show some level of variability in the RMS spectrum. For the subsequent analysis, the Balmer lines $H\alpha$ – $H\delta$, $\text{He II } \lambda 4686$ and $\text{He I } \lambda 5876$ are selected for the subsequent analysis, as they show the most pronounced variation in the RMS spectrum. Because the low-ionization line $\text{OI } \lambda 8446$ has rarely been included in RM studies and shows small but noticeable variability, it is included as well. Two prominent Fe II emission line bands are also present in the optical spectrum as well, one between $\sim 4489 \text{ Å} - 4629 \text{ Å}$, blending with $\text{He I } \lambda 4471$ and $\text{He II } \lambda 4686$, and another between $\sim 5169 \text{ Å} - 5336 \text{ Å}$. The AVG spectrum also shows several narrow forbidden emission lines, with $[\text{O III}] \lambda 4363$, $\lambda 4959$, and $\lambda 5007$ being the most prominent. As they are assumed to be constant over the timescale of the campaign, they show no significant variability in the RMS spectrum.

In the UV spectrum (Figure 4.2), five broad emission lines are identified, which will also be included in the subsequent analysis: $\text{Ly}\alpha$, which overlaps with the $\text{N V } \lambda \lambda 1238, 1242$ doublet; $\text{Si IV } \lambda \lambda 1393, 1402$; $\text{C IV } \lambda \lambda 1548, 1550$; and $\text{He II } \lambda 1640$. $\text{Ly}\alpha$ and $\text{C IV } \lambda \lambda 1548, 1550$ show strong variability, whereas $\text{N V } \lambda \lambda 1238, 1242$ and $\text{He II } \lambda 1640$ vary more weakly but remain detectable. In the RMS spectrum, the variation of $\text{N V } \lambda \lambda 1238, 1242$ is overlapping with $\text{Ly}\alpha$ emission, but is still distinguishable. Similarly, the $\text{He II } \lambda 1640$ variability overlaps with the semi-forbidden $[\text{O III}] \lambda \lambda 1660, 1666$ doublet.

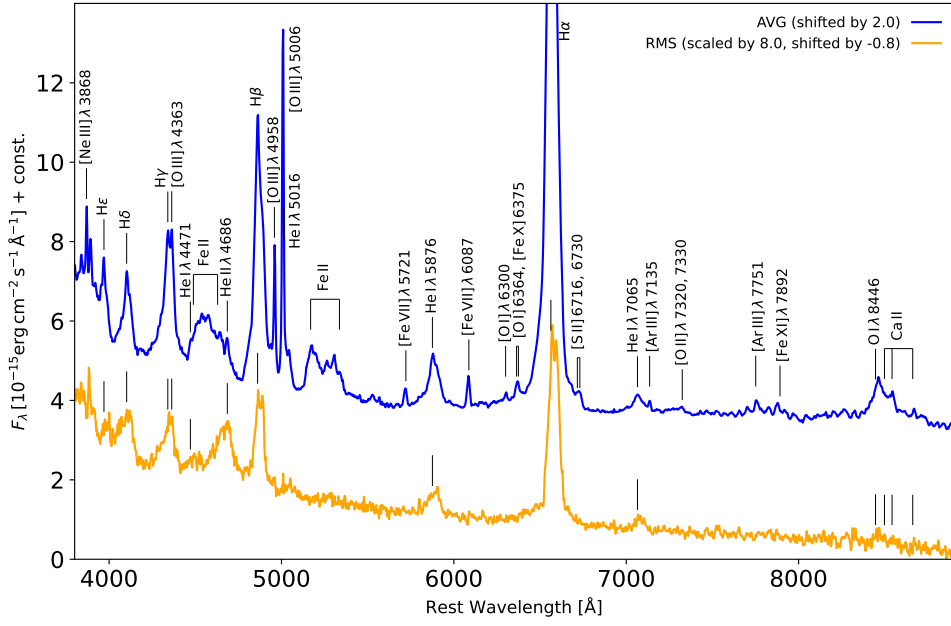


Figure 4.1: Optical-to-NIR AVG and RMS spectrum with identified emission lines.

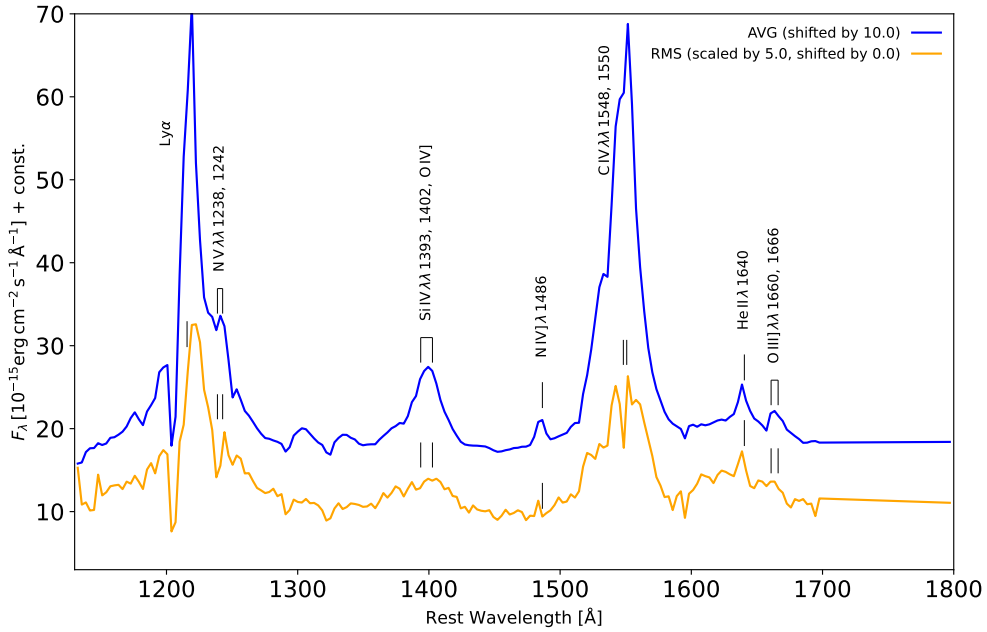


Figure 4.2: UV spectrum AVG and RMS spectrum with identified emission lines

4.2 Emission Line and Continua Measurement

After identifying and selecting suitable emission lines for the subsequent analysis, their fluxes and light curves are measured. This is performed using a Python-based tool called GECHO, developed by M. Probst. This tool is able to import full campaigns, determine AVG and RMS spectra, extracting lightcurves and conduct further measurements, naming here line-width measurements and lags measurement based on the methods of Gaskell & Peterson 1987 and Peterson et al. 2004. These methods are discussed further in Sections 4.4 and 4.5.

The extraction of the light curves with GECHO follows the same principle as in previous RM campaigns (e.g. Kollatschny & Dietrich 1997; Probst et al. 2025). Figure 4.3 shows the GECHO graphical user interface (GUI), which provides a side-by-side view of the campaign’s AVG and RMS spectra. The line flux at each epoch is obtained by integrating the flux density over the wavelength range, marked in red in Figure 4.3. The integration boundaries are chosen to include the variable part of the emission line while excluding contributions from neighbouring lines. To account for the surrounding continuum, a linear pseudo-continuum is estimated from two line-free wavelength windows on the blue and red side of the emission line, shown in grey in Figure 4.3. The adopted integration limits and pseudo-continua for each line are listed in Table 4.1.

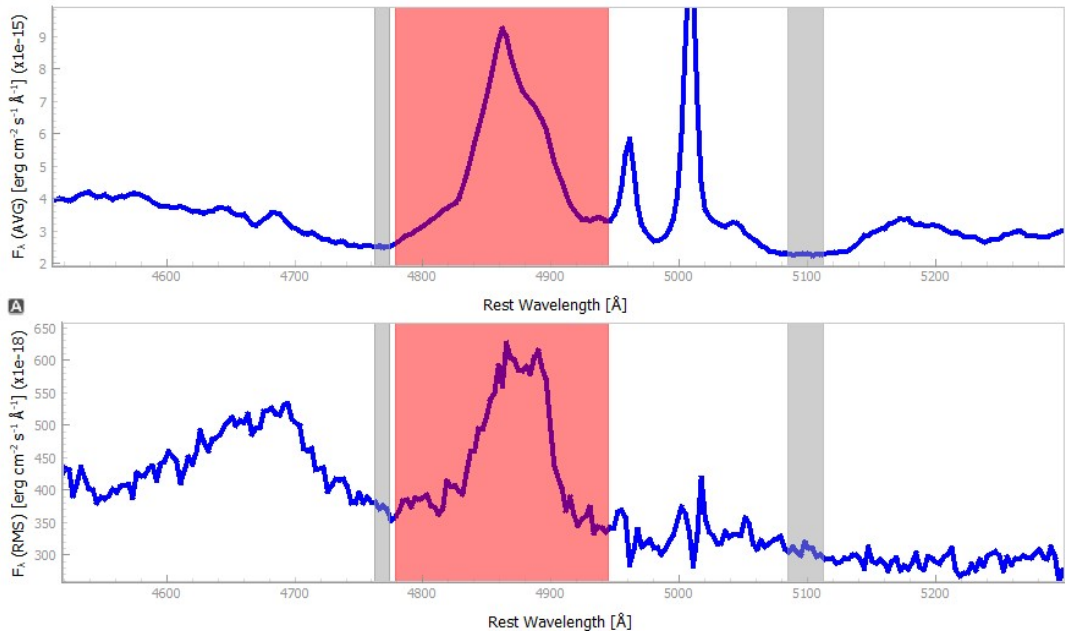


Figure 4.3: Screenshot of the GECHO graphical user interface (GUI). Shown is an example of the selection of the integration boundaries for $H\beta$ and corresponding blue and red pseudo-continuum used to measure the integrated line flux.

In addition to the emission line light curves, continuum light curves are also extracted to serve as a proxy for the variable ionizing continuum. The continuum windows are adopted from (Cackett et al. 2018), and their light curves are extracted with GECHO. The wavelength range for the continua are listed in Table 4.2.

Table 4.1: Integration Limits and Pseudo-Continua range of the measured emission lines

| Line | Integration Limits [Å] | Pseudo-Continua [Å] |
|-----------------------------------|-------------------------------|----------------------------|
| Ly α | 1207 – 1238 | 1151 – 1161, 1461 – 1469 |
| N v $\lambda\lambda$ 1238, 1242 | 1207 – 1238 | 1151 – 1161, 1461 – 1468 |
| Si iv $\lambda\lambda$ 1393, 1402 | 1358 – 1423 | 1151 – 1161, 1461 – 1469 |
| C iv $\lambda\lambda$ 1548, 1550 | 1511 – 1578 | 1461 – 1469, 1680 – 1685 |
| He II λ 1640 | 1599 – 1645 | 1461 – 1468, 1680 – 1685 |
| H α | 6453 – 6695 | 6107 – 6129, 6861 – 6900 |
| H β | 4779 – 4944 | 4762 – 4774, 5085 – 5112 |
| H γ | 4230 – 4427 | 4197 – 4220, 4435 – 4450 |
| H δ | 4035 – 4165 | 4026 – 4033, 4197 – 4220 |
| He I λ 5875 | 5742 – 6039 | 5645 – 5653, 6044 – 6057 |
| He II λ 4685 | 4545 – 4758 | 4435 – 4450, 4762 – 4774 |
| O I λ 8446 | 8380 – 8500 | 8005 – 8031, 8850 – 8955 |
| O III λ 5007 | 4982 – 5033 | 4762 – 4774, 5085 – 5112 |

Table 4.2: Wavelength range of the measured continua

| Line | Integration Limits [Å] |
|-------------|-------------------------------|
| Cont. 1150 | 1151 – 1161 |
| Cont. 4010 | 4026 – 4033 |
| Cont. 4440 | 4435 – 4450 |
| Cont. 5100 | 5085 – 5112 |
| Cont. 6110 | 6107 – 6129 |
| Cont. 6880 | 6861 – 6900 |
| Cont. 8015 | 8005 – 8031 |
| Cont. 8900 | 8864 – 8955 |

4.2.1 Variability Statistics

To quantify the variability of the emission lines and continua variability statistics the definition by Rodriguez-Pascual et al. 1997 are adopted. They name the maximum-to-minimum flux ratio R_{\max} and the fractional variability F_{var} as two common measures of variability. R_{\max} is defined as the ratio of the the extreme of the integrated

fluxes, F_{\min} and F_{\max} , and F_{var} as:

$$F_{\text{var}} = \frac{\sqrt{\sigma_F^2 - \Delta^2}}{\langle F \rangle} \quad (4.1)$$

Here, σ_F^2 denotes the standard deviation, $\langle F \rangle$ the mean flux and Δ^2 the mean square value of the flux uncertainties, which is defined by:

$$\Delta^2 = \frac{1}{N} \sum_{i=1}^N \Delta_i^2 \quad (4.2)$$

The results for all parameters can be found in the Tables 4.3.

First, considering R_{\max} and F_{var} of the continuum lightcurves, all measured continua show similar variability, except for the UV continuum around 1150 Å, which shows significantly higher variability with $R_{\max} = 2.58$ and $F_{\text{var}} = 0.28$ than the optical and NIR continua. These continua show a fairly uniform variation between $R_{\max} \simeq 1.33 - 1.59$ and $F_{\text{var}} \simeq 0.08 - 0.14$.

The lightcurves of the Balmer emission lines exhibit lower variability, which increases towards the higher-order Balmer lines, with values between $R_{\max} \simeq 1.15 - 1.52$ and $F_{\text{var}} \simeq 0.03 - 0.1$. The helium lightcurves show a similar variability to H δ with values between $R_{\max} \simeq 1.48 - 1.62$ and $F_{\text{var}} \simeq 0.09 - 0.11$ and the OI $\lambda 8446$ a similar variability to the Balmer lines with $R_{\max} \simeq 1.22$ and $F_{\text{var}} \simeq 0.04$.

The variability of the emission line lightcurves in the UV region is on a similar level as that of the helium light curves in the optical region, with $R_{\max} \simeq 1.42 - 1.62$ and $F_{\text{var}} \simeq 0.14$, with the exception of the He II, $\lambda 1640$ lightcurve, which shows significant higher variability with $R_{\max} \simeq 3.12$ and $F_{\text{var}} \simeq 0.31$.

4.2.2 Uncertainties Estimation

The uncertainties of the continuum and emission-line light curves are estimated based on the spectral noise and a systematic uncertainty introduced by the inter-calibration.

For the continuum light curves, the per-epoch noise is estimated as

$$\sigma_i^{\text{cont}} = \frac{\sigma_{f_i}}{\sqrt{N}}, \quad (4.3)$$

where σ_{f_i} denotes the standard deviation of the flux density within the selected continuum window in epoch i , and N is the number of pixels within that window. For the emission-line light curves, the noise is estimated from the scatter in the

interpolated pseudo-continuum, σ_i^{noise} , as

$$\sigma_i^{\text{line}} = \frac{\sigma_i^{\text{p.cont.}} \Delta\lambda}{\sqrt{N}}, \quad (4.4)$$

where $\Delta\lambda$ denotes the integration range of the emission line and N is the number of pixels across the integration window.

As each epoch has been scaled to the flux of the narrow [O,III] $\lambda 5007$ line after the intercalibration, the systematic uncertainty introduced by the intercalibration is estimated from its fractional variability, $F_{\text{var}}^{[\text{O III}] \lambda 5007}$. The total uncertainty of the measured flux at epoch i , f_i , is then

$$\sigma_i = \sqrt{(\sigma_i^{\text{cal.}})^2 + (\sigma_{\text{noise},i})^2}, \quad (4.5)$$

with

$$\sigma_i^{\text{cal.}} = F_{\text{var}}^{[\text{O III}] \lambda 5007} f_i. \quad (4.6)$$

Here, $\sigma_{\text{noise},i}$ corresponds to σ_i^{cont} for continuum light curves or to σ_i^{line} for emission-line light curves.

Table 4.3: Variability statistics of the measured continua and emission lines with minimum flux F_{\min} and maximum flux density or integrated flux F_{\max} , peak-to-peak ratio R_{\max} , mean $\langle F \rangle$, standard deviation σ_F and fractional variation F_{var} .

| Continuum/Line | F_{\min} | F_{\max} | R_{\max} | $\langle F \rangle$ | σ_F | F_{var} |
|-----------------------------------|------------|------------|------------|---------------------|------------|------------------|
| Cont. 1150 | 0.52 | 1.35 | 2.58 | 0.86 | 0.25 | 0.28 |
| Cont. 4010 | 2.68 | 4.21 | 1.57 | 3.49 | 0.47 | 0.14 |
| Cont. 4440 | 2.42 | 3.73 | 1.54 | 3.14 | 0.39 | 0.12 |
| Cont. 5100 | 1.77 | 2.77 | 1.57 | 2.29 | 0.3 | 0.13 |
| Cont. 6110 | 1.49 | 2.27 | 1.53 | 1.9 | 0.23 | 0.12 |
| Cont. 6880 | 1.33 | 2.01 | 1.5 | 1.72 | 0.2 | 0.11 |
| Cont. 8015 | 1.18 | 1.69 | 1.43 | 1.48 | 0.15 | 0.1 |
| Cont. 8900 | 1.14 | 1.52 | 1.33 | 1.38 | 0.11 | 0.08 |
| Ly α | 66.87 | 94.88 | 1.42 | 82.21 | 8.03 | 0.1 |
| N v $\lambda\lambda$ 1238, 1242 | 18.87 | 32.7 | 1.73 | 24.23 | 3.54 | 0.15 |
| Si iv $\lambda\lambda$ 1393, 1402 | 21.93 | 35.5 | 1.62 | 27.92 | 3.88 | 0.14 |
| C iv $\lambda\lambda$ 1548, 1550 | 115.31 | 165.57 | 1.44 | 138.77 | 12.12 | 0.09 |
| He II λ 1640 | 6.83 | 21.29 | 3.12 | 13.29 | 4.13 | 0.31 |
| H α | 130.83 | 149.85 | 1.15 | 141.35 | 4.83 | 0.03 |
| H β | 38.29 | 45.4 | 1.19 | 42.32 | 1.94 | 0.05 |
| H γ | 18.82 | 24.38 | 1.3 | 21.91 | 1.29 | 0.06 |
| H δ | 7.17 | 10.92 | 1.52 | 9.13 | 0.94 | 0.1 |
| He II λ 4685 | 11.93 | 17.7 | 1.48 | 14.82 | 1.6 | 0.11 |
| He I λ 5875 | 8.53 | 13.82 | 1.62 | 11.58 | 1.01 | 0.09 |
| O I λ 8446 | 7.47 | 9.13 | 1.22 | 8.32 | 0.37 | 0.04 |

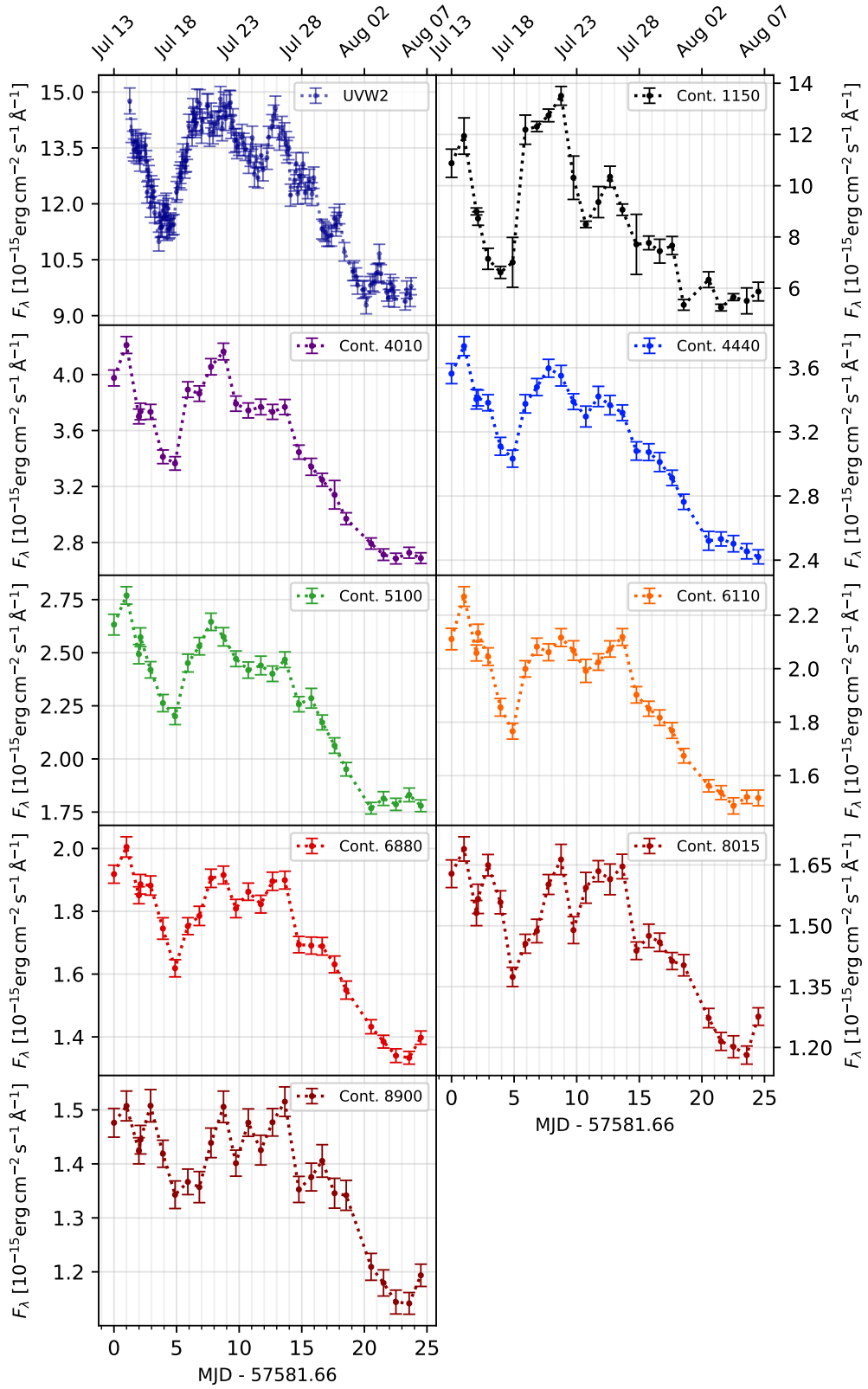


Figure 4.4: Comparison of the continua lightcurves. The first panel shows the UVW2 continuum lightcurve obtained from McHardy et al. 2018, while the other panels show the measured continua defined in Table 4.2

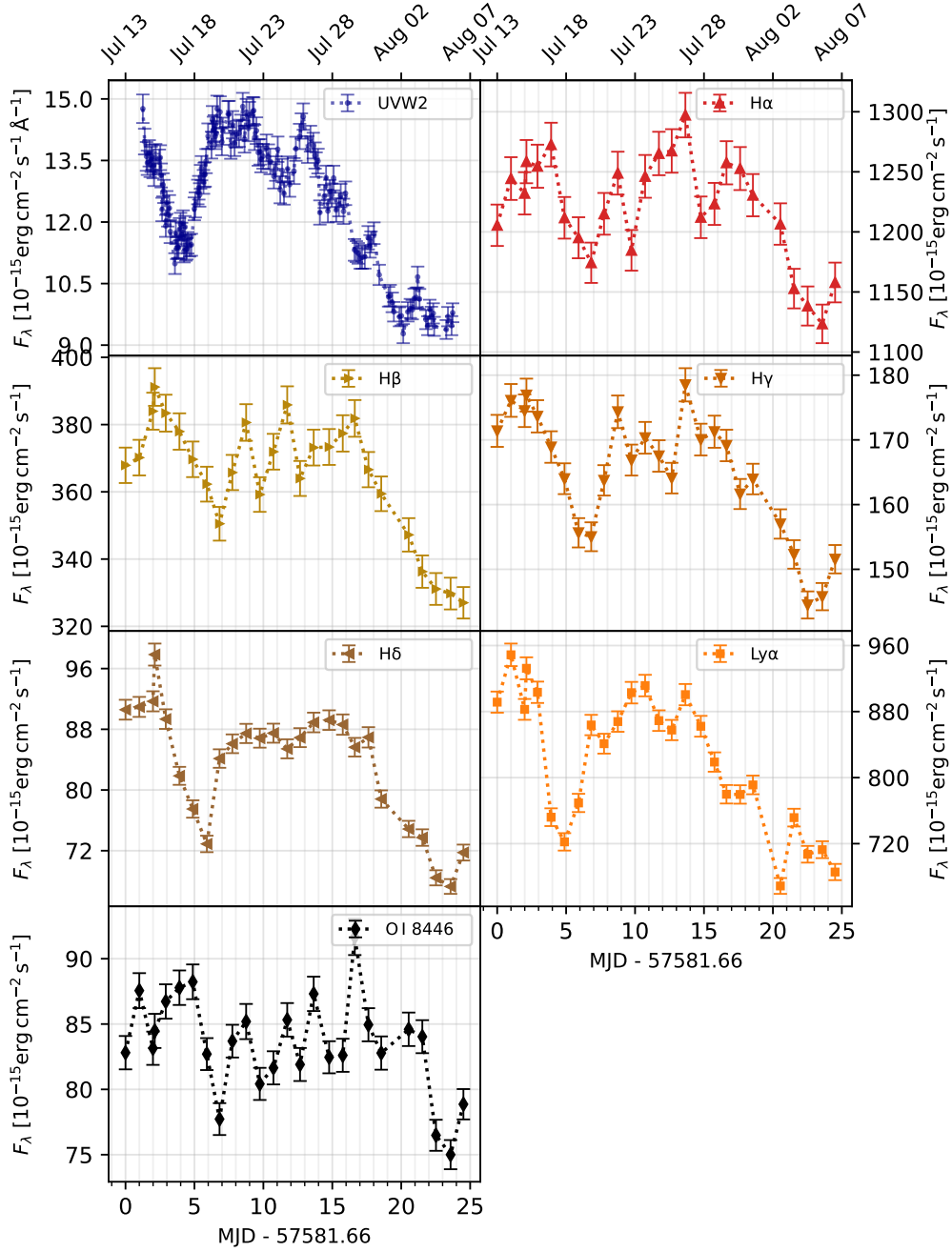


Figure 4.5: Comparison of the Balmer-line, Ly α , and O I λ 8446 light curves with the UVW2 reference light curve in the first panel. The UVW2 light curve is adopted from McHardy et al. 2018.

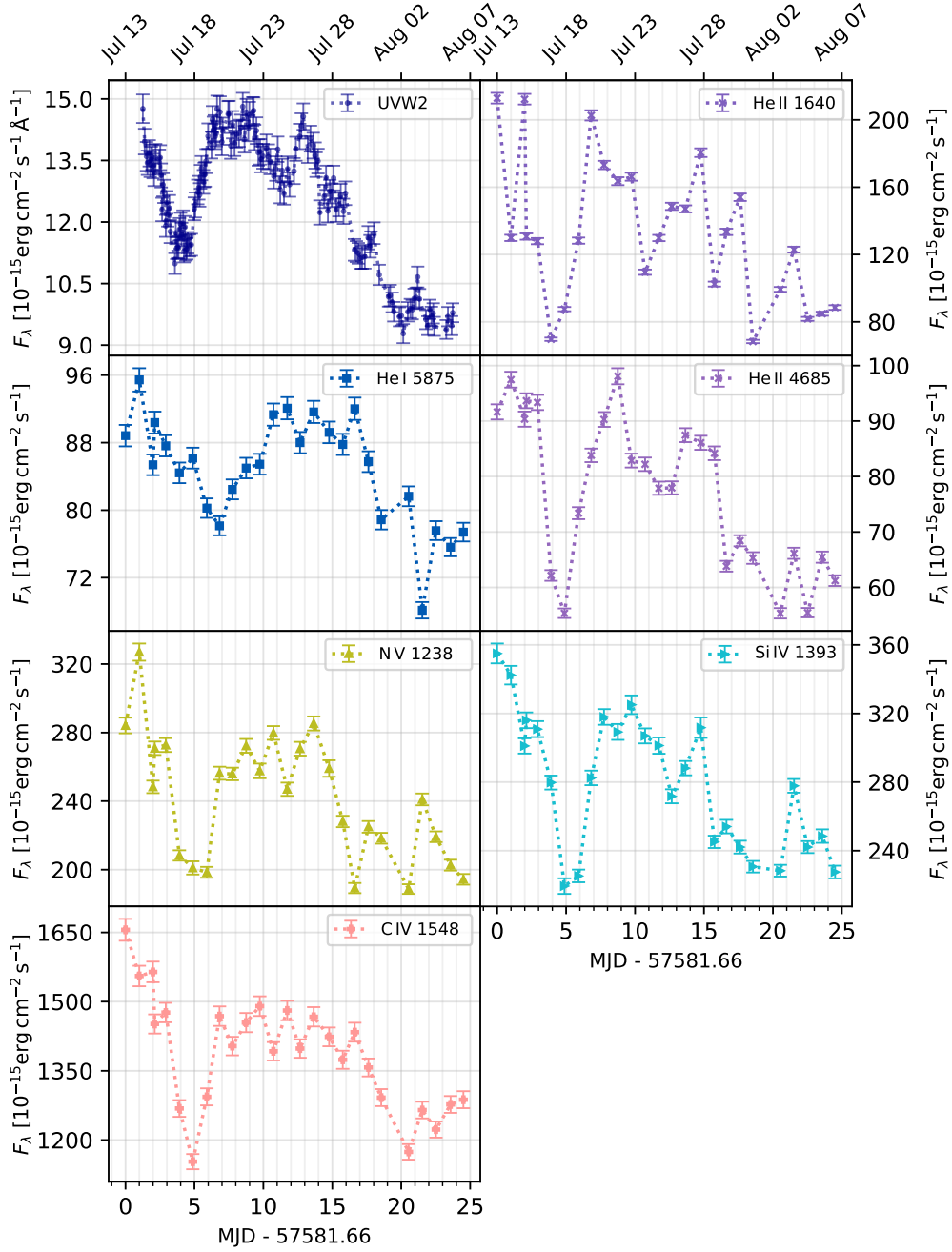


Figure 4.6: Comparison of the Helium and UV light curves with the UVW2 reference light curve in the first panel. The UVW2 light curve is adopted from McHardy et al. 2018.

4.3 Lightcurves

The extracted continuum and emission-line light curves are shown in Figures 4.4, 4.5, and 4.6. In addition to the extracted HST light curves, the UVOT UVW2 lightcurve is included in the subsequent analysis, which was taken with *Swift* by McHardy et al. 2018 and has also been used in Cackett et al. 2018. IT shows a higher sample size and was taken during nearly every orbit for 6.4 d between July 13 and July 18, 2016 (McHardy et al. 2018). The central wavelength of the UVW2 lightcurve is located at about 1930 Å (McHardy et al. 2018).

When compared, all continuum light curves show a broadly similar shape (see Figure 4.4). The light curves start at high flux and then decrease by about 50–80% relative to their maxima within the first 1–4 days, reaching a minimum between days 4 and 5. Afterwards, the flux increases again in all light curves. The UV continua show a plateau-like behaviour from days 6 to 9, followed by a smaller decline between days 9 and 13, before rising again to a peak around day 13. A similar pattern is also noticeable in the other continuum light curves, but becomes less clear at higher wavelengths. While the optical continua also show higher flux levels between days 6 and 9 than between days 9 and 13, the near-IR continua display a more scattered plateau over this interval. Towards the end of the campaign, the flux decreases again towards a minimum, with smaller short-term fluctuations, followed by a slight rise in the final days of the campaign in the UV and NIR bands.

The estimation of the physical distance between the SMBH and the region from which the emission lines originate is the main goal of this RM analysis. Assuming that the continuum radiation originates from the accretion disk, it is common to use the bluest available continuum as reference for the time lag estimation, which is expected to originate closest to the SMBH (Ochmann et al. 2026). In this analysis, this would be the continuum around 1150 Å. Nevertheless, the UVW2 continuum was selected as the main reference lightcurve for the subsequent analysis due to its higher sampling rate. To accommodate this, the delay between the UV continuum light curve around 1150 Å and the UVW2 light curve has to be taken into account. Figures 4.5 and 4.6 show the lightcurves of the measured broad emission lines in the optical-to-NIR range and in the UV range respectively. Overall, similarities to the shape of the UVW2 lightcurve are noticeable: A strong decrease in flux, followed by a central part with higher flux and a decrease towards the end of the campaign. The main exceptions are the O I λ 8446 and He II λ 1640 lightcurves, which are much more scattered than the others. Here, it has to be noted, that the integration boundaries of He II λ 1640 did not include parts of its red flank, as it is blended with the semi-

forbidden emission line doublet O III] $\lambda\lambda 1660, 1666$. Nevertheless, it is possible to notice a pronounced minimum similar to that in the UVW2 light curve in these curves.

By comparing these features, a shift of a few days between the light curves is already apparent. The flux minima of the Balmer lines, O I $\lambda 8446$, and He I $\lambda 5875$ occur between days 6 and 7, whereas the minima of the He II light curves and the UV emission lines Ly α , Si IV $\lambda\lambda 1393, 1402$, and C IV $\lambda\lambda 1548, 1550$ occur between days 4 and 5. This provides a first estimate of a time lag of about 2–3 days for the first group of emission lines and about 0–1 days for the second group. A more detailed investigation of the time lags is presented in Section 4.5.

4.4 Line Profiles

By analyzing the shape and line width of the emission line profiles it is possible to draw conclusions about the kinematics of their emitting region. Equally to the lightcurve extraction, a correction of the underlying continuum is necessary to enable comparison between the extracted profiles. Following the same procedure done for the lightcurves, an underlying linear continuum is interpolated, using line-free wavelength widows on the blue and red side for each emission line in both the AVG and RMS spectra. The selected boundaries of the pseudo-continua are listed in Table 4.4. By subtracting this interpolated continuum, a new zero-flux baseline for each line profile gets defined. Subsequently, the line profile is converted to velocity space using the relativistic Doppler equation

$$v_i = c \cdot \frac{\lambda_i^2 - \lambda_{\text{central}}^2}{\lambda_i^2 + \lambda_{\text{central}}^2}. \quad (4.7)$$

Here, λ_i denotes the wavelength values, λ_{central} the central wavelength of the emission line in rest-frame and c the speed of light. Finally, the flux is getting normalized to the maximum of each line profile. Figure 4.7 shows an overview of the extracted and normalized line profiles. For the doublet the rest-frame wavelength of the second line gets used as the central wavelength of the emission line.

4.4.1 FWHM

The height of the line profile is defined between its maximum and the zero-flux baseline. For line profiles which show clearly distinguishable flanks without overlapping profiles of neighboring lines, the measurement of their FWHM is performed

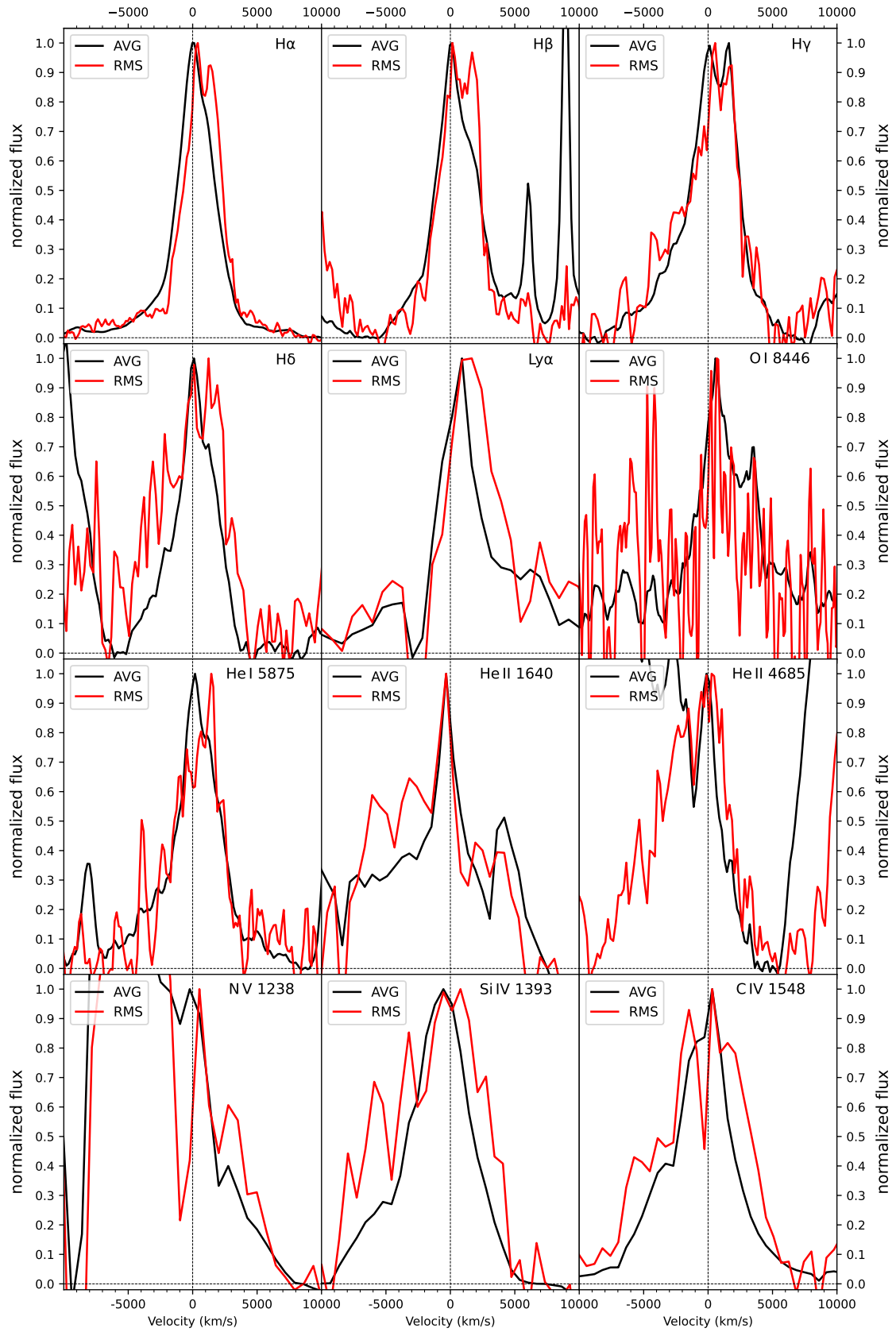


Figure 4.7: Normalized line profiles in the AVG and RMS spectra

Table 4.4: Boundaries of the blue and red pseudo-continua used for the interpolation of underlying continua for line profile extraction.

| Line | Pseudo-Continua (avg) [Å] | Pseudo-Continua (rms) [Å] |
|-----------------------------------|---------------------------|---------------------------|
| H α | 6194 – 6216, 6861 – 6900 | 6279 – 6301, 6742 – 6781 |
| H β | 4762 – 4774, 5085 – 5112 | 4762 – 4774, 4967 – 4984 |
| H γ | 4197 – 4220, 4435 – 4450 | 4197 – 4220, 4417 – 4429 |
| H δ | 4026 – 4033, 4197 – 4221 | 4006 – 4016, 4197 – 4211 |
| O I λ 8446 | 7999 – 8025, 8775 – 8798 | 8222 – 8238, 8748 – 8767 |
| He I λ 5875 | 5679 – 5697, 6044 – 6057 | 5736 – 5753, 6027 – 6045 |
| He II λ 1640 | 1461 – 1468, 1679 – 1685 | 1461 – 1468, 1679 – 1685 |
| He II λ 4685 | 4198 – 4225, 4762 – 4774 | 4543 – 4554, 4766 – 4778 |
| Ly α | 1151 – 1161, 1270 – 1285 | 1151 – 1161, 1340 – 1355 |
| N V $\lambda\lambda$ 1283, 1242 | 1151 – 1161, 1270 – 1285 | 1151 – 1161, 1340 – 1355 |
| Si IV $\lambda\lambda$ 1393, 1402 | 1350 – 1360, 1430 – 1440 | 1340 – 1355, 1430 – 1440 |
| C IV $\lambda\lambda$ 1548, 1550 | 1461 – 1468, 1679 – 1685 | 1461 – 1468, 1679 – 1685 |

with GECHO. This is done by linear interpolation between the two intersections of the line profile at the height 0.5. If no data point is found at exactly 0.5, the two neighboring points are used to linearly interpolate the velocity at the cross-section of at 0.5.

The line profiles of Ly α , the Balmer lines, He I λ 5875, C IV $\lambda\lambda$ 1548, 1550, Si IV $\lambda\lambda$ 1238, 1242 and He II λ 1640 show a distinguishable line profile at half height in both their AVG and RMS spectra. For the line profile of He II λ 4685 this only applies to its RMS profile, as its blue flank of its AVG profile is blended by the Fe II band between 4489 Å and 4629 Å. The FWHM measurement for the previous named emission lines are therefore performed with GECHO.

For the profiles, that are partly blended with neighboring line emission, the FWHM gets estimated, by doubling the width of the distinguishable flank of the profile in relation to the zero-velocity line. This is done for the AVG profile of He II λ 4685, using its red flank as reference. The same approach is used for the N V $\lambda\lambda$ 1238, 1242 doublet in both AVG and RMS spectra, as it is blended with the Ly α profile.

The FWHM measurements for O I λ 8446 is excluded from the subsequent analysis. Its AVG profile is blended with the Ca II λ 8498, λ 8542, λ 8662 triplet, which makes it difficult to decompose. Although it was shown in Ochmann et al. 2025, that O I λ 8446 in NGC4593 shows a similar shape that the as the Ca lines, it was not attempted in this work. In addition to that, the RMS profile shows very strong noise. While variability is noticeable, a clear profile is not distinguishable from the surrounding spectrum. The resulting FWHM values are listed in Table 4.5.

It has to be noted, that the line profiles of the AVG spectrum can also includes narrow components of the respective emission line (Peterson 1997), as well in some

cases a overlapping profile of a close narrow emission line (e.g. the [O III] $\lambda 4363$ next to $H\gamma$). The narrow components are hard to isolate in the profiles, which is why no attempt was made to decompose the AVG profiles. Having no narrow components in the RMS profiles, their FWHM will be used in subsequent analysis to describe the velocity dispersion of their emitting region.

The uncertainties are estimated based on the instrumental dispersion of the gratings (see Table 3.1), the shape of the line profiles (see Figure 4.7). $H\alpha$ and $\text{He I } \lambda 5875$ are measured with the G750L grating with a dispersion of $4.97 (\text{\AA}/\text{pixel})$; $H\beta$, $H\gamma$, $H\delta$, and $\text{He II } \lambda 4685$ are measured with the G430L grating with a dispersion of $2.73 (\text{\AA}/\text{pixel})$; and the UV emission lines are measured with the G140L grating with a dispersion of $0.6 (\text{\AA}/\text{pixel})$. By using Equation 4.7, this transforms to an equivalent dispersion per pixel in velocity space, listed in Table ???. This dispersion is used as a minimum estimate for the uncertainty estimation.

The FWHM uncertainties of the RMS profiles of $H\gamma$, $\text{He I } \lambda 5875$, and the He II lines are scaled up due to their profile shape and noise. The RMS profile of $H\delta$ it is much more scattered and extended at his blue flank at half height, which is why its uncertainty is estimated significantly higher. Same is done for the FWHM of $\text{Ly}\alpha$, as it is blended with absorption in its blue flank and with the $\text{N IV } \lambda\lambda 1238, 1242$ doublet in its red flank. The FWHM uncertainties for the profiles of the three doublets are estimated higher as well, due to their shape and superposition of their broad components. Finally, the uncertainties for the AVG and RMS profiles of $\text{N V } \lambda\lambda 1238, 1242$ and for the AVG profile of $\text{He II } \lambda 4685$ are set significantly higher, since they are estimated based on the width of only one profile flank.

Table 4.5: Measured FWHM and of the AVG and RMS line profiles.

| Line | FWHM (avg)[km/s] | FWHM (rms)[km/s] |
|---|------------------|------------------|
| $\text{Ly}\alpha$ | 3800 ± 350 | 4600 ± 500 |
| $H\alpha$ | 300 ± 250 | 3100 ± 250 |
| $H\beta$ | 3400 ± 200 | 3400 ± 200 |
| $H\gamma$ | 4100 ± 200 | 3900 ± 400 |
| $H\delta$ | 3400 ± 250 | 5900 ± 1000 |
| $\text{He I } \lambda 5875$ | 3500 ± 300 | 4000 ± 400 |
| $\text{He II } \lambda 1640$ | 2900 ± 500 | 6900 ± 1000 |
| $\text{He II } \lambda 4685$ | 1800 ± 600 | 6000 ± 400 |
| $\text{N V } \lambda\lambda 1238, 1242$ | 3200 ± 800 | 3400 ± 1000 |
| $\text{Si IV } \lambda\lambda 1393, 1402$ | 5200 ± 500 | 10000 ± 1000 |
| $\text{C IV } \lambda\lambda 1548, 1550$ | 5400 ± 500 | 8400 ± 1000 |

4.4.2 Balmer Line-Profiles

Looking at the comparison of the Balmer RMS profiles in Figure 4.8, they all show a overall similar shape. The centre of the profiles is shifted to positive velocities, with the peaks located between ~ 0 – 500 km s^{-1} and between ~ 1500 – 2000 km s^{-1} . Both peaks show different values of flux, with higher values in the more blue peak, giving the profiles an asymmetric double-peak shape. The profile of $\text{H}\delta$ shows an additional peak at about 1000 km s^{-1} with a nearly similar flux than the blue peak of its profile.

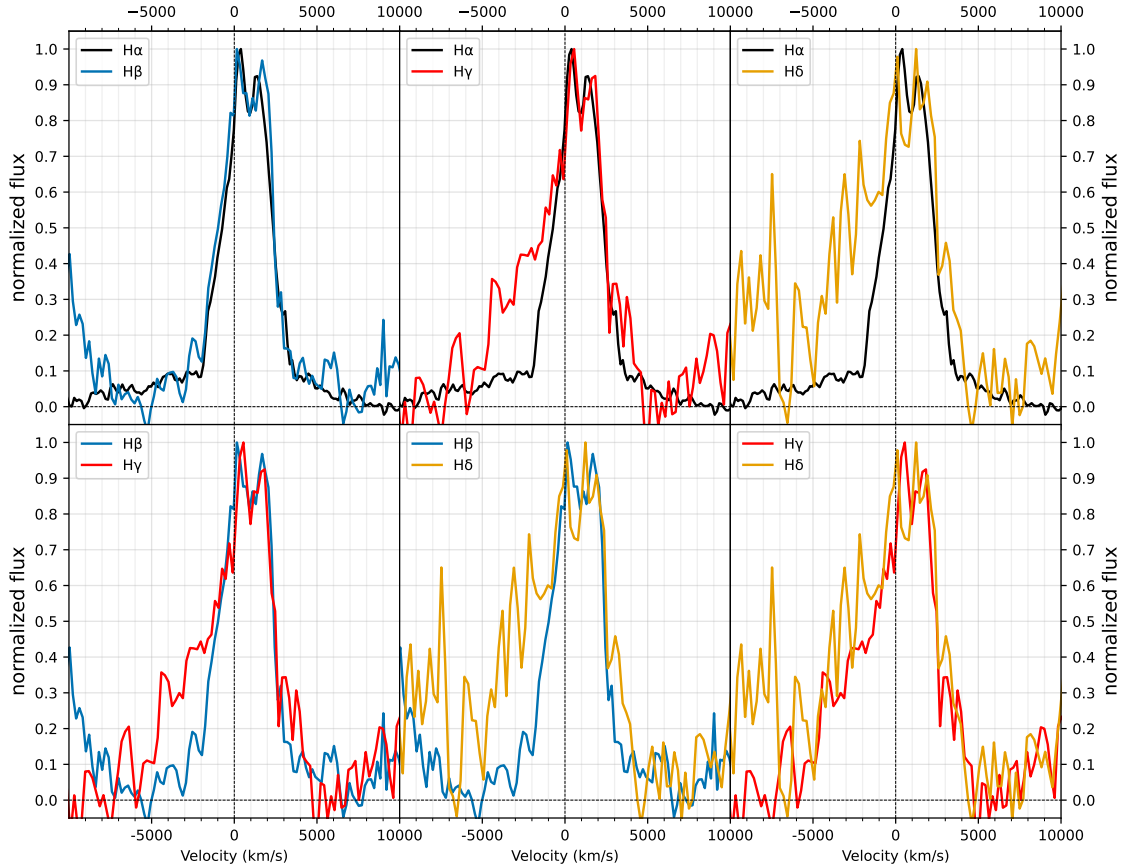


Figure 4.8: Comparison of the normalized RMS line profiles of the Balmer lines $\text{H}\alpha$, $\text{H}\beta$, $\text{H}\gamma$ and $\text{H}\delta$.

Looking in more detail into the shape of RMS profiles, the $\text{H}\alpha$ and $\text{H}\beta$ profiles show a strong similarity to each other, with both wings exhibiting a steep slope. The red wing of the $\text{H}\gamma$ and $\text{H}\delta$ profiles follows the same slope, which ends in a small peak at about $\sim 3000 \text{ km s}^{-1}$. The $\text{H}\gamma$ and $\text{H}\delta$ profiles show a more extended blue wing. The $\text{H}\delta$ profile is the most noisy of the Balmer RMS profiles. Still a close similarity to the $\text{H}\gamma$ profile is noticeable, showing the same broad blue wing. This also leads to higher FWHM value of $\sim 3900 \pm 400 \text{ km s}^{-1}$ for $\text{H}\gamma$ and $\sim 5900 \pm 1000 \text{ km s}^{-1}$

for $H\delta$ compared to the values of $H\alpha$ and $H\beta$ with $\sim 3100 \pm 250 \text{ km s}^{-1}$ and $\sim 3400 \pm 200 \text{ km s}^{-1}$. Taking the similarities of the RMS profile shapes, it can be assumed that all four Balmer lines emerge under similar kinematic properties.

Looking at Figure 4.7 it can be seen, that most of the RMS profile is located within the red wing of the AVG profiles, suggesting that a largely part of the measured variation originates at positive velocities of the emitting region.

4.4.3 Helium Line-Profiles

The RMS profiles, as well as a comparison of the $\text{He I } \lambda 5875$, $\text{He II } \lambda 4685$ and $\text{He II } \lambda 1640$ is shown in Figure 4.9. Their RMS profiles are more noisy than the Balmer RMS profiles, due to lower signal to noise ratio, but are still clearly distinguishable from the surrounding continuum.

First looking at the RMS profile of $\text{He I } \lambda 5875$, shift to positive velocities is noticeable similar to the Balmer RMS profiles, with its maximum located at about 1500 km s^{-1} . Going from the maximum, the profile shows a more extended blue wing and a steeper and narrower red wing, with a FWHM of about 4000 ± 400 .

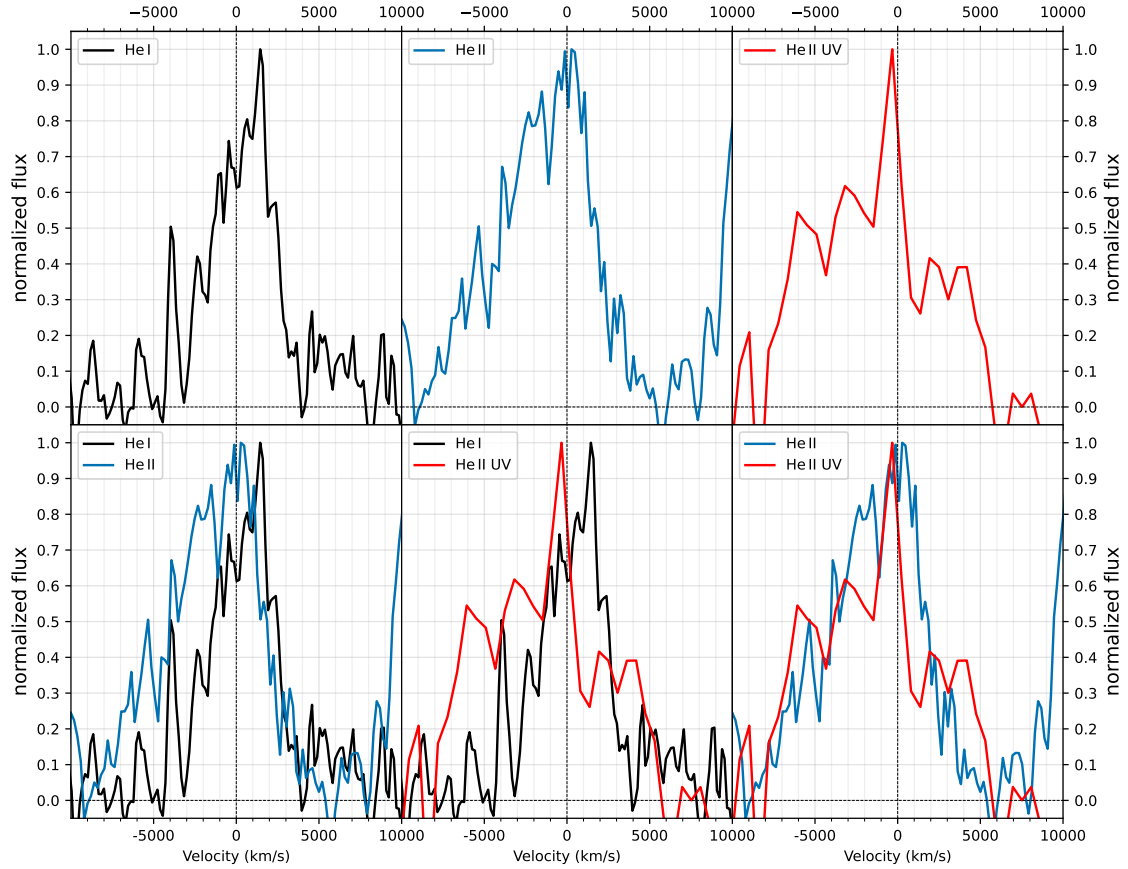


Figure 4.9: Comparison of the normalized RMS line profiles of the Helium lines

A similar shape can be noticed for the RMS profile of He II $\lambda 4685$. While its profile is not shifted, like for He I $\lambda 5875$, it also shows a more extended blue wing and narrow red wing, with a FWHM of about $6000 \pm 400 \text{ km s}^{-1}$.

The RMS profile of the UV Helium line He II $\lambda 1640$ is even more noisy, compared to the RMS profiles of the other Helium lines due to its lower signal to noise ratio. Like the He II $\lambda 4685$ RMS profile its maximum is located somewhere around 0 km s^{-1} and also exhibits a more extended blue wing and a steep slope in its red wing. At around 2000 km s^{-1} its RMS profile is blended with the RMS profile of semi-forbidden doublet O III] $\lambda\lambda 1660, 1666$. Still, its contribution to the RMS profile of He II $\lambda 1640$ stays below the half height of the profile and does not influence the FWHM measurement with a value of about $6900 \pm 1000 \text{ km s}^{-1}$.

Comparing the RMS profiles of the He lines, all three show a similar shape with a extended blue wing and a narrow red wing, with He I $\lambda 5875$ exhibiting a narrower FWHM and a shift towards positive velocities, than the He II RMS profiles, who shows FWHM in the same order of magnitude.

4.4.4 UV Line Profiles

Figure 4.10 shows the RMS profiles of the Ly α line, the N V $\lambda\lambda 1238, 1242$ doublet, the Si IV $\lambda\lambda 1393, 1402$ doublet and the C IV $\lambda\lambda 1548, 1550$ doublet. Starting with Ly α , its RMS profile is blended with line absorption in its blue flank, as well as with the N V $\lambda\lambda 1238, 1242$ doublet in his red wing. Still, its central part is good distinguishable. Similar to the Balmer lines, the most parts, as well as the highest flux is shifted towards positive velocities. It shows a steep blue wing and a slightly broader red wing, which a small broadening at about half height, resulting in a FWHM of about $\sim 4600 \pm 350 \text{ km s}^{-1}$.

The RMS profile of the neighboring N V $\lambda\lambda 1238, 1242$ doublet is blended with absorption as well as with the Ly α RMS profile. This makes its RMS profile difficult to distinguish. Still it was attempted to estimate its FWHM by taking the width of the red wing of the central peak, resulting in an FWHM of about $3400 \pm 1000 \text{ km s}^{-1}$. The RMS profile Si IV $\lambda\lambda 1393, 1402$ doublet shows a very broad and scattered profile and is blended with the semi-forbidden line doublet O IV] $\lambda\lambda 1397, 1400$. This leads to a very broad FWHM of about $\sim 10000 \pm 1000 \text{ km s}^{-1}$. Due to the noise profile and because of a possible interference with the O IV] $\lambda\lambda 1397, 1400$ doublet, the measured FWHM value will not taken into account for the subsequent analysis. Finally, the RMS profile of the C IV $\lambda\lambda 1548, 1550$ doublet shows a very asymmetric profile with a broad plateau like blue wing, with flux staying below half height of the maximum until about -3000 km s^{-1} . The centre of the RMS profile is shows a

double-peak-like shape with a narrower blue peak and a broader red peak. They are located at about $\sim -1500 \text{ km s}^{-1}$ and 250 km s^{-1} , with higher flux in the red peak. Between the peaks the flux drops below half of the maximum, due to blending with absorption, which is why the left wing of the blue peak and the right wing of the red peak has been used to measure the FWHM with $\sim 8400 \pm 1000$.

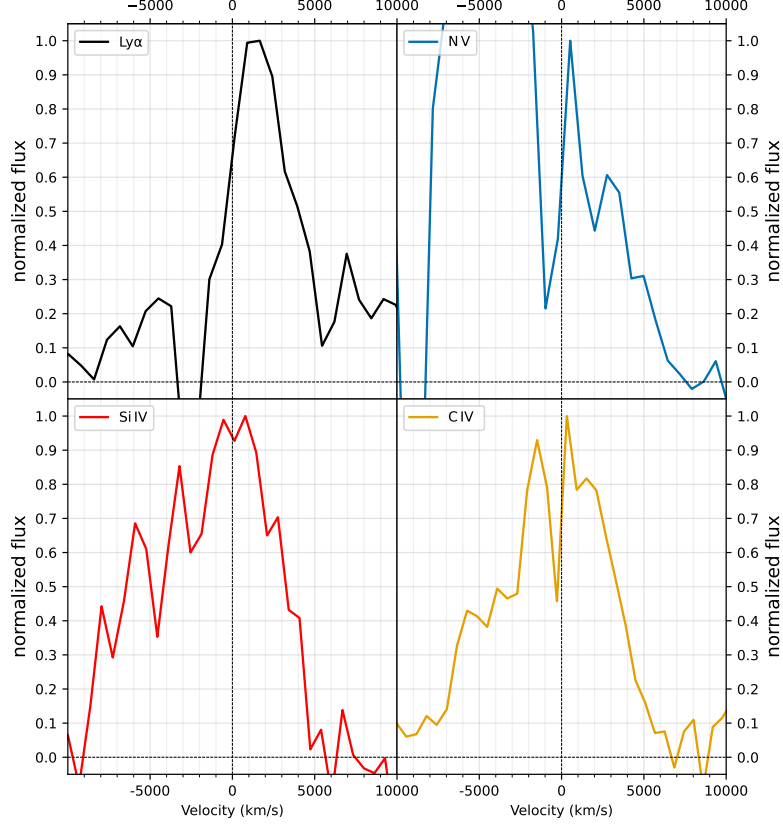


Figure 4.10: Comparison of the normalized RMS line profiles of the UV lines

4.5 Time Lag

The time lag of the measured emission lines relative to the ionizing continuum is determined from the lag between the emission-line light curve and the UVW2 light curve. In section 4.3 it has already been discussed that it is common to use the most blue continuum as a reference as a proxy for the ionized continuum. By using the Swift UVW2 light curve with an effective wavelength of $\sim 1930 \text{ \AA}$, the lag between the two continua must be therefore added to the emission-line lag estimate. The time lag between two lightcurves is measured, by determining the cross-correlation function (CCF) of these curves and measuring the centroid of the CCF for values above 80% of the peak, as described in Section 2.2.2. This calculation is done with

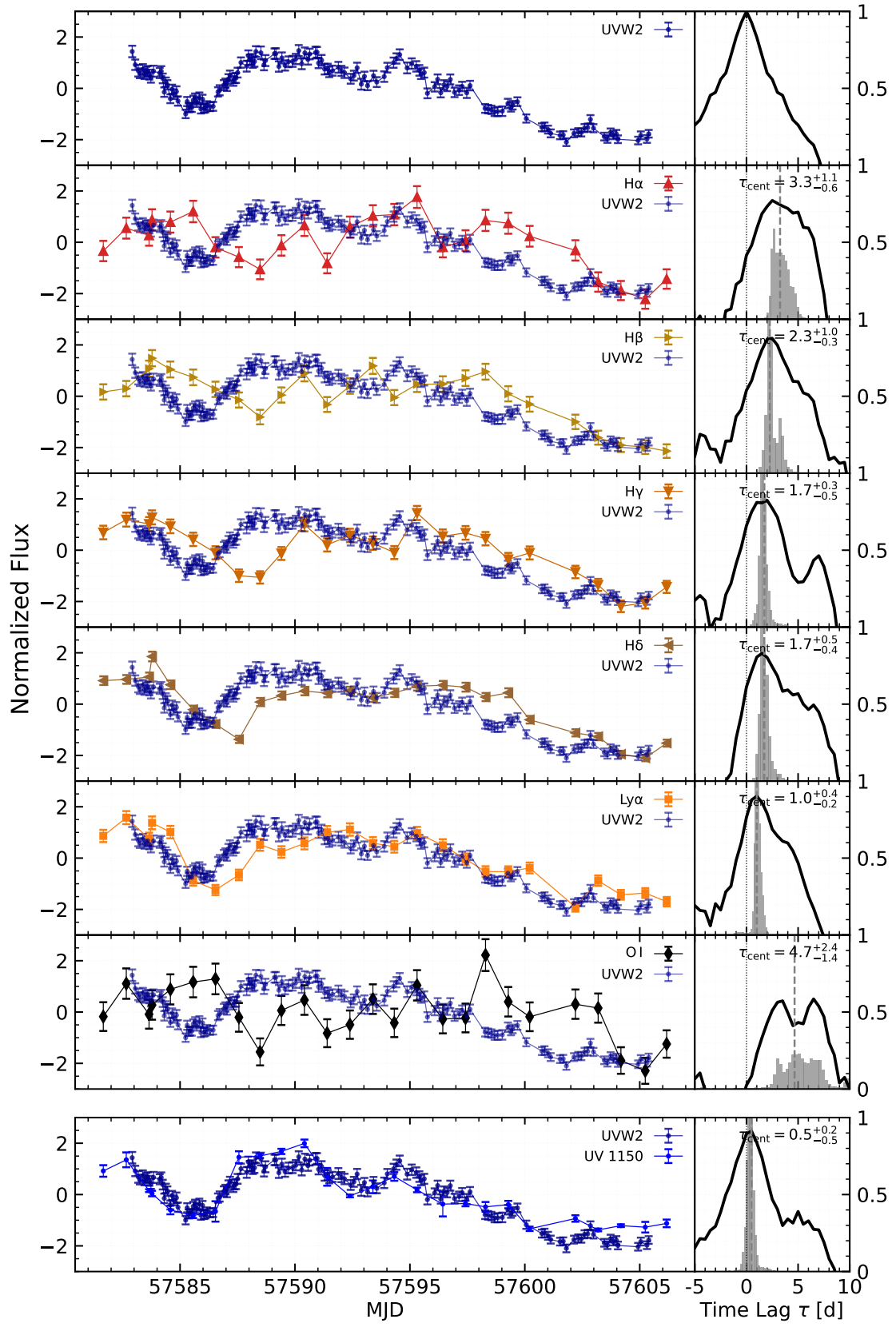


Figure 4.11: Compared lightcurves and CCFs H α , H β , H γ , He I λ 5875, He II λ 4685 and O I λ 8446 with UVW2 as reference lightcurve.

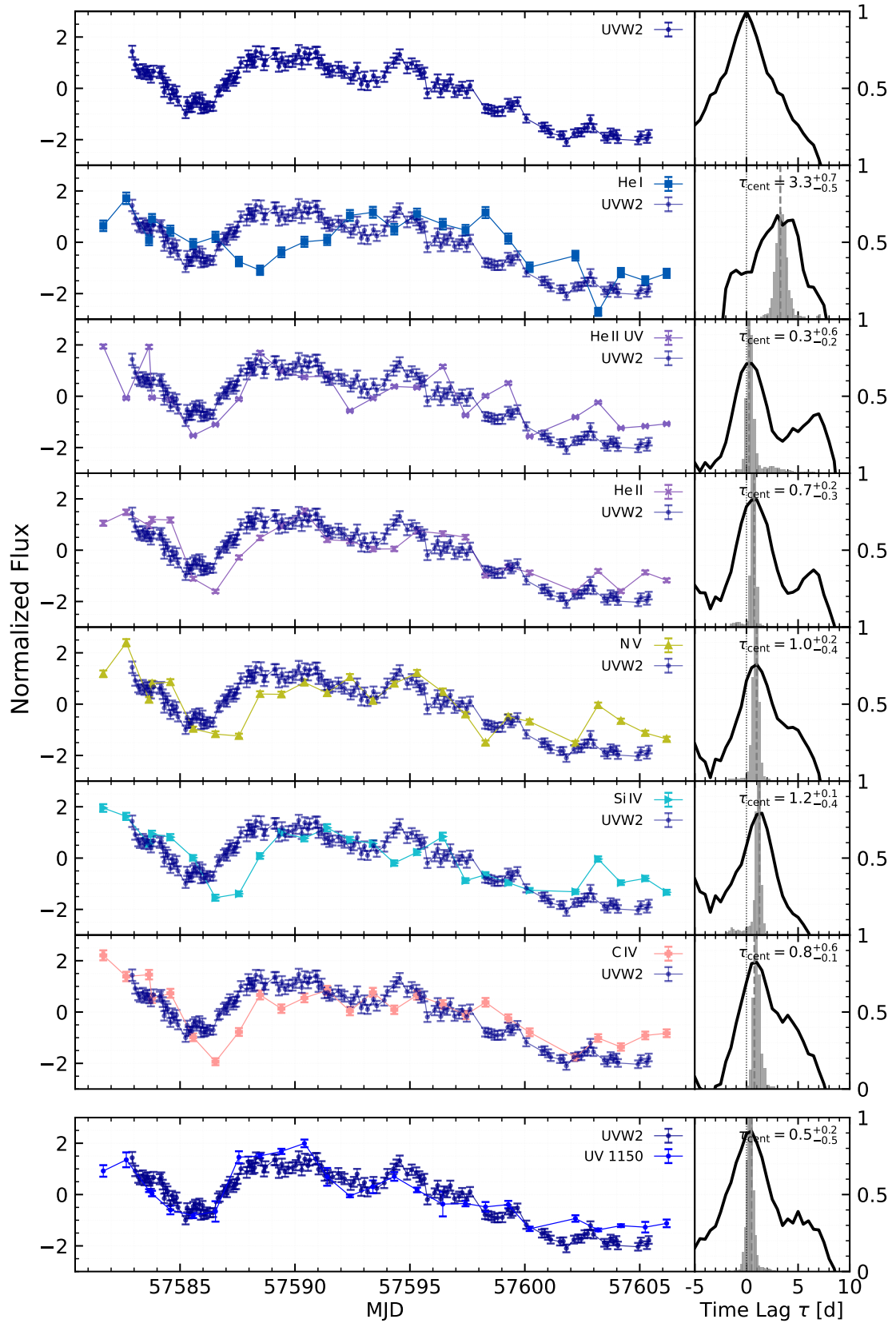


Figure 4.12: Compared lightcurves and CCFs of UV lines with UVW2 as reference lightcurve.

GECHO, which applies the interpolated cross-correlation function (ICCF) method introduced by Gaskell & Peterson 1987. The emission-line and reference light curves are normalized by subtracting the respective mean value from each data point. To increase the effective sampling and to measure the correlation between two unevenly sampled light curves, flux values between data points are linearly interpolated for both light curves. The normalized light curves and the resulting CCFs are presented in Figures 4.11 and 4.12. Additionally, the top panel of each figure displays the UVW2 light curve together with its auto-correlation function, while the bottom panel compares both lightcurves of the UVW2 and the UV continuum around 1150 Å and shows the corresponding CCF. The resulting time lags between the UVW2 continuum and each light curve are listed in Table 4.6. The centroid uncertainties are estimated using the flux randomization/random subset selection (FR/RSS) method described by Peterson et al. 1998, with 10000 iterations and a lag bin size of 0.5 days (see Section 2.2.2). The resulting centroid distribution is displayed by the gray histogram in the above named figures.

Overall, the CCFs of all measured emission lines show strong correlations with pronounced peak values between ~ 0.7 and ~ 0.9 , except for the CCF of O I 8446, which exhibits two local maxima at values of around ~ 0.6 . The two He II lines shows the shortest lag relative to the UVW2 light curve, with an average lag of approximately ~ 0.5 days within the uncertainties. He II 4685 shows a higher peak correlation of approximately ~ 0.8 compared to He II 1640, which reaches values of around ~ 0.7 . The CCFs of the other UV emission lines Ly α , N V 1238, Si IV 1393 and C IV 1548 peak at values above ~ 0.8 , with Ly α reaching a maximum of approximately ~ 0.9 . All of these lines show similar lags of about ~ 1 day within their uncertainties. The Balmer lines exhibit larger lags. H α and H β lag behind the UVW2 light curve by $3.3^{+1.1}_{-0.6}$ and $2.3^{+1.0}_{-0.3}$ days, respectively, while H γ and H δ show shorter lags of $1.7^{+0.2}_{-0.4}$ and $1.7^{+0.4}_{-0.4}$ days. Among the Balmer lines, H β shows the highest peak correlation, exceeding ~ 0.85 , whereas H α exhibits the lowest correlation, with values of around ~ 0.8 . Compared to H γ and H δ , the CCFs of H α and H β exhibit broader peaks and wider centroid distributions with larger uncertainties and slightly higher time lag values. He I 5875 and O I 8446 show the lowest correlations with the UVW2 light curve, with peak values of approximately ~ 0.7 and ~ 0.6 , respectively. He I 5875 shows a lag of $3.3^{+0.7}_{-0.4}$ days, which is of the same order as the lags measured for H α and H β within the uncertainties. while O I 8446 exhibits the longest lag of $4.7^{+2.4}_{-1.4}$ days relative to UVW2, with large uncertainties caused by the comparatively low CCF peak correlation.

Table 4.6: Centroid and Peak Time Lag for UVW2.

| Line | τ_{cent} [d] | Line | τ_{cent} [d] |
|-------------|--------------------------|-----------------------------------|--------------------------|
| H α | $3.3^{+1.1}_{-0.6}$ | He I 5875 | $3.3^{+0.7}_{-0.4}$ |
| H β | $2.3^{+1.0}_{-0.3}$ | He II 1640 | $0.3^{+0.6}_{-0.2}$ |
| H γ | $1.7^{+0.2}_{-0.4}$ | He II 4685 | $0.7^{+0.1}_{-0.3}$ |
| H δ | $1.7^{+0.4}_{-0.4}$ | N V $\lambda\lambda$ 1238, 1242 | $1.0^{+0.2}_{-0.4}$ |
| Ly α | $1.0^{+0.4}_{-0.2}$ | Si IV $\lambda\lambda$ 1393, 1402 | $1.2^{+0.1}_{-0.4}$ |
| O I 8446 | $4.7^{+2.4}_{-1.4}$ | C IV $\lambda\lambda$ 1548, 1550 | $0.8^{+0.5}_{-0.1}$ |

4.6 Black Hole Mass

The final step of the RM analysis is now the estimation of mass of the SMBH. To do that, the virial theorem gets applied following the method of Peterson et al. 2004. The FWHM of the RMS profiles is used to describe the velocity dispersion ΔV which is why a value of $f = 1.8$ gets assumed for the scale factor following Probst et al. 2025 (see Section 2.2.3). Taking equation 2.7, 2.8 and 2.9 the SMBH mass can be estimated based on the time lag and FWHM of for each emission line using:

$$M_{\text{BH}} = 1.8 \cdot \frac{c \cdot \tau_{\text{centroid}} \text{FWHM}^2}{G}. \quad (4.8)$$

As discussed in Section 4.4, O I λ 8446, and Si IV $\lambda\lambda$ 1238, 1242 are not included, due to not measurable or significant FWHM values. The resulting SMBH mass results, as well as the corresponding time lag and FWHM values of the broad emission lines are listed in Table 4.7. To obtain a final estimation for the SMBH mass, an inverse-variance weighted mean is calculated. Since the uncertainties are asymmetric the higher gets adopted, $\sigma_i = \max(\sigma_i^-, \sigma_i^+)$. The weighted mean is then given by

$$\bar{M}_{\text{BH}} = \frac{\sum_i w_i M_{\text{BH},i}}{\sum_i w_i}, \quad w_i = \frac{1}{\sigma_i^2}, \quad (4.9)$$

with an uncertainty

$$\sigma_{\bar{M}} = \left(\sum_i w_i \right)^{-1/2}. \quad (4.10)$$

This yields the weighted-mean SMBH mass of $\bar{M}_{\text{BH}} \approx (0.89 \pm 0.16) \times 10^7 M_{\odot}$.

It has to be noted, that the scale factor of $f = 1.8$ does not account the low-inclination $i \sim 11^\circ$ of the elliptic accretion disk, modeled in Ochmann et al. 2024. Adopting the scaling relation $f \sim \sin^{-2}(i)$ introduced by Krolik 2001, a value of $f \sim 27.5$ would be needed to account for the low inclination. Krolik 2001 used the line dispersion to parameterize the velocity dispersion, which is why the relation

$\sigma_{\text{line}} \approx \text{FWHM}/2$ (Peterson et al. 2004) has to be accounted again. Due to the square relation of the velocity dispersion to the black hole mass seen in Equation 4.8, the scale factor finally gets corrected to a value $f \sim 6.8$. Subsequently the found BH mass has to be multiplied by a additional factor of 3.77.

Subsequently, the weighted-mean SMBH mass yields $\bar{M}_{\text{BH,corr}} \approx (3.35 \pm 0.62) \times 10^7 M_{\odot}$.

Table 4.7: Estimated time lags, FWHM and SMBH masses.

| Line | τ_{cent} [d] | FWHM (rms)[km/s] | $M_{\text{BH}}[10^7 M_{\odot}]$ |
|---------------------------|--------------------------|------------------|---------------------------------|
| Ly α | $1.0^{+0.4}_{-0.2}$ | 4600 ± 500 | $0.7^{+0.3}_{-0.2}$ |
| H α | $3.2^{+1.0}_{-0.6}$ | 3100 ± 250 | $1.1^{+0.6}_{-0.4}$ |
| H β | $2.3^{+1.0}_{-0.3}$ | 3400 ± 200 | $0.9^{+0.6}_{-0.2}$ |
| H γ | $1.7^{+0.2}_{-0.4}$ | 3900 ± 300 | $0.9^{+0.3}_{-0.3}$ |
| H δ | $1.7^{+0.4}_{-0.4}$ | 5900 ± 1000 | $1.5^{+0.6}_{-0.5}$ |
| He I λ 5876 | $3.3^{+0.7}_{-0.4}$ | 4000 ± 300 | $1.8^{+0.7}_{-0.5}$ |
| He II λ 1640 | $0.3^{+0.6}_{-0.2}$ | 6900 ± 1000 | $0.4^{+1.2}_{-0.3}$ |
| He II λ 4686 | $0.7^{+0.1}_{-0.3}$ | 6000 ± 300 | $0.9^{+0.2}_{-0.4}$ |
| N V λ 1238, 1242 | $1.0^{+0.2}_{-0.4}$ | 3400 ± 1000 | $0.4^{+0.4}_{-0.3}$ |
| C IV λ 1548, 1550 | $0.8^{+0.5}_{-0.1}$ | 8400 ± 1000 | $1.9^{+1.7}_{-0.2}$ |

4.7 Bowen Fluorescence of O I λ 8446

Emission lines in the optical range, like the Balmer and helium lines, are commonly used in many reverberation-mapping campaigns, as they are easily accessible for nearby AGN (Ochmann et al. 2026). Other lines, such as the low-ionization line O I λ 8446, have not been of major interest in such campaigns, mostly because of observational limitations (Ochmann et al. 2026). This is why the variability of the O I λ 8446 line in this campaign is of particular interest, as the line can be enhanced by Bowen fluorescence, pumped by Ly β emission (Grandi 1980). Unfortunately, Ly β lies outside the spectral range of the Cackett et al. 2018 campaign. However, because the Ly α and Ly β lines are expected to originate under similar physical conditions (Ochmann et al. 2026), Ly α can be used as a proxy for Ly β . H α is used to investigate the location of the O I λ 8446 emitting region relative to the Balmer-line emitting region.

Therefore, the time lags between the UVW2 and emission-line lightcurves, as well as the CCFs and time lags between O I λ 8446 and Ly α , between H α and Ly α , and between O I λ 8446 and H α , are calculated and shown in Figure 4.13. All lightcurve show a strong correlation between $\sim 0.75 - 0.8$, with the exception of the O I λ 8446 and UVW2 lightcurves, which show a maximum correlation of only 0.6. The time

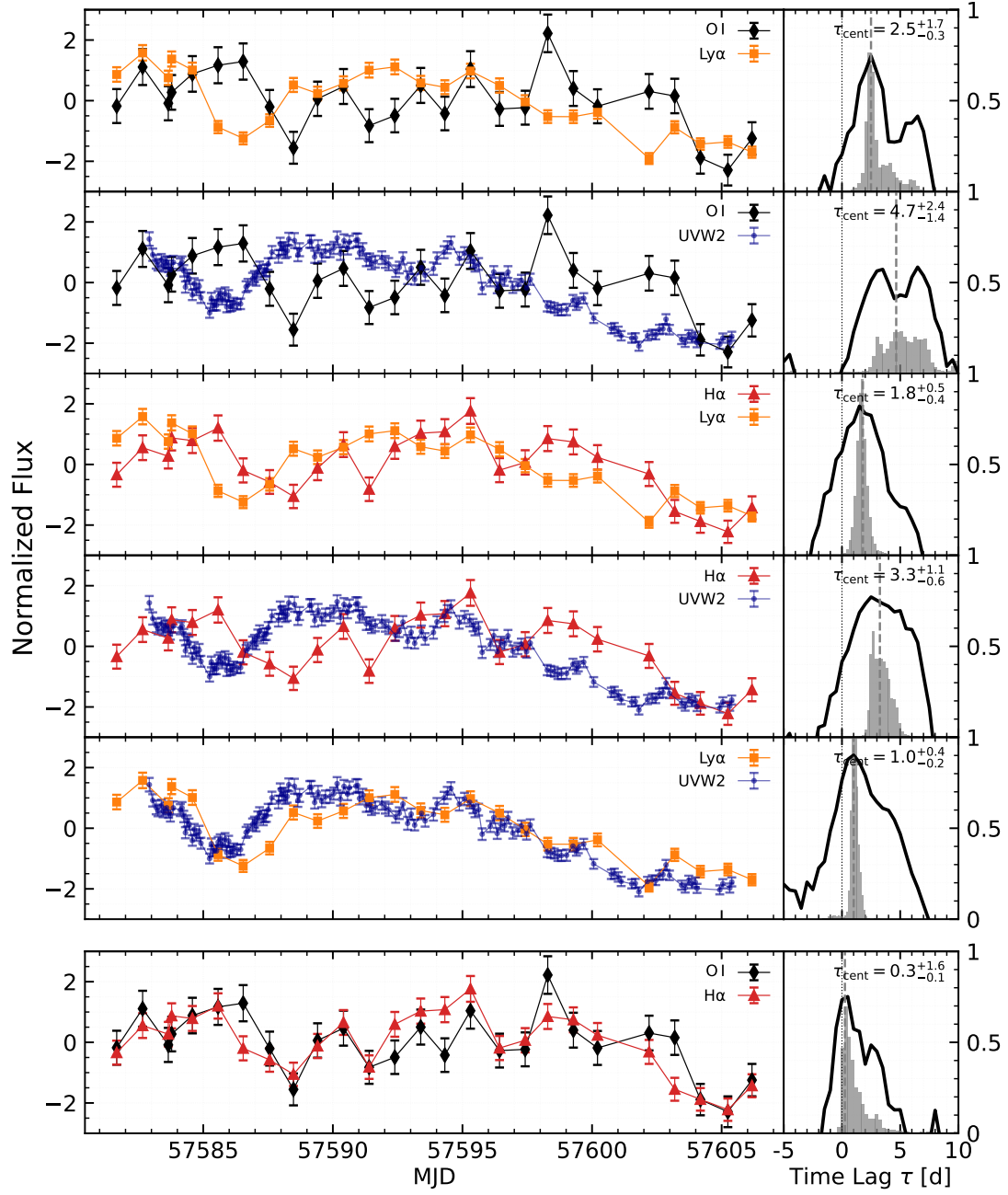


Figure 4.13: Compared lightcurves and CCFs for Bowen Fluorescence.

lags and their uncertainties are calculated as before. O I λ 8446 lags behind Ly α by $2.5^{+1.7}_{-0.3}$ days and behind UVW2 by $4.7^{+2.4}_{-1.4}$ days, while H α lags behind Ly α by $1.8^{+0.5}_{-0.5}$ days and behind UVW2 by $3.3^{+1.1}_{-0.6}$ days. A difference in the response time of about 0.5–1 days between O I λ 8446 and H α is noticeable, but are not significant within the uncertainties. Looking at the O I λ 8446 and H α lightcurves, they also show a strong correlation, with O I λ 8446 lagging behind H α by about $0.3^{+1.6}_{-0.1}$ days. With the Ly α light curve lagging behind the UVW2 light curve by $1.0^{+0.4}_{-0.2}$ days, the total lag along the Bowen-fluorescence path from UVW2 to Ly α and from Ly α to O I λ 8446 sums to ~ 3.5 days, which lies within the uncertainties of the time lag between the H α and UVW2 light curves.

5. Discussion

The nearby Seyfert I galaxy NGC 4593 has been monitored in several earlier RM studies (e.g. Kollatschny & Dietrich 1997; Denney et al. 2006; Cackett et al. 2018). In a recent study, Cackett et al. 2018 conducted an observing campaign of NGC 4593 with HST (PI: Cackett, E.M, Prop ID 14121), covering the optical to near-infrared range between $\sim 3900 \text{ \AA}$ – 9000 \AA as well as the UV range between $\sim 1100 \text{ \AA}$ – 1700 \AA . Only a few other AGN have been monitored by HST, and the high cadence of nearly daily observations makes this campaign of particular interests for a RM campaign. This enabled a RM analysis of the BLR of NGC 4593 based on a HST/STIS campaign for the first time, including broad emission lines that had not previously been monitored (e.g. UV lines), and allowed an examination of the BLR structure of the galaxy. In addition the Bowen fluorescent emission line $\text{O I } \lambda 8446$ was included. Given the wavelength coverage of the campaign, it was possible to examine its Bowen fluorescence relation to $\text{Ly}\beta$, which has not previously been monitored in a RM campaign. Also, the UV continuum around 1150 \AA was used as a proxy for the ionizing continuum instead of an optical continuum, as adopted in earlier works (e.g. Kollatschny & Dietrich 1997; Denney et al. 2006), since it is assumed to originate closer to the SMBH (Collin-Souffrin & Lasota 1988). The more densely sampled *Swift* UVOT UVW2 light curve presented by McHardy et al. 2018 has been compared to the light curve of the 1150 \AA continuum and showed a strong similarity. Owing to its higher cadence, the UVW2 light curve is adopted as the reference light curve for the RM analysis presented here. This analysis covered the UV emission lines $\text{Ly}\alpha$, $\text{N V } \lambda\lambda 1238, 1242$, $\text{Si IV } \lambda\lambda 1393, 1402$, $\text{C IV } \lambda\lambda 1548, 1550$ and $\text{He II } \lambda 1640$, the optical emission lines $\text{H}\alpha$ - $\text{H}\delta$, $\text{He II } \lambda 4686$ and $\text{He I } \lambda 5876$ and the NIR emission line $\text{O I } \lambda 8446$, which allowed an extended structural analysis of the BLR of NGC 4593 compared to earlier campaigns (Kollatschny & Dietrich 1997; Denney et al. 2006; Williams et al. 2018).

5.1 Structure of the BLR

5.1.1 Time Lags

The extracted light curves of the emission lines showed an overall similar shape, with strong correlation with the UVW2 light curve and CCF peak values between 0.7–0.9. Only the O I λ 8446 light curve showed a lower peak correlation with UVW2 of 0.6, as its variability is primary driven through Bowen fluorescence, which will be further discussed in Section 5.3.

H α and H β showed different time lags of $3.3^{+1.1}_{-0.6}$ and $2.3^{+1.0}_{-0.3}$ days which are in good agreement with the results of earlier works (Kollatschny & Dietrich 1997; Denney et al. 2006; Williams et al. 2018). The higher-order Balmer lines H γ and H δ show a significantly shorter time lags with $1.7^{+0.2}_{-0.4}$ days and $1.7^{+0.4}_{-0.4}$ days, which follows the trend seen in other Seyfert galaxies that higher ordered Balmer lines show shorter time lags compared to the lower ordered Balmer lines (e.g. Gaskell & Sparke 1986; Kollatschny et al. 2001). It was also possible to infer the time lag of Ly α , which shows a even shorter time lag of $1.0^{+0.4}_{-0.2}$ days.

The helium lines show differences in time lag as well, depending on their ionization. He I λ 5876 lags $3.3^{+0.7}_{-0.4}$ days behind UVW2, while the higher-ionized He II λ 1640 and He II λ 4686 exhibit a much faster response times, with lags of $0.3^{+0.6}_{-0.2}$ days and $0.7^{+0.1}_{-0.3}$ days, respectively. Therefore the emitting region of He I is located at the same distance as the H α weighted BLR, while the He II lines originate much shorter distance to the ionizing continuum. The high-ionized UV lines all show similar lags within uncertainties, with measured values of $1.0^{+0.2}_{-0.4}$, $1.2^{+0.1}_{-0.4}$ and $0.8^{+0.5}_{-0.1}$ days for N V λ 1238, 1242, Si IV λ 1393, 1402 and C IV λ 1548, 1550, respectively. Therefore, the broad emission lines show a tendency that higher ionized broad emission lines exhibit shorter time lags than lower ionized broad emission lines, which implies an ionization stratification structure of the BLR (Collin-Souffrin & Lasota 1988; Gaskell & Sparke 1986; Kollatschny et al. 2001).

Since UVW2 lags behind the extracted HST/STIS 1150 Å continuum by approximately 0.5 days, this offset must be added to obtain the final BLR radii for each emission line.

5.1.2 Line Profiles

The RMS line profiles of the monitored emission lines all show an overall asymmetric shape. The Balmer line profiles show a similar asymmetric, double-peaked structure and are shifted toward positive velocities. This shift is also noticeable in the Ly α

profile and He I $\lambda 5876$ profile. This indicates that most of the line variability of these lines originates from the receding part of the emitting region.

Opposing to that, the maxima of the higher-ionization He II $\lambda 1640$ and He II $\lambda 4686$ profiles are located around their rest-frame wavelengths. A similar behavior is observed in the RMS profiles of the high-ionized UV lines N V $\lambda\lambda 1238, 1242$, Si IV $\lambda\lambda 1393, 1402$ and C IV $\lambda\lambda 1548, 1550$. High-ionized broad emission lines often show a blue-shift compared to lower-ionized broad emission lines (Gaskell 1982), which could be an explanation for the shift in the RMS profile.

H α and H β show comparatively steeper blue wings, whereas H γ and H δ exhibit more extended blue wings, implying that they may probe somewhat different kinematic conditions than H α and H β , which is also reflected in their line widths. The measured FWHM values of H α with $3100 \pm 250 \text{ km s}^{-1}$ agree well with previously reported line widths, while H β with $3400 \pm 200 \text{ km s}^{-1}$ shows a slightly smaller value (e.g. Kollatschny & Dietrich 1997; Denney et al. 2006). The broader blue wings of H γ and H δ result in higher FWHM values of $3900 \pm 400 \text{ km s}^{-1}$ and $5900 \pm 1000 \text{ km s}^{-1}$, respectively. A similar line width can also be seen for Ly α with FWHM of $4600 \pm 500 \text{ km s}^{-1}$, although it has to be noted that its line profile exhibits absorption.

The RMS profiles of the helium lines exhibit an extended blue wing and a steep red wing with the He II lines showing broader line widths. This results in FWHM values of $4000 \pm 400 \text{ km s}^{-1}$ for He I $\lambda 5876$, and broader values of $6000 \pm 400 \text{ km s}^{-1}$ for He II $\lambda 4686$ and $6900 \pm 1000 \text{ km s}^{-1}$ for He II $\lambda 1640$, respectively. The line profiles of the high-ionized UV lines partly exhibit absorption and show high noise, making it difficult to determine their FWHM values and resulting in significantly higher uncertainties compared to the other emission lines. The FWHM values of the UV emission lines were determined to be $3400 \pm 1000 \text{ km s}^{-1}$ for N V $\lambda\lambda 1238, 1242$ and $8400 \pm 500 \text{ km s}^{-1}$ for C IV $\lambda\lambda 1548, 1550$, respectively. The FWHM of the Si IV $\lambda\lambda 1393, 1402$ RMS profile could not be reliably estimated due to possible blending with O IV] emission, which cannot be separated from its profile. The estimated FWHM of N V $\lambda\lambda 1238, 1242$ must also be treated with caution, as it was approximated using only the red wing, since the blue wing is blended with Ly α .

5.2 Black Hole Mass

Based on the reverberation mapping results, virial products were derived for the selected emission lines, and the SMBH mass was estimated using a scale factor of $f = 6.9$. The adopted scale factor accounts for the low inclination angle of $i \sim 11^\circ$

reported by Ochmann et al. 2024. Its estimation is based on the relation $f \sim \sin^{-2}(i)$ (Krolik 2001), which captures the inclination dependence of the observed line-of-sight velocity dispersion. Since the velocity width is parameterized via the FWHM in this work rather than the line dispersion, an additional conversion was applied using $\sigma_{\text{line}} \approx \text{FWHM}/2$ (Peterson et al. 2004). Using this approach, an inverse-variance-weighted mean BH mass of $\bar{M}_{\text{BH}} = (3.35 \pm 0.62) \times 10^7, M_{\odot}$ was obtained from the determined values of each suitable emission line. Earlier works reported values in the same order of magnitude, e.g. $M \approx 1.4 \times 10^7 M_{\odot}$ (Kollatschny & Dietrich 1997) and $M = (9.8 \pm 2.1) \times 10^6 M_{\odot}$ (Denney et al. 2006). Using a similar approach, Kollatschny & Dietrich 1997 monitored $\text{H}\alpha$ and estimated the SMBH mass using a scale factor of 1.5, whereas Denney et al. 2006 monitored $\text{H}\beta$ and used a scale factor of 5.5. Rescaling these values to the scale factor of 6.9 used here yields $M \approx 6.44 \times 10^7, M_{\odot}$ (Kollatschny & Dietrich 1997) and $M = (1.23 \pm 0.26) \times 10^7, M_{\odot}$ (Denney et al. 2006). Therefore, the SMBH mass found in this analysis is consistent in order of magnitude with these earlier estimates.

5.3 Variation and Bowen Fluorescence of O I $\lambda 8446$

The low-ionization line O I $\lambda 8446$ was included in the RM analysis, as it exhibits noticeable variability in its RMS spectrum and is known to be a Bowen fluorescence line pumped by $\text{Ly}\beta$ emission (Grandi 1980). Being monitored in an HST/STIS campaign, it allowed the examination of its relation to $\text{Ly}\beta$ for the first time in an RM analysis. Although $\text{Ly}\beta$ is not covered by the observations, $\text{Ly}\alpha$ was used as a proxy to investigate the expected Bowen fluorescence connection to O I $\lambda 8446$. As described in Section 2.3, $\text{Ly}\beta$ excites O I through a near-resonant transition at $\lambda 1025 \text{ \AA}$. This is followed by decay via O I $\lambda 11287$ and subsequently by O I $\lambda 8446$, producing the observed O I $\lambda 8446$ emission (see Figure 2.5). This cascade is expected to occur with a photon ratio of 1:1 (Grandi 1980). Ochmann et al. 2026 reported a photon ratio of ~ 0.8 between O I $\lambda 8446$ and O I $\lambda 11287$ (taken from the near-infrared SpeX spectra obtained by Landt et al. 2008). This result indicates that $\text{Ly}\beta$ pumping is the main excitation mechanism for O I $\lambda 8446$ in NGC 4593. In addition, the comparison shown in Figure 4.13 demonstrates that O I $\lambda 8446$ exhibits a significantly stronger correlation with $\text{Ly}\alpha$ than with UVW2, further supporting this interpretation. Therefore, the emitting region of O I is likely located at a distance corresponding to a lag of ~ 3.5 days from the ionizing continuum, consistent with the Bowen fluorescence scenario, rather than the $4.7^{+2.4}_{-1.4}$ days implied by the direct lag relative to UVW2 under the assumption of recombination as the main

excitation mechanism. With that, the Bowen fluorescence lag of O I corresponds to the radius of the emitting region of H α with $3.3^{+1.1}_{-0.6}$ days. Since H α and O I λ 8446 also exhibits a strong correlation with a minimal time shift of ~ 0.3 days, it can be inferred that O I λ 8446 is emitted at approximately the same radius as H α within uncertainties.

5.4 Summary

This thesis presents the results of the first reverberation mapping analysis of the BLR of the Seyfert I galaxy NGC 4593 based on an HST/STIS campaign (PI: Cackett, E.M, Prop ID 14121). This dataset is ideally suited for a RM analysis of the BLR, thanks to its daily cadence and wavelength coverage of parts of the UV and optical to NIR regime. This allowed to examine the structure of the BLR on more detail than earlier RM analysis, by including broad emission lines, that has not been covered in a RM analysis of NGC 4593 before. The found time lags and FWHM are listed in Table 4.6 and 4.5, respectively. The higher order Balmer line exhibit shorter time lags and slightly differences in their RMS line profiles and line widths compared to H α and H β . Ly α lags even shorter than the Blamer lines, showing a similar line width to the higher order Balmer lines within uncertainties. He I λ 5876 show a approximately similar time lag as H α while the higher ionized He II exhibit much shorter time lags with significantly broader line widths than He I λ 5876. Finally, the high-ionized UV emission lines all show similar short time lags compared to the lower-ionized Balmer lines. This shows a tendency that higher ionized broad emission lines showing shorter time lags and broader line widths than lower ionized broad emission lines, which implies an ionization stratification structure of the BLR. Based on the virial mass of the reverberation-mapped broad lines a SMBH mass of $\bar{M}_{\text{BH}} = (3.35 \pm 0.62) \times 10^7 M_{\odot}$ has been found, which agrees in order of magnitude with the results of earlier studies (e.g. Kollatschny & Dietrich 1997; Denney et al. 2006).

Additionally, variability of the low-ionization line O I λ 8446 has been detected for the first time in a RM analysis. Line diagnostics showed that this variability is majorly through Ly β fluorescence, which makes O I λ 8446 the first Bowen-fluorescence line, investigated in a RM analysis. The radius of its emission region, following the Bowen-fluorescence process, was found at approximately the same radius as the emitting region of H α .

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A. Additional Tables