Chapter 2:
Spectroscopic methods

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Testing AGN outflow and accretion models with SDSS quasar demographics

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Abstract. One commonly-invoked launching mechanism for AGN outflows is radiation line driving. This mechanism depends closely on the SED of the ionizing continuum, and so is inherently linked to the structure of the accretion flow. Theories of radiation line-driven winds therefore provide testable predictions as a function of black hole (BH) mass and accretion rate. In this work we confront these predictions using the ultraviolet emission line properties of 190,000 quasars from SDSS DR17. We quantify how the shape of CIV 1549Å and the equivalent width (EW) of HeII 1640Å depend on the BH mass and Eddington ratio inferred from MgII 2800Å. The blueshift of the CIV emission line is commonly interpreted as a tracer of quasar outflows, while the HeII EW traces the strength of the 10-100 eV continuum which photo-ionizes the ultraviolet emission line regions. Above $L/L_{\rm Edd} > 0.2$, there is a strong mass dependence in both CIV blueshift and HeII EW. Large CIV blueshifts are observed only in regions with both high BH mass and high accretion rate, consistent with predictions for radiation line driven winds. The observed trends in HeII and 2 keV X-ray strength are broadly consistent with theoretical models of AGN SEDs, where the ionizing SED depends on the accretion disc temperature and the strength of the soft excess. At $L/L_{\rm Edd} < 0.2$, we find a dramatic switch in behaviour: the ultraviolet emission properties show much weaker trends, and no longer agree with SED models, hinting at changes in the structure of the broad line region. Overall the observed emission line properties are generally consistent with the radiation line driving scenario, where quasar winds are governed by the SED, which itself results from the accretion flow and hence depends on both the SMBH mass and accretion rate.

Keywords. quasars: emission lines

1. Introduction

A *quasar* is a luminous AGN, in which accretion onto the central supermassive black hole (BH) produces a large amount of electromagnetic radiation which can outshine the starlight from the host galaxy. Quasars emit across many wavebands, with a plethora of emission line features in the rest-frame ultraviolet and optical (Vanden Berk *et al.* 2001). These include both broad and narrow emission features. In the rest-frame ultraviolet, the broad lines can be further subdivided into high- and low-ionization species. The low-ionization lines are commonly observed to be symmetrical, suggestive of virialized gas surrounding the central BH. These can be used to estimate the mass of the BH, and all BH mass estimates in this presentation have been derived from the low-ionization MgII 2800Å line. In contrast, the high-ionization rest-frame ultraviolet emission lines display a diversity in their kinematic profiles (Richards *et al.* 2011; Temple *et al.* 2020, 2021a,b). Some objects show strong, symmetric line emission, while others show weaker emission which is skewed and blueshifted, suggesting ionized gas outflows along the line-of-sight to the observer. The outflow signatures seen in the CIV 1550Å line have been observed to correlate with other outflow signatures: the kinematics of [OIII] 5008Å (Coatman *et al.* 2019) and broad ultraviolet absorption features (Rankine *et al.* 2020).

1.1. *Some interesting questions*

The previous observational results outlined above naturally raise the question: *What drives the diversity of ultraviolet outflow properties in quasars?* The CIV morphology is known to correlate with luminosity, but the bolometeric luminosity is a function of both the BH mass and the normalised accretion rate $L/L_{\rm Edd}$. One can further ask: *Which of these parameters is responsible for driving the wind?*

1.2. *BH wind launching mechanisms and Quasar SEDs*

At the same time, one can also think about the launching mechanism which produces the outflows traced by the ultraviolet emission features. BH winds can be launched by thermal pressure, MHD processes, or radiation pressure on dust and/or lines. CIV outflows are likely too fast for thermal winds, and the theory of MHD processes is not yet sufficiently well developed to yield testable predictions for the behaviour of BH winds. On the other hand, radiation line driving is highly sensitive to the shape of the ionizing SED. The shape of this SED in turn depends on BH mass and accretion rate (Giustini & Proga 2019), meaning we can now test whether the demographics of CIV outflows are consistent with predictions for radiation line driven winds as a function of $M_{\rm BH}$ and $L/L_{\rm Edd}$.

Quasar SEDs can be modeled with three components (e.g. Kubota & Done 2018). These are (i) thermal emission from the multi-temperature accretion disc, (ii) hard X-ray non-thermal power-law emission from the corona, and (iii) the soft X-ray excess. Radiation line driving depends on both the flux at the line energy *and* the line opacity, which depends on the flux at the ionization edge, leading to a complicated interplay between the SED and the resulting wind.

We would like to measure the ionizing SED directly, but due to absorption from the intervening inter-galactic medium, we instead have to rely on indirect probes. HeII 1640 Å probes the 'unseen' ionizing continuum in the far ultraviolet which we can't observe directly. The relative strength of observed 2 keV emission is quantified through the $\alpha_{\rm ox}$ parameter, and probes the shape of the SED at higher energies, where the SED is sensitive to the accretion rate but plays only a minor role in photo-ionizing the ultraviolet line-emitting regions. With the data which is now available from large quasar surveys, we can compare the observed $\alpha_{\rm ox}$ and HeII strength with predictions from theoretical SED models such as those described by Kubota & Done (2018).

2. Data

The data and results presented in this talk were from a preliminary version of work which has since been published in *MNRAS* (Temple *et al.* 2023). The interested reader is encouraged to consult the *MNRAS* paper for full details. In brief, ≈190,000 quasars from the Sloan Digital Sky Survey with redshifts $1.5 < z < 2.65$ were chosen to have spectroscopic coverage of the CIV, HeII, and MgII ultraviolet emission lines. More than 5,000 of these objects also have 2 keV X-ray data available. Using a quasar SED model (Temple *et al.* 2021c) to infer 3000 Å continuum luminosities, the sample is observed to span 2.5 decades in luminosity. BH masses are estimated from the MgII line as described in Temple *et al.* (2023).

2.1. *Results*

The key results are shown in figures 3, 4, and 5 of Temple *et al.* (2023). Large CIV blueshifts only seen at $L/L_{\rm Edd} > 0.1$ and $M_{\rm BH} > 10^9 M_\odot$, consistent with the theories of radiation line driven winds summarized by Giustini & Proga (2019). Somewhat surprisingly, the CIV blueshift is observed to follow acute-angled wedge-shaped contours in the $L/L_{\rm Edd}$–$M_{\rm BH}$ plane, especially given that $\alpha_{\rm ox}$ does not show the same demographics. However, the observed behavior of the HeII strength matches well with the CIV blueshift, adding credence to the idea that the outflow traced by CIV is governed by the far-ultraviolet continuum.

When comparing to the Kubota & Done (2018) `qsosed` models, we see that the (admittedly somewhat naïve) zero-spin `qsosed` model matches the average $\alpha_{\rm ox}$ as a function of $L/L_{\rm Edd}$ and $M_{\rm BH}$ observed in our sample. Due to an unknown covering factor, we can't compare the observed HeII strength directly with the models, but the general trend in the zero-spin `qsosed` model is consistent with HeII behaviour at $L/L_{\rm Edd} \gtrsim 0.2$. Below this threshold the HeII appears to decouple from the SED predictions, perhaps suggesting changes in the structure of the accretion flow and/or the broad-line region.

3. Conclusions

The key conclusions from this work are:

- Ultraviolet outflow signatures in quasars depend on both the BH mass *and* the accretion rate. Strong CIV outflow signatures are seen in high mass BHs with $L/L_{\rm Edd} > 0.1$, while the strongest line emission is seen in lower mass, high accretion rate objects.
- The ultraviolet emission lines depend on the strength of the ionizing SED in between directly observed X-ray and ultraviolet continuum regions. The strength of HeII emission is therefore probing complementary physics to $\alpha_{\rm ox}$.
- The emission line properties observed in the SDSS quasar population are consistent with a scenario wherein CIV traces a radiation line driven wind.

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