

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). Unlike inactive galaxies such as the Milky Way, the supermassive black hole (SMBH) in an active galaxy continues to accrete matter from its central region. This process generates thermal radiation (Peterson 1997) as well as non-thermal emission such as photoionization and subsequent recombination (Netzer 2013). AGN show strong variability across the entire electromagnetic spectrum, with timescales ranging from hours to days (Ulrich et al. 1997).

A particularly interesting example is the barred spiral galaxy NGC 4593. NGC 4593 shows strong variability from the X-ray to the optical bands (McHardy et al. 2017; Cackett et al. 2018) with several strong broad emission lines, including Balmer lines, Lyman lines and helium lines, among others (Kollatschny & Dietrich 1997; Cackett et al. 2018; Ochmann et al. 2025). Several studies have analysed the structure and kinematics of NGC 4593 (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 lags between the response of the emitting regions to variations in the ionizing continuum to probe the structure and size of the broad-line region (Peterson 1993).

In a recent work, Cackett et al. 2018 conducted 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 from about 1100 Å to 1700 Å and from 3900 Å to 9000 Å. This work focused on the reverberation of the accretion disk of NGC 4593 by analyzing the UV and optical continua (Cackett et al. 2018). This dataset allows me to perform a classical reverberation mapping analysis of the broad emission-lines based on these data, and to determine the mass of the SMBH.

Furthermore, NGC 4593 shows strong emission in the O I λ 8446 emission line and the Ca II λ 8498 λ 8542 λ 8662 triplet (Ochmann et al. 2025). These low-ionization lines have rarely been included in RM campaigns yet. The O I λ 8446 emission line is of

particularly interesting, as it can get enhanced through Bowen fluorescence (Bowen 1947; Grandi 1980). Being present in the Cackett et al. 2018 campaign, it allows its variability and time lag to 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 $^{-1}$, outshining entire galaxies by several orders of magnitude (Peterson 1997). Historically, several stellar-based models were proposed, 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 an AGN and its variability, which is central to reverberation mapping analysis.



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

2.1.1 Structure and Spectral Features of an AGN

Figure 2.1 shows a schematic illustration of an AGN, consisting 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). In some cases, relativistic jets are launched perpendicular to the plane of the accretion disk (Urry & Padovani 1995). The following subsections 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). It extends from the innermost stable circular orbit (ISCO) near the event horizon out to distances of several light-days. 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 BLR and NLR. 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 gas clouds near the nucleus 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.

Modelling the geometry of the BLR is challenging, because several emission lines have to be considered, whose intensities vary in response to changes in the continuum radiation (Netzer 2013). A common model assumes a spherical distribution of clouds connected to the accretion disk and located between the accretion disk and the dusty torus (Goad et al. 2012). Broad emission lines arise from permitted transitions such as $\text{H}\alpha$, $\text{H}\beta$, and $\text{Ly}\alpha$ (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 $[\text{O III}] \lambda 5007$, 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 also originate in the NLR, multi-component emission-line profiles can be observed in AGN spectra (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).

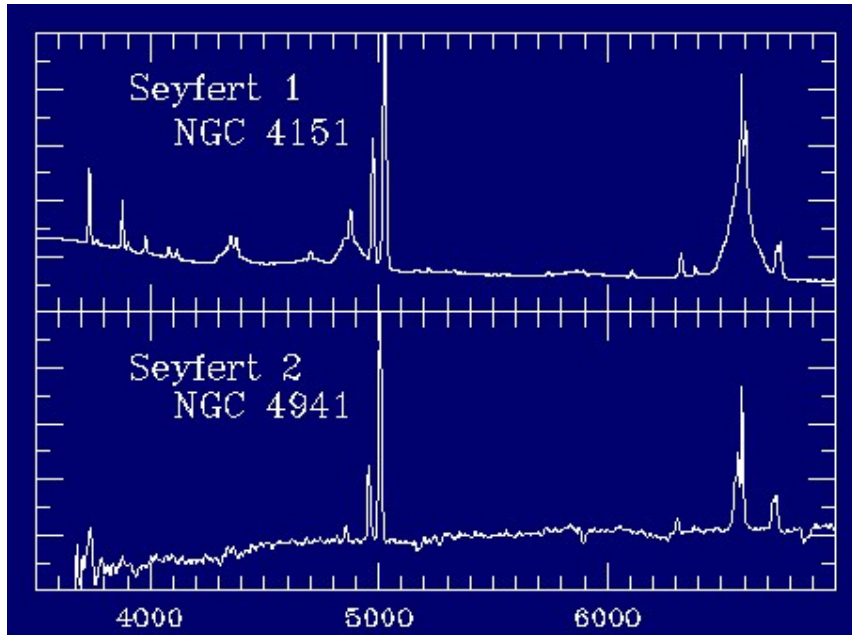


Figure 2.2: An example of Seyfert I and Seyfert II spectra illustrating their differences. Broad lines, such as the highlighted $H\alpha$ and $H\beta$, are only present in the Seyfert I spectrum, whereas forbidden [O III] lines are visible in both cases. Adapted from (Keel 2002).

2.1.2 Classification

AGNs get classified in subgroups based on their spectral features, which are strongly dependent to their intrinsic structure. The key parameters for this classification are luminosity, emission-line profiles and radio properties. Based on those parameters AGN get grouped into Seyfert galaxies, quasars and radio galaxies. They get further subdivided based on the appearance of broad and narrow emission lines. Some examples for these sub-classes are narrow-line Seyfert I galaxies (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 mainly classified into the sub-classes Seyfert I and Seyfert II based on the presence of broad emission lines. Figure 2.2 highlights the differences of the spectra of Type I and Type II Seyfert galaxies.

Seyfert I galaxies, such as NGC 4593, show both broad and narrow emission lines in their optical spectra. The broad lines, such as $H\alpha$ and $H\beta$, typically have full widths at half maximum (FWHM) of several thousand kilometers per second and from the fast-moving, high-density gas in the BLR (Peterson 1997). In contrast, narrow lines, including prominent forbidden transitions like $[\text{O III}] \lambda 5007$ or $[\text{N II}] \lambda 6584$, originate from the slow-moving, low-density gas in the NLR (Peterson 1997). The presence of both components in the spectrum allows for a clear classification as a Seyfert I galaxy, 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 ratio of the broad towards the narrow 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). The fact that the optical spectrum shows multi-component lines with both broad and narrow components, suggests that these emission lines originate in the BLR and the NLR in the respective ratio (Peterson 1997).

In comparison, Seyfert II galaxies completely lack these broad components in their optical spectra, likely due to orientation-dependent obscuration by the dusty torus. Following that the classification of a Seyfert galaxies strongly depends on the viewing angle of the observer, which is the key point for the Unified Model of AGN, which will be deepened in section 2.1.3 (Peterson 1997).

Another notable subclass is the group of so-called narrow-line Seyfert I galaxies (NLS1s). They show most of the features of Seyfert 1 or 1.5 galaxies, except that the usually broad lines, such as the H I or He I lines, exhibit FWHM values that are only slightly larger than those of the narrow lines. They show a wide dispersion of spectral properties, with some objects have very strong Fe II emission, whereas others show almost none. This indicates that NLS1s do not form a homogeneous class (Osterbrock & Pogge 1985). NLS1s are thought to have low-mass black holes accreting at high Eddington rates, suggesting they may represent a young evolutionary phase of AGN activity (Peterson 2011; Netzer 2013). Another possible explanation is an orientation effect. When an NLS1 is observed at a very low inclination, the projected velocities are reduced, which leads to smaller observed Doppler broadening and therefore to narrow lines (Osterbrock & Pogge 1985).

Additional AGN Classes

In addition to Seyfert galaxies, there are several other classes of AGN. Quasars, which stands for quasi-stellar radio sources, are even more luminous than Seyfert galaxies and are typically found at higher redshifts. While the host galaxies of Seyfert galaxies are still observable, quasars completely outshine their host galaxies. Since quasars show similar emission characteristics to Seyfert galaxies, the modern distinction is based mainly on luminosity: quasars are classified as high-luminosity AGNs, while Seyfert galaxies represent the lower-luminosity end (Netzer 2013).

Radio galaxies form another important AGN class, distinguished by their strong radio emission and prominent jets, typically found in elliptical host galaxies. When their jets are aligned close to our 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 shows an illustration of the Unification Model, which was postulated by Robert Antonucci in 1993. He proposed that the visible differences in AGN spectra are not due to fundamentally different structures. Instead, they arise mainly from the viewing angle toward the AGN center and from obscuration by the dusty torus (Antonucci 1993).

The figure shows with what type the same AGN would get classified depending on the observers viewing angle. Like mentioned before, the dusty torus plays a key role here, as it surrounds the central region of the AGN, the accretion disk and the fast-moving BLR. If the observer's line of sight is blocked by the torus, only radio emission, the optical/UV continuum and narrow-line emission from the NLR outside the torus can be detected. In this case, the AGN is classified as a Seyfert 2 galaxy, as the broad emission lines originating from the BLR are obscured and the optical/UV continuum from the accretion disk is only partially visible. The observer essentially views the AGN from a flat angle, looking directly at the torus. If, on the other hand, the observer has a direct view into the central region of the AGN, not obscured by the torus, the fast moving gas clouds of the BLR as well as the optical/UV emission continuum from the accretion disk become visible. In this case, both broad and narrow emission lines are visible, meaning the AGN is classified as a Seyfert 1 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, on the other hand, 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 (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).

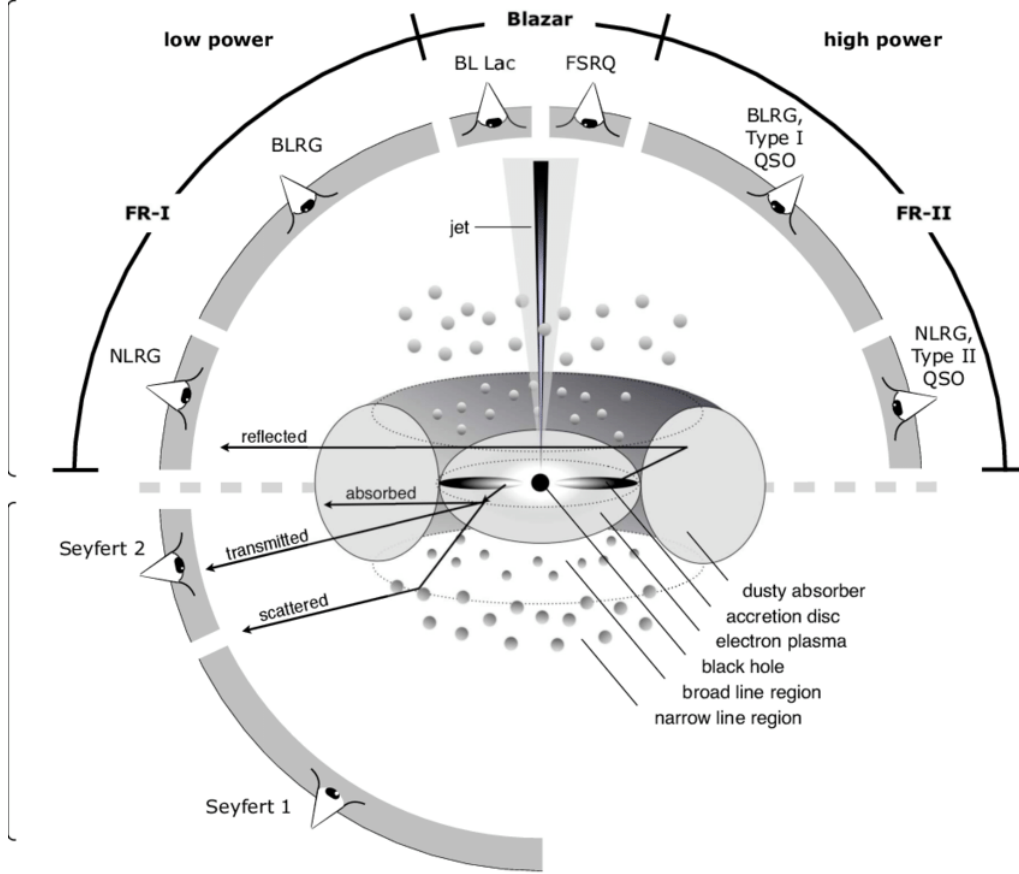


Figure 2.3: This graphic shows a schematic of the unification model of an AGN. The figure was adopted from (Beckmann & Shrader 2013).

2.1.4 Variability

The variability of active galactic nuclei (AGNs) 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; Ochmann et al. 2024). 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 me-

chanical 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., the broad-line region, 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 (Cackett et al. 2018).

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 (Cackett et al. 2021). The time lag τ corresponds to the average light-travel time between the photoionizing continuum source and the line-emitting regions. Assuming an idealized BLR consisting of spherically distributed clouds (Goad et al. 2012), then τ can be written as (Peterson



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

1997)

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

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).

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 (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 (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.



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 observation campaign of NGC4593 in 2016 by Cackett et al. 2018. 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 $RA = 12^h39^m39.44^s$, $Dec = -05^\circ20'39.03''$ (J2000) and has a redshift of $z = 0.0083 \pm 0.0005$, corresponding to a distance of ~ 35.9 Mpc (Koss et al. 2022) 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; Cackett et al. 2018; Ochmann et al. 2025). Several variability and reverberation-mapping campaigns have monitored different broad emission lines, including 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 a eccentric of $e \approx 0.22$ and a low-inclination of $i \approx 11^\circ$ Ochmann et al. 2024.

3.2 The 2016 Hst Campaign

The campaign of Cackett et al. 2018 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. Observa-

tions 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. 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). Remaining hot pixels were removed manually by interpolating the flux from neighboring pixels.

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

Grating	Range [Å]	Exp. Time [s]	Res. Power	Dispersion [Å/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

Reverberation mapping requires multiple epochs to capture variability. For the 2016 campaign of NGC 4593, 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 4000Å to 9000Å.

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 [O III] $\lambda 5007$. This indicates small wavelength misalignment between epochs.

Therefore, an intercalibration anchored to the narrow [O III] $\lambda 5007$ line was performed. This was achieved by shifting the wavelengths of the individual spectra and scaling the 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 flux of 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 \AA .

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 due to its limited reliability. 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] $\lambda 5007$ 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

This RM analysis starts with the identification of emission and absorption lines within the AVG spectrum. Figures 4.1 and 4.2 show the optical to near-infrared range between 3900Å and 9000Å and the UV range between 1100Å and 1700Å, respectively. Looking at Figure 4.1, it is possible to identify prominent broad emission lines in the AVG spectrum are the Balmer-Lines up to H ϵ , with H α being the strongest followed by H β and H γ , and several He-emission lines such as He I λ 4471, He II λ 4685, the He I λ 5015, He I λ 5875, He I λ 7065. Another significant broad emission line complex appears in the NIR part of the spectrum, including the O I λ 8446 emission line and the Ca II λ 8498 λ 8542 λ 8662 triplet. All of those lines show significant variation in the RMS, especially the Balmer-lines and the He II λ 4685 and He I λ 5875 with very good distinguishable profiles. The He I λ 4471, the He I λ 5015, the He I λ 7065, the O I λ 8446 emission line and the Ca II λ 8498 λ 8542 λ 8662 triplet show smaller but still noticeable variation. The He I λ 4471 and He I λ 5875 lines are blended with a Fe II emission line group in the AVG, which is vanishing in the RMS, as it shows no variation. The same applies to the Fe II emission line group around 5200 Å.

Apart from the broad emission lines, the AVG spectrum shows strong forbidden [O III] narrow emission lines. [O III] λ 5007 and [O III] λ 4958 are strong enough to be distinguishable, while the [O III] λ 4363 blends with H γ . As narrow lines they and several more weaker narrow lines, show no variability in the RMS spectrum over the period of the campaign.

The campaign also included an UV spectrum between 1000 Å and 1700 Å, which is shown in Figure 4.2. There are several broad lines in the UV spectrum, naming the Ly α line, which overlaps with the N V λ λ 1238, 1242 doublet, the Si IV λ λ 1393, 1402 doublet, the C IV λ λ 1548, 1550 doublet and the He II λ 1640 line. Ly α and C IV λ λ 1548, 1550

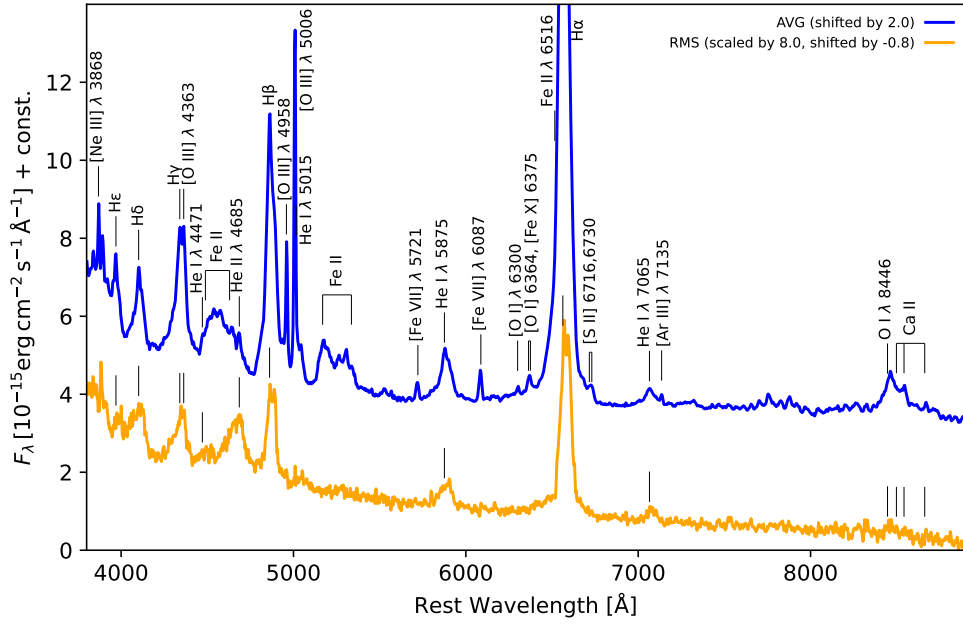


Figure 4.1: Optical-to-NIR AVG and RMS spectrum with identified emission lines.

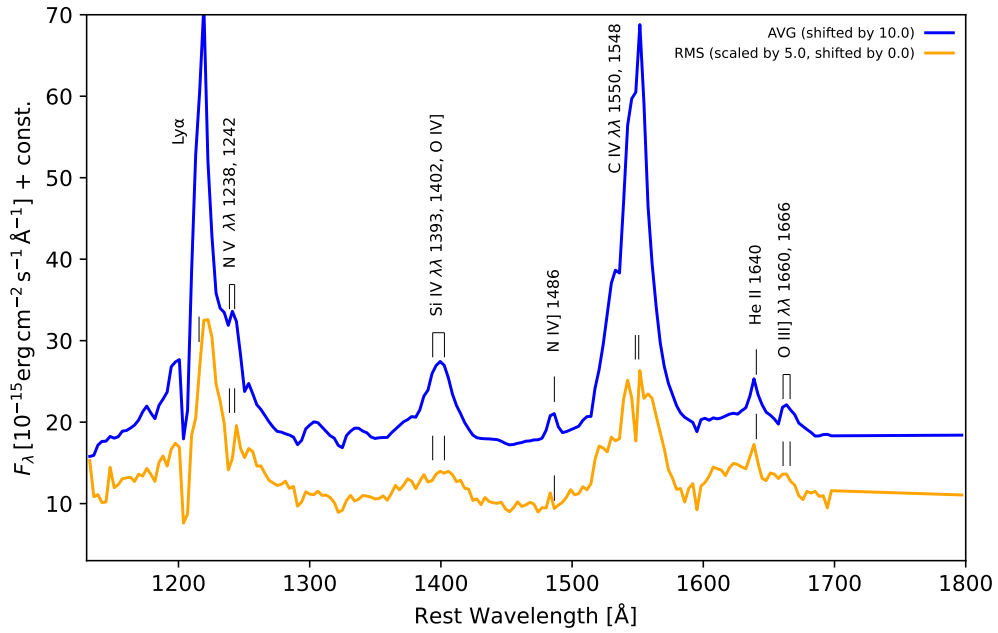


Figure 4.2: UV spectrum AVG and RMS spectrum with identified emission lines

show strong variation, while the variation of $\text{N V } \lambda\lambda 1238, 1242$ and $\text{He II } \lambda 1640$ is weaker but still noticeable. Like in the AVG spectrum, the variation of $\text{N V } \lambda\lambda 1238, 1242$ is overlapping with $\text{Ly}\alpha$ emission in the RMS as well, but is still distinguishable. The same applies to the variation of $\text{He II } \lambda 1640$, which is overlapping with the semi-forbidden line doublet $\text{O III] } \lambda\lambda 1660, 1666$.

4.2 Emission Line and Continua Measurement

After identifying the emission lines, the next step of the analysis is to measure the fluxes of those lines. This is done with the help of a python-based tool called GECHO created by M. Probst. It enables to import full campaigns, determine the AVG and RMS spectra, extracting lightcurves and do further measurements, naming here line-width measurements and lags measurement using the ICCF methode (Gaskell & Peterson 1987; Peterson et al. 2004), which will be further discussed in Section 4.4 and 4.5.

With help of GECHO the flux density gets integrated over the extent of each emission line for every observed spectrum of the campaign. Here it is important to define the integration limits so that all of the emission line flux is measured in this way. To ensure this, a parallel view of the AVG- and RMS-spectrum was used to define those integration limits, and to ensured, that no component of any other line is contributing to the line flux of the measured line. Additionally, the integration boundaries get selected, making sure they span a similar area in velocity space for every emission line. To accounting the surrounding continuum a linear underlying continuum gets interpolated and subtracted first. For this interpolation, sections on the blue and red side of the emission line with no line contribution gets selected. The chosen integration limits and pseudo-continua are listed in Table 4.1.

To measure the delay between the ionizing continuum and the emission lines it is necessary to extract lightcurves of selected continua in the AVG spectrum. Continua lightcurves are getting extracted by measuring the mean flux density of a sufficiently large region without line emission or absorption. The chosen integration limits for the continua can be found in Table 4.2.

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

Line	Integration Limits [Å]	Pseudo-Continua [Å]
Ly α	1207 – 1238	1151 – 1161, 1461 – 1469
Nv $\lambda\lambda$ 1238, 1242	1207 – 1238	1151 – 1161, 1461 – 1468
Siv $\lambda\lambda$ 1393, 1402	1358 – 1423	1151 – 1161, 1461 – 1469
Civ $\lambda\lambda$ 1548, 1550	1511 – 1578	1461 – 1469, 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
HeI λ 5875	5742 – 6039	5645 – 5653, 6044 – 6057
HeII λ 1640	1599 – 1645	1461 – 1468, 1680 – 1685
HeII λ 4685	4545 – 4758	4435 – 4450, 4762 – 4774
OI λ 8446	8380 – 8498	8005 – 8031, 8850 – 8955
OIII λ 5007	4982 – 5033	4762 – 4774, 5085 – 5112

Table 4.2: Integration Limits 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 lower-order 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 HeII, $\lambda 1640$ lightcurve, which shows significant higher variability with $R_{\max} \simeq 3.12$ and $F_{\text{var}} \simeq 0.31$.

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. 5600	1.36	2.15	1.59	1.82	0.25	0.14
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
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
HeII $\lambda 4685$	11.93	17.7	1.48	14.82	1.6	0.11
HeI $\lambda 5875$	8.53	13.82	1.62	11.58	1.01	0.09
OI $\lambda 8446$	7.47	9.13	1.22	8.32	0.37	0.04
Ly α	66.87	94.88	1.42	82.21	8.03	0.1
SiIV $\lambda\lambda 1393, 1402$	21.93	35.5	1.62	27.92	3.88	0.14
CIV $\lambda\lambda 1548, 1550$	115.31	165.57	1.44	138.77	12.12	0.09
HeII $\lambda 1640$	6.83	21.29	3.12	13.29	4.13	0.31

4.2.2 Uncertainties Estimation

The uncertainties of the continuum and emission-line lightcurves are estimated from two components. The first component originates from the noise in the flux densities over the pixels within the integration bounds, N_{pixel} . For the continuum lightcurves, the noise uncertainty is estimated as

$$\sigma_{\text{noise}}^{\text{cont}} = \frac{\sigma_F}{\sqrt{N_{\text{pixel}}^{\text{cont}}}}, \quad (4.3)$$

where σ_F denotes the standard deviation of the flux density within the selected continuum window. Since the emission-line lightcurves are extracted by integrating the continuum-subtracted flux density, the corresponding noise uncertainty is estimated using the noise measured from the used pseudo-continua, $\sigma_{\text{noise}}^{\text{p.cont.}}$:

$$\sigma_{\text{noise}}^{\text{lines}} = \frac{\sigma_{\text{noise}}^{\text{p.cont.}} \cdot \Delta\lambda}{\sqrt{N_{\text{pixel}}^{\text{line}}}}. \quad (4.4)$$

Here, $\Delta\lambda$ denotes the integration window used for the emission line, and $N_{\text{pixel}}^{\text{line}}$ denotes the number of pixels within this window.

The second component originates from the intercalibration of the epochs of the campaign. The flux of each epoch is scaled based on the narrow emission line [O III] $\lambda 5007$, which is assumed to be constant over the campaign. To account for the systematic uncertainty introduced by the intercalibration, the fractional variability of [O III] $\lambda 5007$ is multiplied by the integrated flux values f_i and used as a proxy for the intercalibration uncertainty:

$$\sigma_i^{\text{cal.}} = F_{\text{var}}^{[\text{O III}] \lambda 5007} \cdot f_i. \quad (4.5)$$

This yields the total light-curve uncertainty:

$$\sigma_i = \sqrt{(\sigma_i^{\text{cal.}})^2 + (\sigma_{\text{noise}})^2}, \quad (4.6)$$

where σ_{noise} corresponds to $\sigma_{\text{noise}}^{\text{cont}}$ for continuum light curves and to $\sigma_{\text{noise}}^{\text{lines}}$ for emission-line light curves.

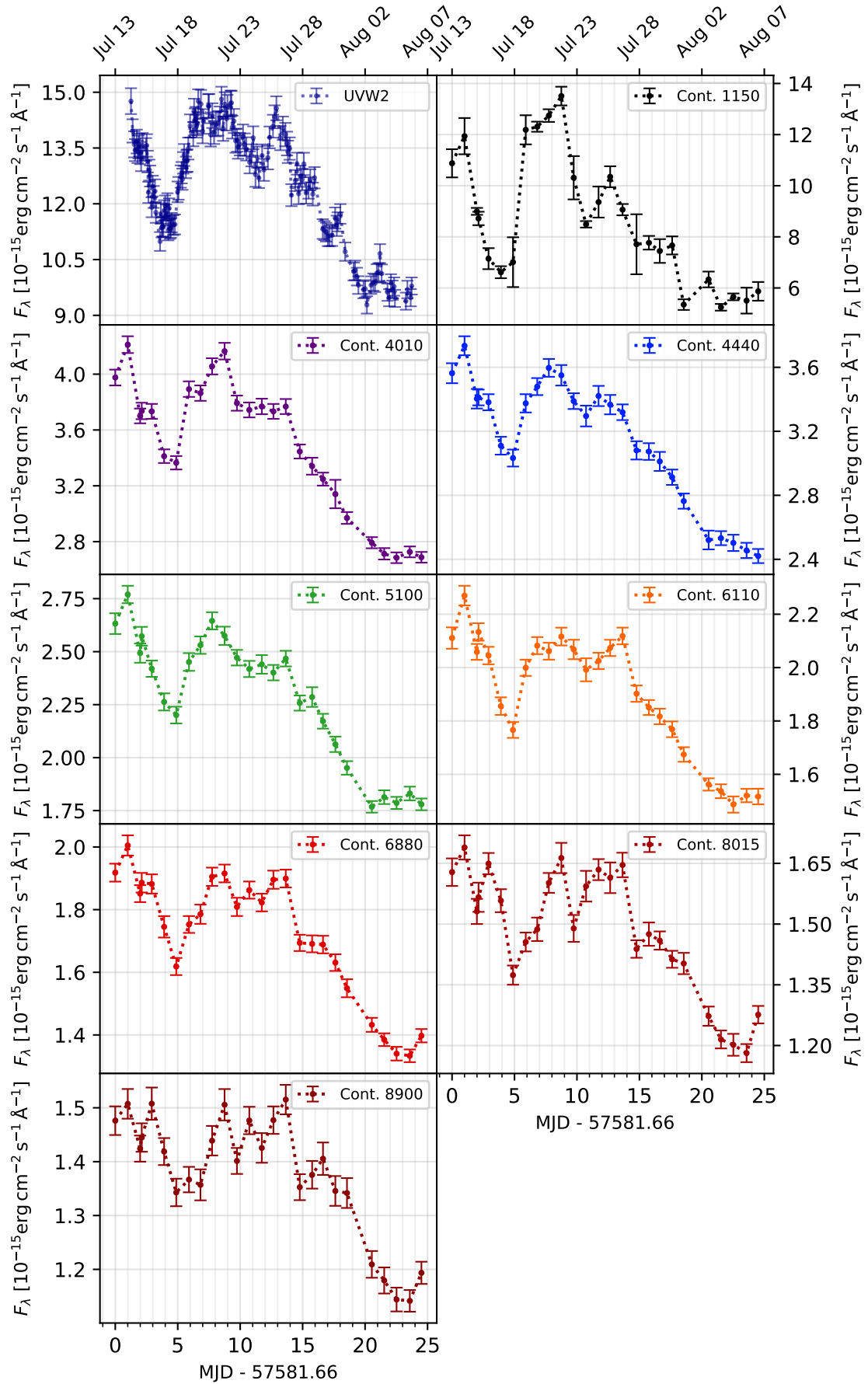


Figure 4.3: Comparison of the continuum lightcurves. The first panel shows the UVW2 continuum lightcurve obtained from McHardy et al. 2018, while the other panels show the measured continua defined in Table 4.2

4.3 Lightcurves

The extracted lightcurves of the continua and emission lines are shown in Figures 4.3, 4.4, and 4.5. In addition to the measured lightcurves of the HST campaign, the UVOT UVW2 lightcurve taken with *Swift* by McHardy et al. 2018, which was also used in Cackett et al. 2018, is included in this analysis, as it has a higher sampling rate than the light curves of the HST campaign. The spectra were 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 measured continuum lightcurves show a roughly similar shape (see Figure 4.3). The lightcurves start at a high flux level, followed by a significant decrease of about 50–80% relative to the maximum-to-minimum range of each curve approximately between the 1st and 6th day, with the minimum at around the 4th day. A central region follows, with again high flux with variation depending on the wavelength range of the continua. For the UV continua, this plateau ranges from the 6th to the 9th day and is followed by another smaller decrease in flux between the 9th and 13th day, before it increases again with peak at around the 13th day. Subsequently, the flux decreases, with small interim variation, towards a minimum at the end of the campaign. The continua between 4010 Å and 6110 Å also show a plateau-like shape between the 6th and 14th day, except for a small increase in flux between the 7th and 10th day, before decreasing again. The red and NIR continua show a roughly constant plateau between the 8th and 14th day, before decreasing in the same way as the other light curves, with another small, more pronounced flux plateau between the 15th and 17th day.

One goal of this reverberation mapping analysis is to estimate the physical distance between the SMBH and the region from which the emission lines originate. 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 case, 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 lightcurve around 1150 Å and the UVW2 lightcurve has to be taken into account.

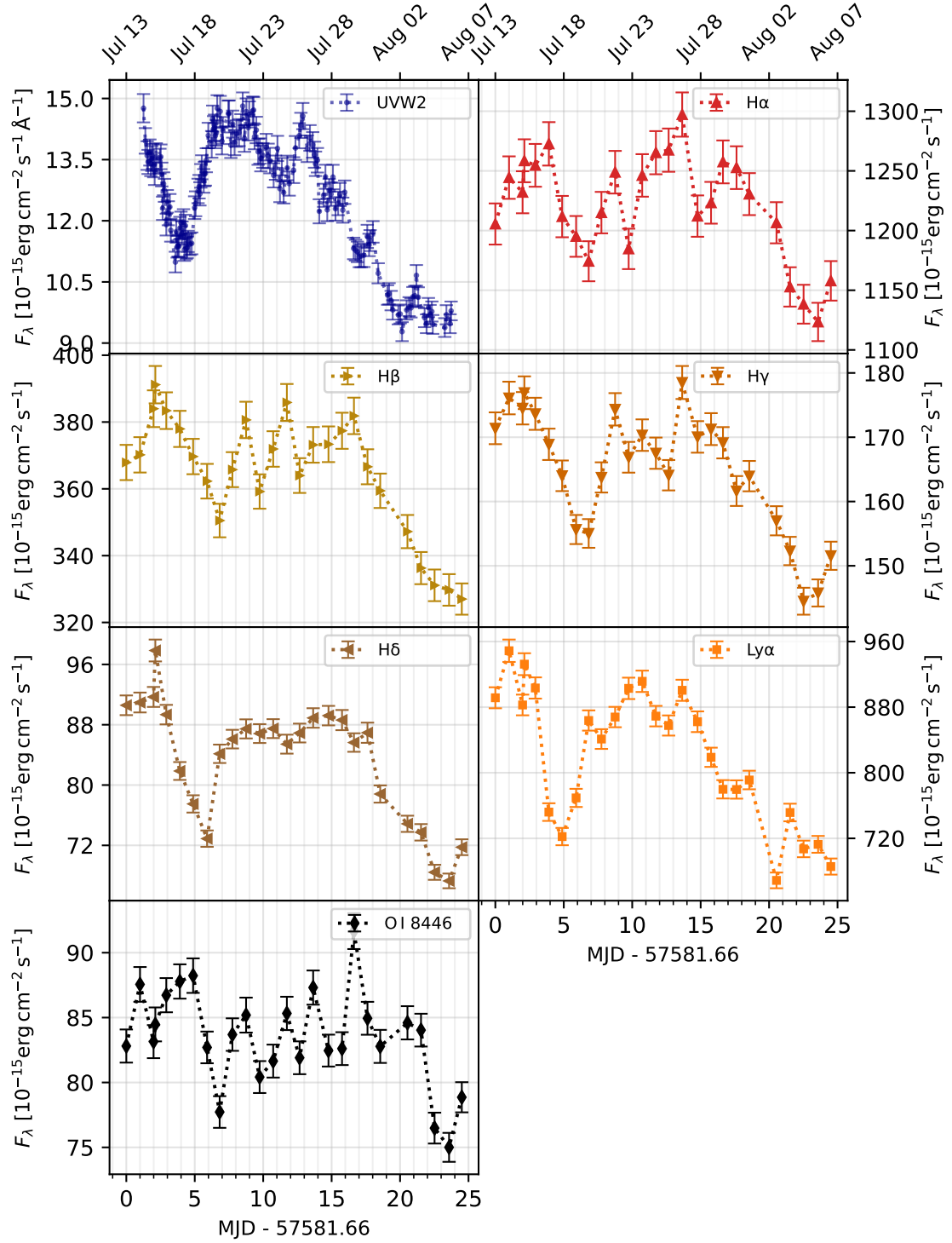


Figure 4.4: Comparison of the emission-line lightcurves to the UVW2 reference lightcurve in the first panel. The UVW2 lightcurve was obtained from McHardy et al. 2018

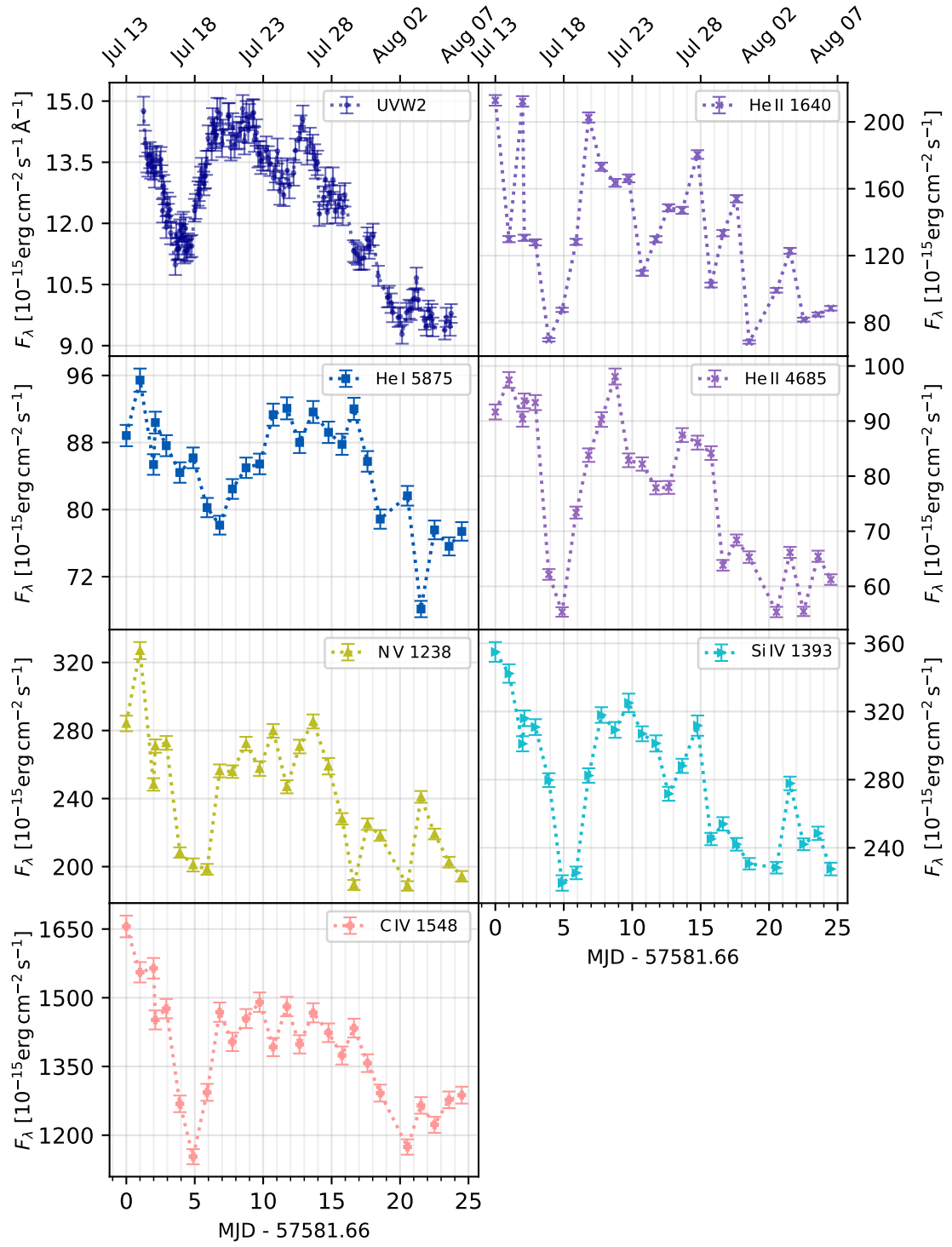


Figure 4.5: Comparison of the emission-line lightcurves to the UVW2 reference lightcurve in the first panel. The UVW2 lightcurve was obtained from McHardy et al. 2018

Figures 4.4 and 4.5 show the lightcurves of the measured broad emission lines in the optical-to-NIR range and in the UV range. Overall, the light curves show a similar shape to the UVW2 lightcurve: a high or increasing flux in the first few days, a pronounced minimum, a plateau-like central part that is fluctuating in some cases, 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 λ 8446, and He I λ 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

Following up, the line profiles of the broad lines get extracted. This is done for both, the AVG and RMS spectra. By analyzing their shape and line width 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 a chosen blue and red pseudo-continuum 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

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

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 4.6 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.

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 λ λ 1283, 1242	1151 – 1161, 1270 – 1285	1151 – 1161, 1340 – 1355
Si IV λ λ 1393, 1402	1350 – 1360, 1430 – 1440	1340 – 1355, 1430 – 1440
C IV λ λ 1548, 1550	1461 – 1468, 1679 – 1685	1461 – 1468, 1679 – 1685

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 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 λ λ 1548, 1550, Si IV λ λ 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 λ λ 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 $\text{OI } \lambda 8446$ 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 4.6.

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 $[\text{O III}] \lambda 4363$ next to $\text{H}\gamma$). 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 4.6). $\text{H}\alpha$ and $\text{He I } \lambda 5875$ are measured with the G750L grating with a dispersion of $4.97 (\text{\AA}/\text{pixel})$; $\text{H}\beta$, $\text{H}\gamma$, $\text{H}\delta$, 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 4.5. This dispersion is used as a minimum estimate for the uncertainty estimation.

The FWHM uncertainties of the RMS profiles of $\text{H}\gamma$, $\text{He I } \lambda 5875$, and the He II lines are scaled up due to their profile shape and noise. The RMS profile of $\text{H}\delta$ 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.

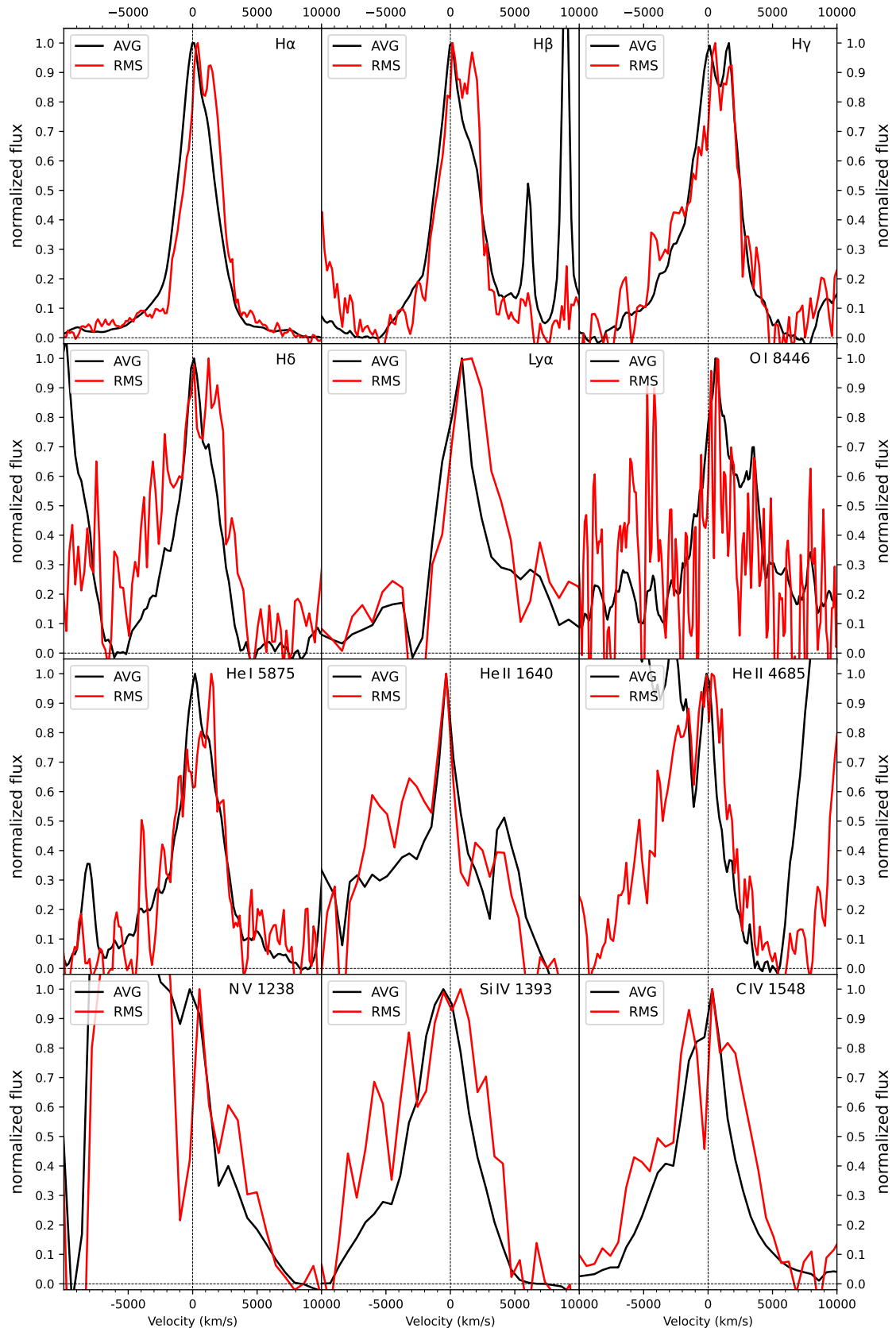


Figure 4.6: A plot of the AVG and RMS line profiles.

Table 4.5: Dispersion of grating in velocity space.

Line	Dispersion [$\frac{\text{km}}{\text{s}}$ /pixel]
Ly α	144.0
H α	222.9
H β	169.3
H γ	189.6
H δ	200.6
He I λ 5875	249.0
He II λ 1640	106.7
He II λ 4685	175.6
N V λ λ 1242	141.3
C IV λ λ 1548	113.1

Table 4.6: Measured FWHM and of the AVG and RMS line profiles.

Line	FWHM (avg)[km/s]	FWHM (rms)[km/s]
Ly α	3819 ± 350	4566 ± 350
H α	2974 ± 250	3111 ± 250
H β	3439 ± 200	3437 ± 200
H γ	4067 ± 200	3852 ± 400
H δ	3398 ± 250	5905 ± 1000
He I λ 5875	3477 ± 300	3952 ± 400
He II λ 1640	2847 ± 500	6891 ± 600
He II λ 4685	1839 ± 600	5971 ± 400
N V λ λ 1238, 1242	3216 ± 800	3383 ± 1000
Si IV λ λ 1238, 1242	5184 ± 500	10005 ± 1000
C IV λ λ 1548, 1550	5413 ± 500	8428 ± 500

4.4.2 Balmer Line-Profiles

Looking at the comparison of the Balmer RMS profiles in Figure 4.7, they all show a overall similar shape. The center of the profiles is shifted to positive velocities, with the peaks located between $\sim 0\text{--}500 \text{ km s}^{-1}$ and between $\sim 1500\text{--}2000 \text{ km s}^{-1}$. 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 H δ shows an additional peak at about 1000 km s^{-1} with a nearly similar flux than the blue peak of its profile.

Looking in more detail into the shape of RMS profiles, the profiles of H α and H β show the most similarity to each other, with both of their flanks following a similar shape. The same applies to the red flanks of H γ and H δ with steep slope and a small peak at about $\sim 3000 \text{ km s}^{-1}$. Only the blue flank of H γ and H δ is more extended

and noisy as for $H\alpha$ and $H\beta$. This leads to a slightly higher FWHM value for $H\gamma$ with $\sim 3900 \pm 400 \text{ km s}^{-1}$ compared to the values of $H\alpha$ and $H\beta$ with $\sim 3100 \pm 250 \text{ km s}^{-1}$ and $\sim 3400 \pm 200 \text{ km s}^{-1}$ and a much higher value of $\sim 5900 \pm 1000 \text{ km s}^{-1}$ for $H\delta$. 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 4.6 it can be seen, that most of the RMS profile is located within the red flank of the AVG profiles, suggesting that a largely part of the measured variation originates at positive velocities of the emitting region.

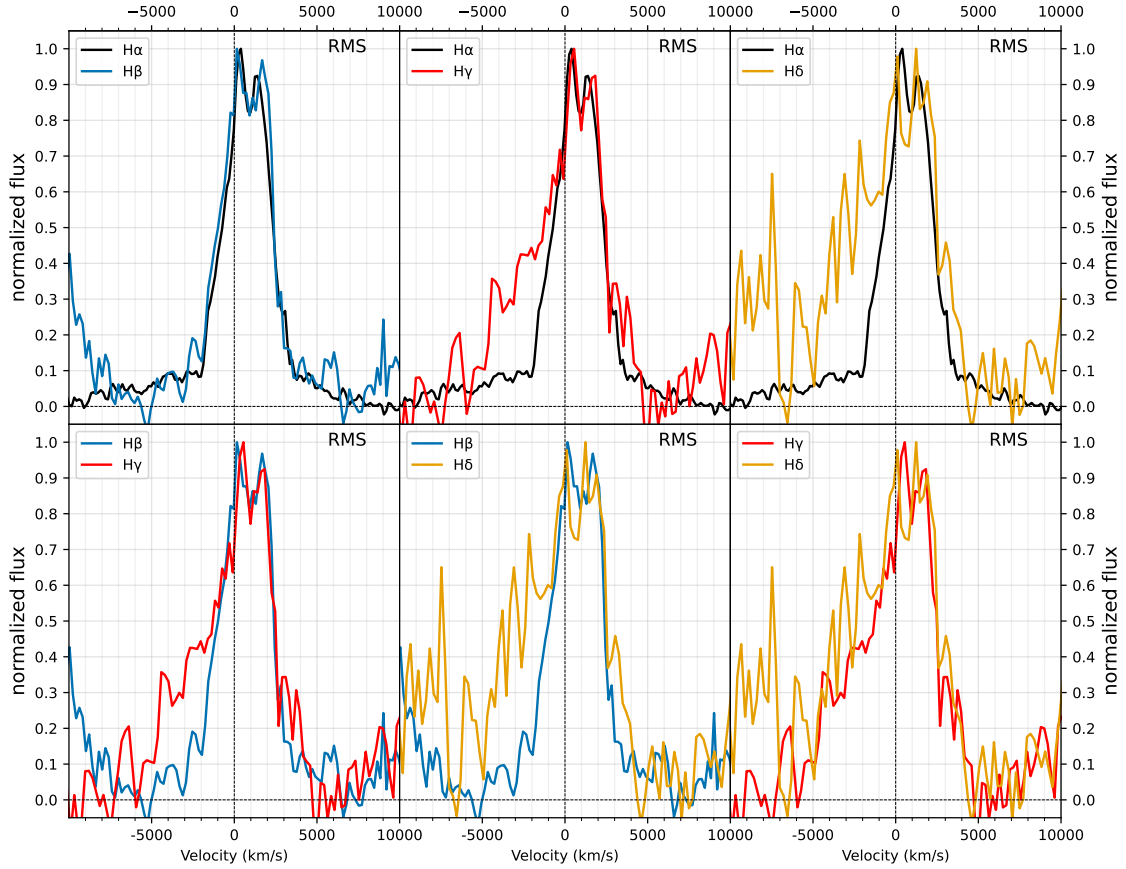


Figure 4.7: Comparison of the normalized AVG line profiles of the Balmer lines $H\alpha$, $H\beta$, $H\gamma$ and $H\delta$ in velocity space.

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 4.8. 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 no-

ticeable 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 flank and a steeper and narrower red flank, with a FWHM of about 4000 ± 400 .

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 flank and narrow red flank, 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 flank and a steep slope in its red flank. 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 $6900 \pm 600 \text{ km s}^{-1}$.

Comparing the RMS profiles of the He lines, all three show a similar shape with a extended blue flank and a narrow red flank, 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.

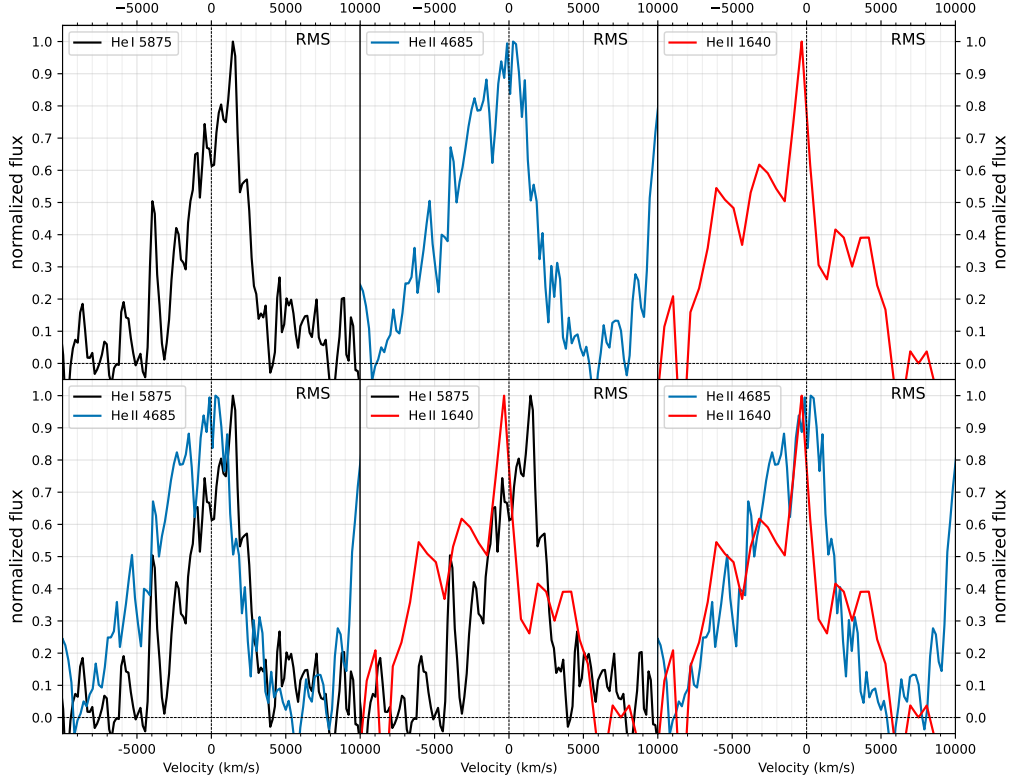


Figure 4.8: Comparison of the AVG and RMS line profiles of the Helium lines He I $\lambda 5875$ vs He II $\lambda 4685$.

4.4.4 UV Line Profiles

Figure 4.9 shows the RMS profiles of the $\text{Ly}\alpha$ line, the $\text{N v } \lambda\lambda 1238, 1242$ doublet, the $\text{Si iv } \lambda\lambda 1393, 1402$ doublet and the $\text{C iv } \lambda\lambda 1548, 1550$ doublet. Starting with $\text{Ly}\alpha$, its RMS profile is blended with line absorption in its blue flank, as well as with the $\text{N v } \lambda\lambda 1238, 1242$ doublet in his red flank. 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 flank and a slightly broader red flank, which a small broadening at about half height, resulting in a FWHM of about $\sim 4500 \pm 350 \text{ km s}^{-1}$.

The RMS profile of the neighboring $\text{N v } \lambda\lambda 1238, 1242$ doublet is blended with absorption as well as with the $\text{Ly}\alpha$ 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 flank of the central peak, resulting in an FWHM of about 3383 ± 1000 .

The RMS profile $\text{Si iv } \lambda\lambda 1393, 1402$ doublet shows a very broad and scattered profile and is blended with the semi-forbidden line doublet $\text{O iv } \lambda\lambda 1397, 1400$. 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 $\text{O iv } \lambda\lambda 1397, 1400$ doublet, the measured FWHM value will not taken into account for the subsequent analysis as well.

Finally, the RMS profile of the $\text{C iv } \lambda\lambda 1548, 1550$ 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 center 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 which is why the left flank of the blue peak and the right flank of the red peak has been used to measure the FWHM.

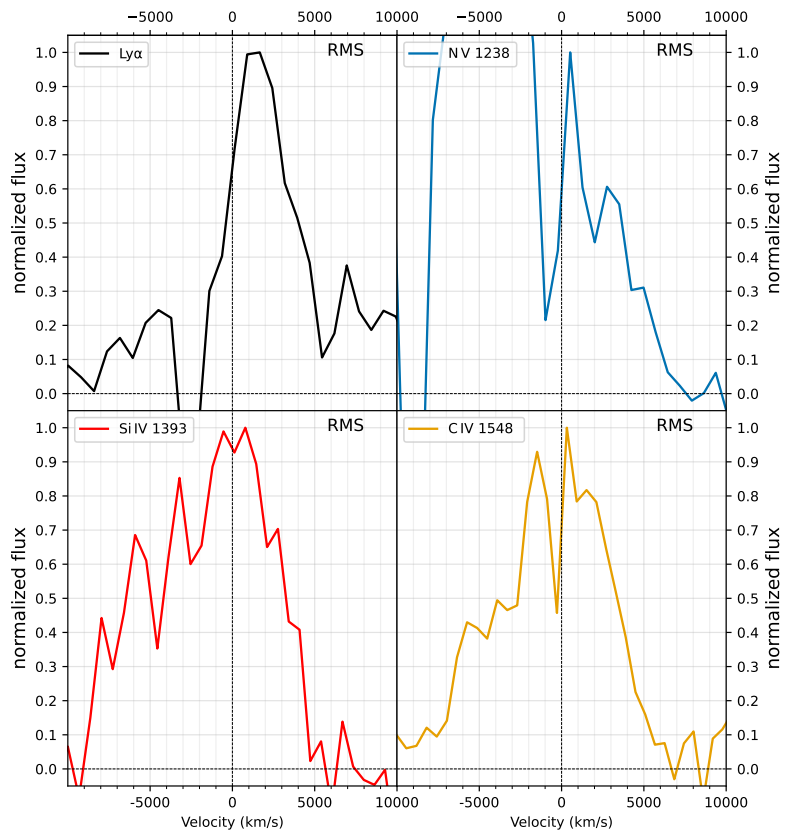


Figure 4.9: UV

4.5 Time Lag

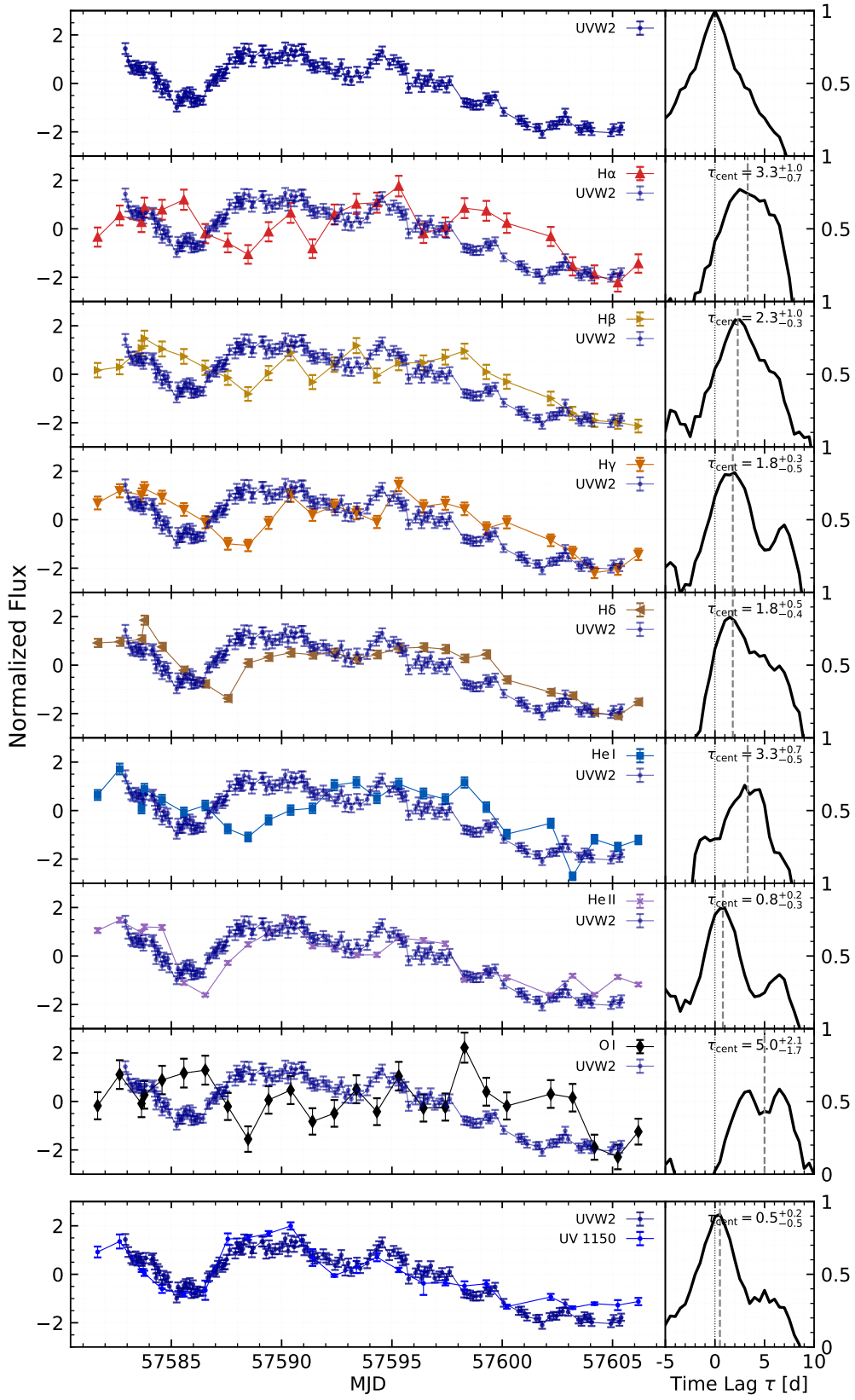


Figure 4.10: Compared lightcurves and CCFs H α , H β , H γ , He I λ 5875, He II λ 4685 and O I λ 8446 with UVW2 as reference lightcurve.

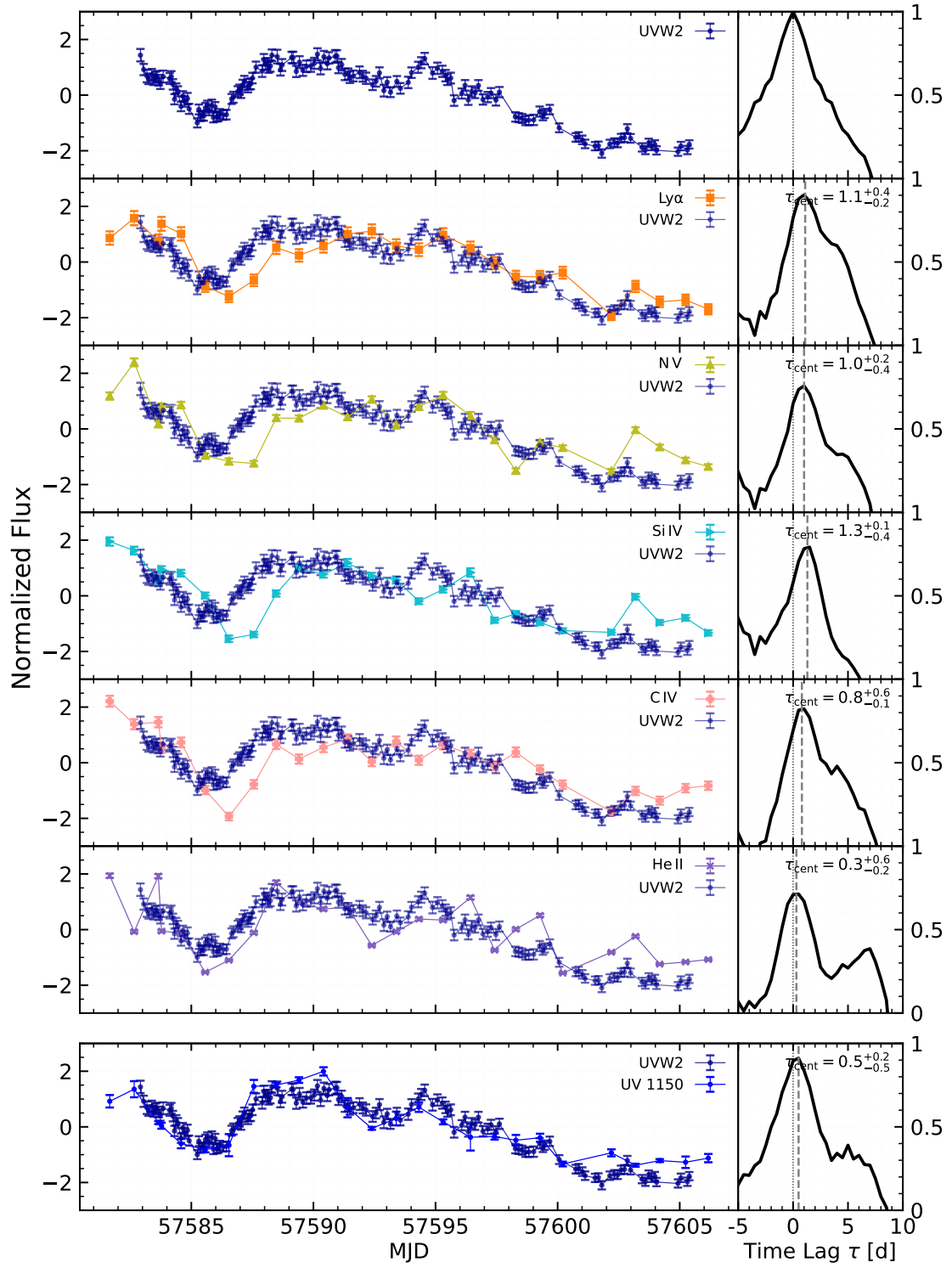


Figure 4.11: Compared lightcurves and CCFs of UV lines with UVW2 as reference lightcurve.

Table 4.7: Centroid and Peak Time Lag for UVW2.

Line	τ_{cent} [d]
Ly α	$1.0^{+0.4}_{-0.2}$
H α	$3.2^{+1.0}_{-0.6}$
H β	$2.3^{+1.0}_{-0.3}$
H γ	$1.7^{+0.2}_{-0.4}$
H δ	$1.7^{+0.4}_{-0.4}$
He I λ 5875	$3.3^{+0.7}_{-0.4}$
He II λ 1640	$0.3^{+0.6}_{-0.2}$
He II λ 4685	$0.7^{+0.1}_{-0.3}$
N V λ 1238	$1.0^{+0.2}_{-0.4}$
O I λ 8446	$5.0^{+2.1}_{-1.7}$
Si IV $\lambda\lambda$ 1393, 1402	$1.2^{+0.1}_{-0.4}$
C IV λ 1548	$0.8^{+0.5}_{-0.0}$

4.6 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). The time delay between the ionizing continuum and O I λ 8446 should be consistent with a time delay in which continuum variations drive Ly β variations, which in turn drive part of the O I λ 8446 response. 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 4.12. All lightcurve show a strong correlation between $\approx 0.75 - 0.8$, with the exception of the O I λ 8446 and UVW2 lightcurves, which show a maximum correlation of only 0.6. The time lags and their uncertainties are calculated as before. O I, λ 8446 lags behind Ly α by $2.5^{+1.8}_{-0.4}$ days and behind UVW2 by $5.0^{+2.1}_{-1.7}$ days, while H α lags behind Ly α by $1.8-0.5^{+0.5}$ days and behind UVW2 by $3.3^{+1.0}_{-0.7}$ days. A difference in the response

time of about 0.5–1 days between $\text{O I } \lambda 8446$ and $\text{H}\alpha$ is noticeable, but are not significant within the uncertainties. Looking at the $\text{O I } \lambda 8446$ and $\text{H}\alpha$ lightcurves, they also show a strong correlation, with $\text{O I } \lambda 8446$ lagging behind $\text{H}\alpha$ by about $0.3^{+2.0}_{-0.1}$ days. With the $\text{Ly}\alpha$ light curve lagging behind the UVW2 light curve by $1.1^{+0.4}_{-0.2}$ days, the total lag along the Bowen-fluorescence path from UVW2 to $\text{Ly}\alpha$ and from $\text{Ly}\alpha$ to $\text{O I } \lambda 8446$ sums to ≈ 3.6 days, which lies within the uncertainties of the time lag between the $\text{H}\alpha$ and UVW2 light curves.

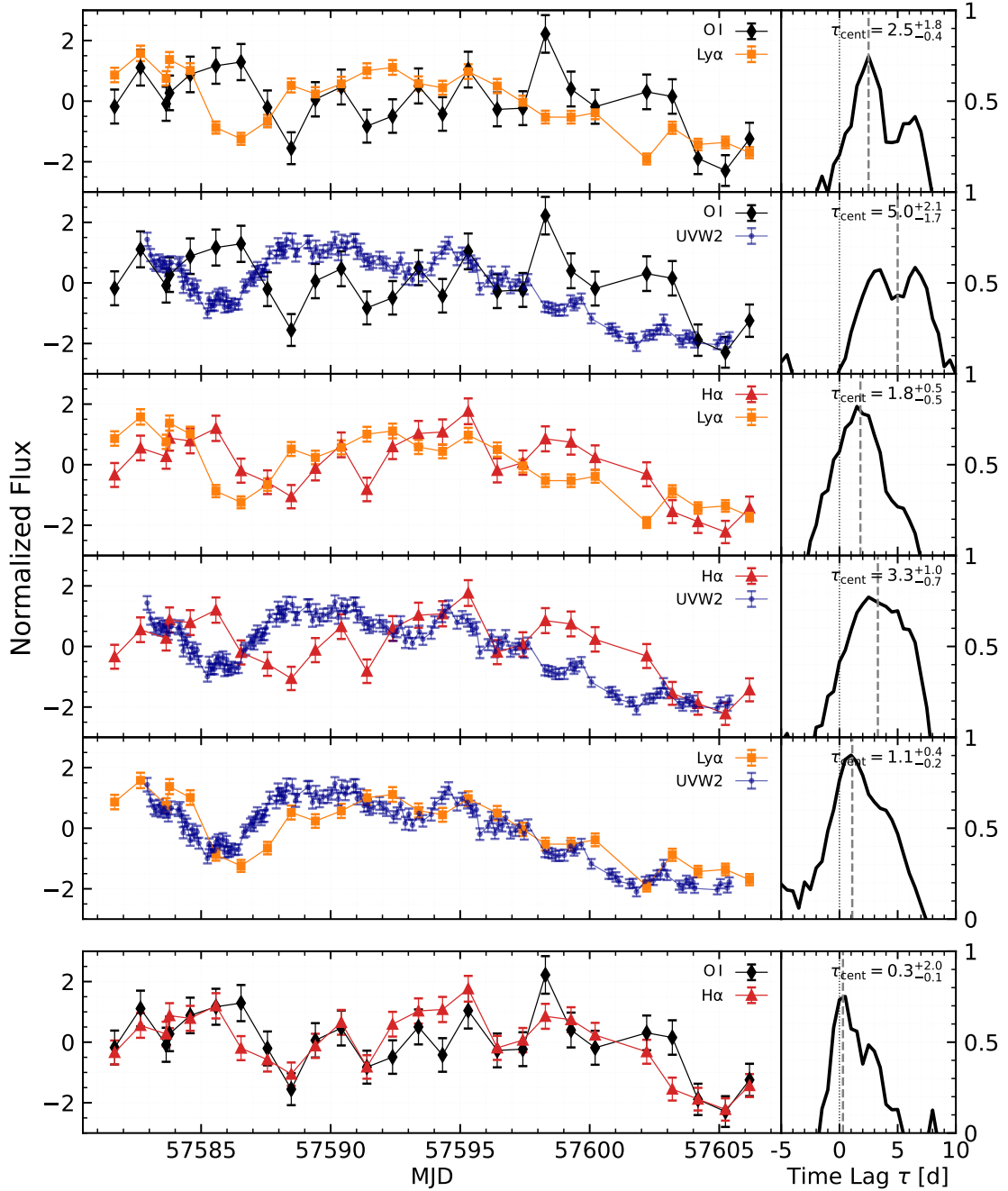


Figure 4.12: Compared lightcurves and CCFs for Bowen Fluorescence.

4.7 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 $\lambda 8446$, 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 4.8. To obtain a final estimation for the SMBH mass, an inverse-variance weighted mean is calculated. Since the uncertainties are asymmetric a symmetric 1σ uncertainty for the weights gets adopted, $\sigma_i = (\sigma_i^- + \sigma_i^+)/2$. 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 $\bar{M}_{\text{BH}} \approx (0.9 \pm 0.1) \times 10^7 M_{\odot}$.

Table 4.8: Estimated time lags, FWHM and SMBH masses.

Line	τ_{cent} [d]	FWHM (rms)[km/s]	$M_{\text{BH}}[10^7 M_{\odot}]$
Ly α	$1.0^{+0.4}_{-0.2}$	4566 ± 150	$0.7^{+0.3}_{-0.2}$
H α	$3.2^{+1.0}_{-0.6}$	3111 ± 250	$1.1^{+0.6}_{-0.4}$
H β	$2.3^{+1.0}_{-0.3}$	3437 ± 200	$0.9^{+0.6}_{-0.2}$
H γ	$1.7^{+0.2}_{-0.4}$	3852 ± 300	$0.9^{+0.3}_{-0.3}$
H δ	$1.7^{+0.4}_{-0.4}$	5905 ± 1000	$1.5^{+0.6}_{-0.5}$
He I $\lambda 5876$	$3.3^{+0.7}_{-0.4}$	3952 ± 300	$1.8^{+0.7}_{-0.5}$
He II $\lambda 1640$	$0.3^{+0.6}_{-0.2}$	6891 ± 600	$0.4^{+1.2}_{-0.3}$
He II $\lambda 4686$	$0.7^{+0.1}_{-0.3}$	5972 ± 300	$0.9^{+0.2}_{-0.4}$
N V $\lambda 1238$	$1.0^{+0.2}_{-0.4}$	3383 ± 1000	$0.4^{+0.4}_{-0.3}$
C IV $\lambda \lambda 1548, 1550$	$0.8^{+0.5}_{-0.1}$	8428 ± 300	$1.9^{+1.7}_{-0.2}$

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 $\bar{M}_{\text{BH,corr}} \approx (3.6 \pm 0.5) \times 10^7 M_\odot$.

5. Discussion

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