Contrib. Astron. Obs. Skalnaté Pleso **56/1**, 102 – 111, (2026)
https://doi.org/10.31577/caosp.2026.56.1.102

Ca II and O I as precision probes of the broad-line region in AGN

M.W. Ochmann[1], M.A. Probst[1], W. Kollatschny[1], L. Diehl[1], E.M. Cackett[2], D. Chelouche[3,4], R. Chini,[5,6], D. Grupe[7], M. Haas[5], K. Horne[8], S. Kaspi[9] and S. Komossa[10]

[1] *Institut für Astrophysik und Geophysik, Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany (E-mail: martin.ochmann@uni-goettingen.de)*

[2] *Department of Physics and Astronomy, Wayne State University, 666 W. Hancock Street, Detroit, MI 48201, USA*

[3] *Department of Physics, Faculty of Natural Sciences, University of Haifa, Haifa 3498838, Israel*

[4] *Haifa Research Center for Theoretical Physics and Astrophysics, University of Haifa, Haifa 3498838, Israel*

[5] *Ruhr University Bochum, Faculty of Physics and Astronomy, Astronomical Institute (AIRUB), 44780 Bochum, Germany*

[6] *Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, 00-716 Warszawa, Poland*

[7] *Department of Physics, Geology, and Engineering Technology, Northern Kentucky University, 1 Nunn Drive, Highland Heights, KY 41099, USA*

[8] *SUPA Physics and Astronomy, University of St. Andrews, Fife, KY16 9SS, United Kingdom*

[9] *School of Physics & Astronomy and the Wise Observatory, The Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv 6997801, Israel*

[10] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*

Received: October 1, 2025; Accepted: October 25, 2025

Abstract. Ca II and O I emission lines in active galactic nuclei (AGN) have been used as powerful diagnostic probes of the broad-line region (BLR) for the past 40 years. In particular, line ratio diagnostics have been used to constrain the physical conditions in the low-ionization phase of the BLR, while line width measurements have provided rough constraints on the location of the emission region relative to the Balmer-emitting phase of the BLR. However, due to limited observational capabilities, detailed line-profile studies of these lines—directly linking Ca II and O I with structural BLR models—have only become possible very recently. Here, we present an overview of our most recent study that has enabled investigations of Ca II and O I emission lines in unprecedented detail, directly linking Ca II triplet emission profiles to the kinematics of a rotating disk. We focus on our results for NGC 4593, but we also provide an outlook on how Ca II and O I open up a new observational window to probe the low-ionization part of the BLR in general.

Key words: NGC 4593 – active galactic nuclei – broad-line region – double-peaked emitter – reverberation mapping

1. Introduction

The O I emission lines and the Ca II triplet ($\lambda\lambda 8498, 8542, 8662$) have long been recognized as powerful diagnostic tools of the physical conditions and excitation mechanisms in active galactic nuclei (AGN). Early foundational works include studies by Grandi (1980, 1983), Persson & McGregor (1985); Persson (1988), Ferland & Persson (1989), and Joly (1989). Strong similarities between the emission-line profiles of these species have been firmly established (Persson, 1988; Rodríguez-Ardila et al., 2002a; Matsuoka et al., 2007) and are interpreted as evidence that the Ca II and O I emitting regions are largely co-spatial and share similar physical conditions. Later studies have adopted a unified view of the two species (e.g., Matsuoka et al., 2008; Marziani et al., 2013; Martínez-Aldama et al., 2015, 2021).

Given the inferred similarity in the physical conditions for Ca II and O I, a central question is where within the BLR these low-ionization lines are emitted. Answers to this question were already given in the earliest studies of Ca II in AGN: Persson (1988) noted that if Ca II triplet emission is observed in AGN, the triplet ratio is usually 1:1:1, indicating that the emission region is optically thick in Ca II. Model calculations later confirmed this conclusion by means of photoionization calculations that placed the emitting region in a cool and dense gas with temperatures of $T \leq 8000\,\mathrm{K}$, densities of $n_H \simeq 10^{12}\,\mathrm{cm}^{-3}$, and column densities of $N_H \geq 10^{23}\,\mathrm{cm}^{-2}$ (Ferland & Persson, 1989; Joly, 1989; Matsuoka et al., 2007). Such physical conditions are characteristic of an outer, cold accretion disk, with Ferland & Persson (1989) and later Dultzin-Hacyan et al. (1999) linking the Ca II emission to a wind or corona above the disk.

However, despite evidence that Ca II emission—and O I emission, for that matter—is closely tied to the atmosphere of an outer accretion disk, disk-line profiles (Chen & Halpern, 1989; Eracleous et al., 1995, 2009) of these species had remained elusive until very recently. Dias dos Santos et al. (2023) reported, for the first time, the detection of a double-peaked O I profile—that of O I λ11287—in the near-infrared spectrum of III Zw 002. Shortly after, Ochmann et al. (2024) reported the detection of double-peaked O I λ8446 as well as of double-peaked near-infrared Ca II triplet profiles in a transient spectrum of NGC 1566. This detection was followed by the detection of double-peaked O I λ8446 and Ca II triplet emission in a non-transient spectrum of NGC 4593 (Ochmann et al., 2025). Here, we summarize the key results of Ochmann et al. (2025) and discuss how future studies of O I and Ca II emission could help to advance our understanding of the BLR.

2. Observations of NGC 4593

NGC 4593 is a local ($z = 0.008312$) face-on Seyfert galaxy, which has been extensively studied in past variability campaigns (e.g., Dietrich et al., 1994; Santos-Lleo et al., 1995; Kollatschny & Dietrich, 1997; Denney et al., 2006; Barth et al., 2015; McHardy et al., 2018; Cackett et al., 2018). The detection of double-peaked O I and Ca II in NGC 4593 was made from a spectrum obtained with VLT/MUSE (Multi Unit Spectroscopic Explorer; Bacon et al., 2010, 2014) IFU spectrograph as part of the ESO program 0103.B-0908 (PI: Knud Jahnke) on 2019 April 28, with a total exposure time of 4800 s. Further details on the observations and data reduction are provided in Ochmann et al. (2025).

3. Results

We analyzed the VLT/MUSE spectrum of NGC 4593 and identified, for the first time, double-peaked profiles in both O I λ8446 and the Ca II triplet. We performed a detailed decomposition of the near-infrared O I λ8446 and Ca II triplet blend in the MUSE spectrum. We assumed identical line profiles of the Ca II triplet lines and used the unblended red wing of the Ca II λ8662 profile as a template for the red wing of Ca II λ8542. In this way, we were able to reconstruct a clean Ca II λ8662 profile, which was used for the final decomposition of the line blend shown in Fig. 1, resulting in a clean, unblended O I λ8446 profile.

The extracted line profiles of O I and Ca II are double-peaked with a full width at half maximum (FWHM) of $\sim$ 3700 km s^{-1}. They exhibit a redward asymmetry with a red-to-blue peak ratio of 4:3. The intensity ratio of the Ca II lines is 1:1:1, suggesting a high-density emission zone in the BLR. The Ca II emission lines show no evidence of a central narrow or intermediate-width component. The profiles of Ca II and O I are remarkably similar, and we especially note the particular similarity in the red wings of both lines. Overall, the similarity between the O I λ8446 and Ca II lines suggests a very similar, overlapping emission region for both line species.

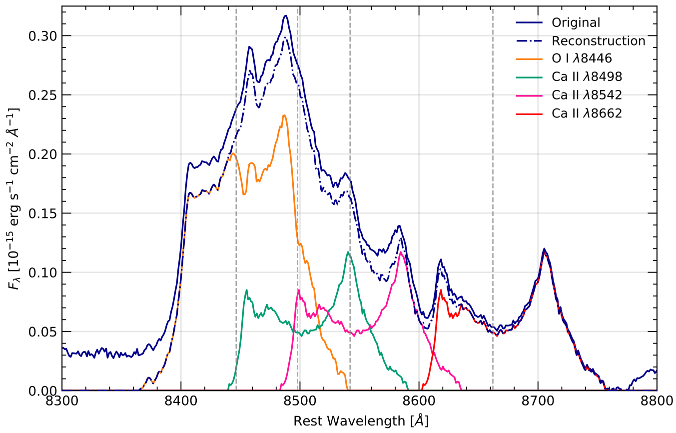

Figure 1. Decomposition of the blended O I λ8446 and Ca II triplet emission lines using the reconstructed Ca II λ8662 profile as a template for all Ca II lines. The difference between original spectrum and reconstructed blend is due to the subtraction of a linear pseudo-continuum beneath each emission line. The central wavelengths of the emission lines are indicated by dashed lines. Data taken from Ochmann et al. (2025).

To test how well the observed double-peaked Ca II profile agrees with predictions from line-emitting, non-axisymmetric accretion disk models, we fitted the profile with the elliptical disk-line model of Eracleous et al. (1995), which has seven free parameters: the inner and outer pericenter distance ξ_1 and ξ_2, the inclination angle i, the major axis orientation ϕ_0, the broadening parameter σ, the disk eccentricity e, and the emissivity power-law index q. The best-fit results are given in Table 1. For details on the fitting procedure see Ochmann et al. (2025).

Table 1. Best-fit parameters for the Ca II λ8662 profile obtained by applying the elliptical line-emitting accretion disk model.

Profile	ξ_1 [r$_g$]	ξ_2 [r$_g$]	i [deg]	ϕ_0 [deg]	σ [km s^{-1}]	e	q
Ca II λ8662	320^{+9}_{-10}	1103^{+29}_{-33}	$10.8^{+0.1}_{-0.1}$	$57.1^{+1.6}_{-1.1}$	65^{+11}_{-8}	$0.22^{+0.01}_{-0.01}$	$-1.27^{+0.05}_{-0.05}$

We find that the double-peaked Ca II λ8662 profile is in good agreement with emission from a non-axisymmetric disk with an eccentricity of $e \sim 0.22$, confined within $\sim 320 - 1100\,\mathrm{r_g}$, and with an inclination of $\sim 11°$. We particularly point out the remarkably low internal turbulence of only $\sigma \sim 65\,\mathrm{km\,s^{-1}}$. This is the lowest value reported for an AGN emission line to date and is significantly lower than typical values obtained for Balmer lines in other sources (e.g., Strateva et al., 2003; Ward et al., 2024).

4. Conclusions from Ochmann et al. (2025)

The emission-line profiles of the Ca II triplet can be well reproduced with the elliptical line-emitting accretion disk model, yielding a rather sharply defined disk (between $\sim 320 - 1100\,\mathrm{r_g}$) with a small eccentricity of $e \sim 0.22$. This is only the second time—after the case of NGC 1566, for which the first double-peaked profiles of the Ca II triplet were reported by Ochmann et al. (2024)—that double-peaked profiles of Ca II have been found[1], linking the Ca II-emitting region directly to the kinematics of a rotating disk, thus bridging the gap to predictions from photoionization calculations (Ferland & Persson, 1989; Joly, 1989) that place this region in the wind or corona of an outer accretion disk. We especially point out the low internal turbulence in Ca II observed for both NGC 4593 and NGC 1566, consistent with high kinematic ordering close to the mid-plane of the disk. This suggests that line broadening in Ca II is primarily due to Keplerian rotation with only minor contributions from turbulence, making these emission lines a valuable tool for studying the BLR by being able to directly trace its kinematics. Such an undisturbed view of BLR dynamics offers great potential for refining BLR models and testing scenarios of complex gas motion, including, for instance, supermassive black hole binaries (SMBHBs) (e.g., Popović, 2012). Obtaining and modeling such high-fidelity line profiles, however, requires data of the highest quality—i.e., with sufficient signal-to-noise ratio, spectral resolution, and a small enough aperture to avoid host-galaxy absorption affecting the Ca II profiles—in order to recover clean line profiles of Ca II and O I.

5. Outlook & Future Prospects

The first detections of clean disk-line profiles in Ca II $\lambda\lambda 8498, 8542, 8662$ and O I $\lambda 8446$ demonstrate the potential of detailed line-profile studies of these low-ionization lines. Further high-quality observations of Ca II and O I emission in additional sources are strongly encouraged to establish these transitions as a novel probe of BLR structure and geometry in AGN. We stress that complex Ca II and O I emission features are already visible in published data (e.g., Persson, 1988; Garcia-Rissmann et al., 2005; Landt et al., 2008), which motivates a closer reinspection of archival spectra to search for further signatures of disk-line or complex emitters.

[1] We note that the double-peaked feature in the Ca II triplet is also discernible in spectra of NGC 4593 already presented by Garcia-Rissmann et al. (2005) and Landt et al. (2008), but had not been recognized until now.

A particularly valuable next step would be reverberation mapping (RM) campaigns of Ca II and O I, especially in AGN exhibiting disk-line profiles (Ochmann et al., submitted). Although RM campaigns exist for other low-ionization lines such as the Balmer series or Mg II λ2800 (e.g., Shen et al., 2016; Czerny et al., 2019), there are so far no dedicated monitoring programs for Ca II or O I. Measuring their lags and velocity-resolved responses would directly link the double-peaked profiles to the size and geometry of the emitting region, thereby testing a disk-plane origin and possible vertical stratification within the BLR through comparison with the RM signatures of other lines.

Notably, Lyβ pumping is assumed to be the dominant excitation mechanism of O I λ8446 in many AGN (e.g., Rudy et al., 1989; Rodríguez-Ardila et al., 2002b; Landt et al., 2008). Therefore, if a variable signal in O I were detected in a source where Lyβ pumping dominates, its variability would likely be causally linked to changes in the Lyβ flux.[2] We propose that this could be utilized in future campaigns to study the structure of the BLR, in particular its vertical stratification: For large enough BLRs, differences between the delay chains from the continuum $\rightarrow$ Lyα/Lyβ $\rightarrow$ O I and that from the continuum $\rightarrow$ Hα/Hβ in light-travel time may become measurable, provided that the different excitation channels operate on spatial scales comparable to the observational cadence. In this framework, the Lyβ line effectively acts as an intermediate reprocessor, introducing an additional delay channel beyond the direct continuum response and thereby allowing a new diagnostic handle on vertical BLR geometry. More precisely, if the bulk of the Lyα/Lyβ emission is generated at some distance from the ionizing source, but not directly along the line of sight to O I or Hα/Hβ, which "see" the ionizing continuum, then the light-travel path from the continuum source via Lyα/Lyβ to O I or Hα is longer than the direct path from the continuum source to O I or Hα. The basic principle of this reverberation mapping utilizing two different, spatially offset drivers, namely the ionizing continuum and the pumping line, is shown in Fig. 2 for a planar BLR geometry with an assumed vertical stratification.

We emphasize that this is a rather simplified picture—for instance, it does not account for the spatial extent of the Lyα/Lyβ-emitting region or the covering factors of the individual BLR phases—but we propose that, depending on the exact geometry, such an approach could convey information about the scale-height-dependent BLR structure.

Acknowledgements. We are grateful to Peter M. Weilbacher for reducing the VLT/MUSE observations of NGC 4593. MWO acknowledges the support of the German Aerospace Center (DLR) within the framework of the "Verbundforschung Astronomie und Astrophysik" through grant 50OR2305 with funds from the BMWK. PMW was partially supported by the BMBF through the ErUM program (VLT-BlueMUSE 05A23BAC). EMC gratefully acknowledges support for program number

[2] In practice, Lyα may serve as a useful proxy for Lyβ, as Lyβ is observationally more challenging to access.

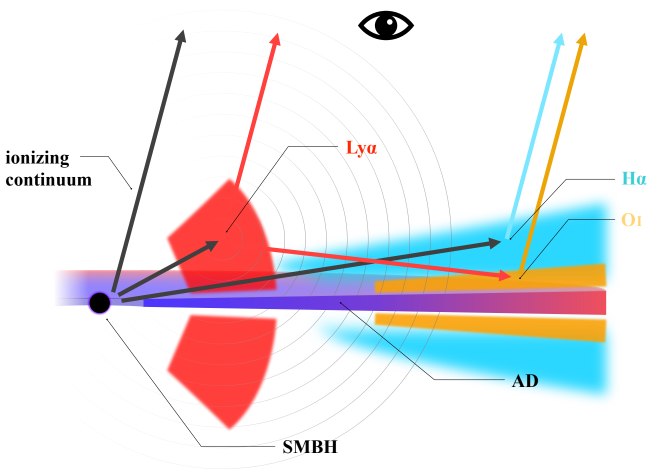

Figure 2. The basic principle of reverberation mapping of a Lyα/Lyβ-pumped emission line such as O I λ8446 for an almost planar BLR geometry with assumed vertical stratification. See text for details. The individual components are not to scale.

14121 provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. Research by DC is partly supported by the Israeli Science Foundation (1650/23). The authors greatly acknowledge support by the DFG grants KO 857/35-1, KO 857/35-2 and CH 71/34-3.

References

Bacon, R., Accardo, M., Adjali, L., et al., The MUSE second-generation VLT instrument. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **7735**, *Ground-based and Airborne Instrumentation for Astronomy III*, 773508

Bacon, R., Vernet, J., Borisova, E., et al., MUSE Commissioning. 2014, *The Messenger*, **157**, 13

Barth, A. J., Bennert, V. N., Canalizo, G., et al., The Lick AGN Monitoring Project 2011: Spectroscopic Campaign and Emission-line Light Curves. 2015, *Astrophysical Journal, Supplement*, **217**, 26, DOI:10.1088/0067-0049/217/2/26

Cackett, E. M., Chiang, C.-Y., McHardy, I., et al., Accretion Disk Reverberation with Hubble Space Telescope Observations of NGC 4593: Evidence for Diffuse Continuum Lags. 2018, *Astrophysical Journal*, **857**, 53, DOI:10.3847/1538-4357/aab4f7

Chen, K. & Halpern, J. P., Structure of Line-emitting Accretion Disks in Active Galactic Nuclei: ARP 102B. 1989, *Astrophysical Journal*, **344**, 115, DOI:10.1086/167782

Czerny, B., Olejak, A., Rałowski, M., et al., Time Delay Measurement of Mg II Line in CTS C30.10 with SALT. 2019, *Astrophysical Journal*, **880**, 46, DOI:10.3847/1538-4357/ab2913

Denney, K. D., Bentz, M. C., Peterson, B. M., et al., The Mass of the Black Hole in the Seyfert 1 Galaxy NGC 4593 from Reverberation Mapping. 2006, *Astrophysical Journal*, **653**, 152, DOI:10.1086/508533

Dias dos Santos, D., Rodríguez-Ardila, A., Panda, S., & Marinello, M., First Observation of a Double-peaked O I Emission in the Near-infrared Spectrum of an Active Galaxy. 2023, *Astrophysical Journal, Letters*, **953**, L3, DOI:10.3847/2041-8213/ace974

Dietrich, M., Kollatschny, W., Alloin, D., et al., Monitoring of active galactic nuclei. IV. The Seyfert 1 galaxy NGC 4593. 1994, *Astronomy and Astrophysics*, **284**, 33

Dultzin-Hacyan, D., Taniguchi, Y., & Uranga, L., Where is the Ca II Triplet Emitting Region in AGN? 1999, in Astronomical Society of the Pacific Conference Series, Vol. **175**, *Structure and Kinematics of Quasar Broad Line Regions*, 303

Eracleous, M., Lewis, K. T., & Flohic, H. M. L. G., Double-peaked emission lines as a probe of the broad-line regions of active galactic nuclei. 2009, *New Astronomy Review*, **53**, 133, DOI:10.1016/j.newar.2009.07.005

Eracleous, M., Livio, M., Halpern, J. P., & Storchi-Bergmann, T., Elliptical Accretion Disks in Active Galactic Nuclei. 1995, *Astrophysical Journal*, **438**, 610, DOI:10.1086/175104

Ferland, G. J. & Persson, S. E., Implications of CA II Emission for Physical Conditions in the Broad-Line Region of Active Galactic Nuclei. 1989, *Astrophysical Journal*, **347**, 656, DOI:10.1086/168156

Garcia-Rissmann, A., Vega, L. R., Asari, N. V., et al., An atlas of calcium triplet spectra of active galaxies. 2005, *Monthly Notices of the RAS*, **359**, 765, DOI:10.1111/j.1365-2966.2005.08957.x

Grandi, S. A., O I λ8446 emission in Seyfert 1 galaxies. 1980, *Astrophysical Journal*, **238**, 10, DOI:10.1086/157952

Grandi, S. A., Reddening indicators for quasars and Seyfert 1 galaxies. 1983, *Astrophysical Journal*, **268**, 591, DOI:10.1086/160982

Joly, M., Formation of CA II lines in active galactic nuclei. 1989, *Astronomy and Astrophysics*, **208**, 47

Kollatschny, W. & Dietrich, M., Balmer emission-line profile variations in NGC 4593. 1997, *Astronomy and Astrophysics*, **323**, 5

Landt, H., Bentz, M. C., Ward, M. J., et al., The Near-Infrared Broad Emission Line Region of Active Galactic Nuclei. I. The Observations. 2008, *Astrophysical Journal, Supplement*, **174**, 282, DOI:10.1086/522373

Martínez-Aldama, M. L., Dultzin, D., Marziani, P., et al., O I and Ca II Observations in Intermediate Redshift Quasars. 2015, *Astrophysical Journal, Supplement*, **217**, 3, DOI:10.1088/0067-0049/217/1/3

Martínez-Aldama, M. L., Panda, S., Czerny, B., et al., The CaFe Project: Optical Fe II and Near-infrared Ca II Triplet Emission in Active Galaxies. II. The Driver(s) of the Ca II and Fe II and Its Potential Use as a Chemical Clock. 2021, *Astrophysical Journal*, **918**, 29, DOI:10.3847/1538-4357/ac03b6

Marziani, P., Martínez-Aldama, M. L., Dultzin, D., & Sulentic, J. W., Low Ionization Emission Lines in Quasars. 2013, *The Astronomical Review*, **8**, 26, DOI:10.1080/21672857.2013.11519727

Matsuoka, Y., Kawara, K., & Oyabu, S., Low-Ionization Emission Regions in Quasars: Gas Properties Probed with Broad O I and Ca II Lines. 2008, *Astrophysical Journal*, **673**, 62, DOI:10.1086/524193

Matsuoka, Y., Oyabu, S., Tsuzuki, Y., & Kawara, K., Observations of O I and Ca II Emission Lines in Quasars: Implications for the Site of Fe II Line Emission. 2007, *Astrophysical Journal*, **663**, 781, DOI:10.1086/518399

McHardy, I. M., Connolly, S. D., Horne, K., et al., X-ray/UV/optical variability of NGC 4593 with Swift: reprocessing of X-rays by an extended reprocessor. 2018, *Monthly Notices of the RAS*, **480**, 2881, DOI:10.1093/mnras/sty1983

Ochmann, M. W., Kollatschny, W., Probst, M. A., et al., The transient event in NGC 1566 from 2017 to 2019. I. An eccentric accretion disk and a turbulent, disk-dominated broad-line region unveiled by double-peaked Ca II and O I lines. 2024, *Astronomy and Astrophysics*, **686**, A17, DOI:10.1051/0004-6361/202348559

Ochmann, M. W., Weilbacher, P. M., Probst, M. A., et al., Double-peaked Ca II traces a relativistic broad-line region disk in NGC 4593. 2025, *Astronomy and Astrophysics*, **697**, L5, DOI:10.1051/0004-6361/202554800

Ochmann, M. W. et al. 2025, submitted to A&A

Persson, S. E., Calcium Infrared Triplet Emission in Active Galactic Nuclei. 1988, *Astrophysical Journal*, **330**, 751, DOI:10.1086/166509

Persson, S. E. & McGregor, P. J., Ca II emission in I Zwicky 1. 1985, *Astrophysical Journal*, **290**, 125, DOI:10.1086/162966

Popović, L. Č., Super-massive binary black holes and emission lines in active galactic nuclei. 2012, *New Astronomy Review*, **56**, 74, DOI:10.1016/j.newar.2011.11.001

Rodríguez-Ardila, A., Viegas, S. M., Pastoriza, M. G., & Prato, L., Infrared Fe II Emission in Narrow-Line Seyfert 1 Galaxies. 2002a, *Astrophysical Journal*, **565**, 140, DOI:10.1086/324598

Rodríguez-Ardila, A., Viegas, S. M., Pastoriza, M. G., Prato, L., & Donzelli, C. J., The O I Line Emission in Active Galactic Nuclei Revisited. 2002b, *Astrophysical Journal*, **572**, 94, DOI:10.1086/340192

Rudy, R. J., Rossano, G. S., & Puetter, R. C., Detection of the O i 11287 Angstrom Line in the Seyfert 1 Galaxy I ZW 1. 1989, *Astrophysical Journal*, **342**, 235, DOI:10.1086/167587

Santos-Lleo, M., Clavel, J., Barr, P., et al., Multifrequency monitoring of the Seyfert 1 galaxy NGC 4593 - II. A small, compact nucleus? 1995, *Monthly Notices of the RAS*, **274**, 1, DOI:10.1093/mnras/274.1.1

Shen, Y., Horne, K., Grier, C. J., et al., The Sloan Digital Sky Survey Reverberation Mapping Project: First Broad-line Hβ and Mg II Lags at z 0.3 from Six-month Spectroscopy. 2016, *Astrophysical Journal*, **818**, 30, DOI:10.3847/0004-637X/818/1/30

Strateva, I. V., Strauss, M. A., Hao, L., et al., Double-peaked Low-Ionization Emission Lines in Active Galactic Nuclei. 2003, *Astronomical Journal*, **126**, 1720, DOI:10.1086/378367

Ward, C., Gezari, S., Nugent, P., et al., Panic at the ISCO: Time-varying Double-peaked Broad Lines from Evolving Accretion Disks Are Common among Optically Variable AGNs. 2024, *Astrophysical Journal*, **961**, 172, DOI:10.3847/1538-4357/ad147d