

## NARROW LINE REGION PROPERTIES

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### 1.1 INTRODUCTION

AGN appear to be very efficient at driving outflows, and X-ray and UV spectroscopy reveal high velocity outflows to be nearly ubiquitous on sub-parsec scales in high accretion rate quasars. In recent years, a huge amount of resources have been devoted to searching for observational evidence of galaxy-wide, AGN-driven outflows, which could provide the feedback mechanism necessary to quench star formation in massive galaxies. This has resulted in recent detections of winds in AGN-host galaxies using tracers of atomic, molecular, and ionised gas (e.g. Nesvadba et al., 2006; Arav et al., 2008; Nesvadba et al., 2008; Moe et al., 2009; Dunn et al., 2010; Alexander et al., 2010; Harrison et al., 2012; Harrison et al., 2014; Nesvadba et al., 2010; Rupke and Veilleux, 2013; Veilleux et al., 2013; Nardini et al., 2015; Feruglio et al., 2010; Alatalo et al., 2011; Cimatti et al., 2013; Ciccone et al., 2014).

One particularly successful technique has been observations of forbidden emission lines, which trace warm ( $T \sim 10^4 \text{K}$ ) ionised gas in the narrow line region (NLR). Because of its high equivalent width,  $[\text{O III}]\lambda 5008$  is most studied of the narrow quasar emission lines. In general, the  $[\text{O III}]$  emission appears to consist of two components: a narrow, ‘core’ component, with a velocity close to the systemic redshift of the host galaxy, and a broader ‘wing’ component, which is normally blueshifted. The general consensus is that the core component traces the gravitational potential of the host galaxy, whereas the wing is tracing outflowing gas.

Observations of broad velocity-widths and asymmetries in narrow emission lines stretch back several decades (e.g. Weedman, 1970; Stockton, 1976; Heckman et al., 1981; Veron, 1981; Feldman et al., 1982; Heckman, Miley, and Green, 1984; Vrtilek, 1985; Whittle, 1985; Boroson and Green, 1992). However, the small sample sizes make it difficult to know how representative these observations are. More recently, the advent of large optical spectroscopic surveys (e.g. SDSS) have facilitated studies of the NLR in tens of thousands of AGN (e.g. Boroson, 2005; Greene and Ho, 2005; Zhang et al., 2011; Mullaney et al., 2013; Zakamska and Greene, 2014; Shen and Ho, 2014). This has provided constraints on the prevalence of ionised outflows and, by measuring outflow properties as a function of AGN properties, on the drivers of these outflows. At the same time, there is strong evidence from spatially resolved spectroscopic observations of kine-

matically disturbed gas extended over galaxy scales (e.g. Greene et al., 2009; Greene et al., 2011; Hainline et al., 2013; Harrison et al., 2012; Harrison et al., 2014).

However, these studies do not cover the redshift range when star formation and black hole accretion peaked, and consequently when feedback is predicted to be strongest. At these redshifts the bright optical emission lines are redshifted to near-infrared wavelengths, where observations are much more challenging compared to optical wavelengths. As a consequence, studies at high redshifts have typically relied on relatively small numbers of objects, which might not be representative of the properties of the population (e.g. Netzer et al., 2004; Sulentic et al., 2004; Shen, 2016). Other recent studies have looked at the [O III] emission properties of rare sub-samples - e.g. heavily obscured quasars (Zakamska et al., 2016) and the most luminous quasars (Bischetti et al., 2016). These studies often report exceptionally large [O III] widths, with  $\text{FWHM} > 1000 \text{ km s}^{-1}$  (e.g. Netzer et al., 2004; Nesvadba et al., 2008; Kim et al., 2013; Brusa et al., 2015; Carniani et al., 2015; Perna et al., 2015; Bischetti et al., 2016). This could suggest that AGN efficiency in driving galaxy-wide outflows increases with AGN luminosity (e.g. Hopkins et al. 2016). In addition, [O III] is often very weak, or is missing entirely (e.g. Netzer et al., 2004).

In this chapter we analyse the [O III] properties of a sample of 358 high-luminosity, redshift  $1.5 < z < 4$  quasars. The large sample size will help to put these observations in context of the AGN population as a whole. We will analyse the [O III] emission properties as a function of key properties of the quasar, e.g. BH mass, luminosity, and accretion rate.

## 1.2 QUASAR SAMPLE

We have assembled a catalogue of 358 high-luminosity, redshift  $1.5 < z < 4$  quasars, with spectra taken in the near-infrared. At these redshifts the spectra cover the rest-frame optical region, which includes the broad Balmer H $\beta$  line and the strong, narrow [O III] doublet. There is a significant overlap between the sample presented here and the one used in Coatman et al. (2016b), hereafter paper I. We briefly describe the catalogue below, but refer the reader to Coatman et al. (2016b) for further details, including the reduction procedure.

Two hundred are selected from the SDSS Seventh Data Release (DR7; Schneider et al., 2010). These are observed with LIRIS (Machado et al., 1998) on the William Herschel Telescope (WHT), Triple-Spec (Wilson et al., 2004) on the Astrophysics Research Consortium (ARC) 3.5 m telescope, FIRE (Simcoe et al., 2010) on the Magellan-Baade telescope, the SINFONI integral field spectrograph (Eisenhauer et al., 2003; Bonnet et al., 2004) on the European Southern Observa-

Table 1.1: The numbers of quasars with [O III] line measurements and the spectrographs and telescopes used to obtain the near-infrared spectra. Further details on the instrumental configurations are given in paper I. **Check numbers.**

Spectrograph	Telescope	Number
FIRE	MAGELLAN	32
GNIRS	GEMINI-N	29
ISAAC	VLT	8
LIRIS	WHT	5
NIRI	GEMINI-N	29
NIRSPEC	Keck II	3
SINFONI	VLT	76
SOFI	NTT	78
TRIPLESPEC	ARC-3.5m	27
TRIPLESPEC	P200	46
XSHOOTER	VLT	25
		144

tory (ESO) Very Large Telescope (VLT), SOFI (Moorwood, Cuby, and Lidman, 1998) on the New Technology Telescope (NTT), and TRIPLESPEC on the Palomar 200-inch Hale telescope (P200). One hundred and seventeen were observed to measure accurate redshifts of quasar pairs at very close projected separations (Prochaska and Hennawi, 2009; Lau, Prochaska, and Hennawi, 2015; Hennawi et al., 2015). Spectra were taken with GNIRS (Elias et al., 2006) on the Gemini North telescope, ISAAC (Moorwood et al., 1998) on the European Southern Observatory (ESO) Very Large Telescope (VLT), NIRSPEC (McLean et al., 1998) on the Keck-II telescope, NIRI (Hodapp et al., 2003) also on Gemini North, and XSHOOTER (Vernet et al., 2011), again, on the VLT. Seventy-nine are bright Hamburg-ESO quasars observed with SINFONI, ninety are quasars with archival high-resolution optical spectra observed with SOFI, and four are observed with XSHOOTER and presented in the XQ-100 catalogue (Lopez et al., 2016).

This is the largest study of the narrow line region properties of high- $z$  quasars ever undertaken. The redshift and luminosity coverage of the quasars in our sample is shown in Fig. ??, and the quasar sample is summarised in Table 1.1. Our sample covers much higher redshifts and luminosities than the SDSS sample.

### 1.3 PARAMETERIC MODEL FITS

In this section we describe how we measure the [O III] velocity-width and parameterize asymmetries in the line. We first fit a parameteric model to the [O III] emission, and the nearby H $\beta$  peak. This step is taken solely to enhance the signal-to-noise (SNR) of the spectra and to decompose the emission from H $\beta$  and the [O III] doublet. We then calculate non-parameteric measures of the line profile from the best-fitting model.

Before the model can be fit, the spectra must first be transformed in to the (approximate) quasar rest-frame. This transformation is only for practical purposes and the emission line parameters we will go on to derive are independent of the exact redshift used. The redshift will later be refined using the results from the fit. The redshift used in this transformation is either derived from a multi-component Gaussian fit to the broad H $\alpha$  emission ( $\sim 40$  per cent of our sample) or, when this is not possible, from a preliminary fit to the broad H $\beta$  emission ( $\sim 40$  per cent) or narrow [O III] emission (20 per cent). **Should say whether we use peak/median etc.**

The continuum and optical Fe II emission is modelled and subtracted using a recipe that is identical to the one described in paper I. The following model is then fit to the spectra in the wavelength interval 4700-5100 Å. The fit is done as a function of the Doppler velocity shift, and we adopt the wavelength 4862.721 Å (the laboratory H $\beta$  wavelength) to transform wavelengths into equivalent Doppler velocities.

H $\beta$  is modelled by two Gaussians with non-negative amplitudes and FWHM greater than  $1200 \text{ km s}^{-1}$ . A handful we fix the centroids of the two Gaussians to be the same, normally because of very low S/N or because the blue wing is below the lower wavelength limit of the spectrograph. Any contribution to the H $\beta$  emission from the narrow-line region is weak in the vast majority of our sample, and so we do not include an additional Gaussian component to model this emission. Note: we do in fact include narrow components for eight objects in our sample. Although, for some objects, this could bias our estimate of the velocity-width of the broad component, this information is not used in the analysis presented in this paper.

Each component of the [O III] doublet is fit with one or two Gaussians, depending on the fractional reduced  $\chi^2$  difference between the one- and two-component models. If the addition of the second Gaussian decreases the reduced  $\chi^2$  by more than 5 per cent then the double-Gaussian model is accepted. One hundred and twenty-five are fit with a single Gaussian, 147 with two Gaussians, and [O III] is undetected in a further 78 quasars. When a single Gaussian is used to model each line, the peak flux ratio of the [O III] 4960 Å and 5008 Å components are fixed at the expected 1:3 ratio and the width and

Table 1.2: Approximate physical origin of the ICA components.

Component	Origin
$w_1$	Fe II
$w_2$	H $\beta$
$w_3$	H $\beta$
$w_4$	[O III] core
$w_5$	[O III] core
$w_6$	[O III] wing

velocity offsets are set to be equal. In the double Gaussian fit, the peak flux ratio of the second components is again fixed at 1:3, and the width and velocity offsets are again set to be equal.

In six quasars a significantly better fit was obtained by allowing the flux ratio between the two components to vary. In these quasars the best-fitting peak ratio varies from 0.50 to 0.84, with mean 0.70. **Check ICA component fits to see if this looks real.**

Model parameters were derived using a standard variance-weighted least-squares minimisation procedure employing the Levenberg-Marquardt algorithm. Prior to the fit, the spectra were inspected visually and regions significantly affected by telluric absorption or of low S/N were masked out.

**However, the fits aren't always good. How to be quantitative about this? Chi-squared values indicating bad fits? Also the fact that we sometimes model Fe as OIII. Discuss the limitations of using the Boroson & Greene template? Even if don't use results, should discuss Gaussian fits and their limitations, because that's what most people will be using.**

There is a prominent Fe II emission feature just redward of [O III] $\lambda$ 5007. In some objects the relative strengths of the Fe II lines are significantly different from those of I Zw 1 on which the Fe II template data are based.

It is artificial to decompose the [O III] profile into core and wing using two Gaussians. No theoretical justification that the wing component should have a Gaussian profile. And decomposition depends on S/N, spectral resolution. Instead we use non-parameteric measures from the whole profile.

### 1.3.1 Derived Parameters

All [O III] line properties are derived from the [O III] $\lambda$ 5008 emission, but, as described below, the kinematics of the peak at 4960Å are constrained by our fitting routine to be identical.

We do not attach any physical meaning to the individual Gaussian components used in the model. While it is true that in some

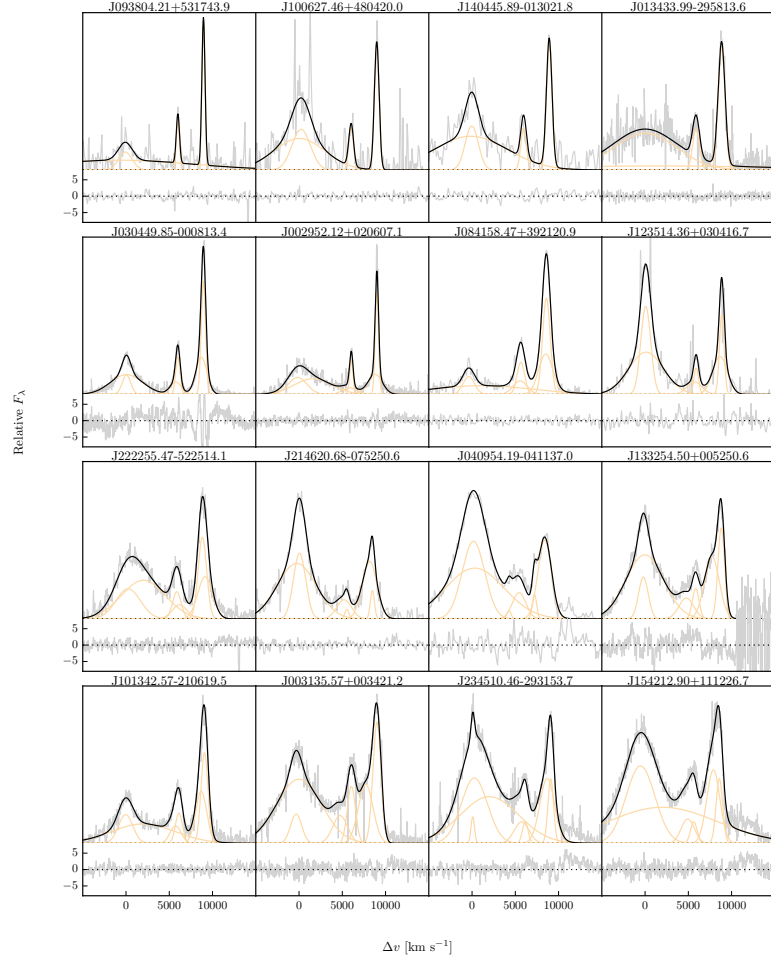


Figure 1.1: Multi-component Gaussian fits to the continuum-subtracted  $H\beta/[O\text{III}]$  emission in 16 quasars, chosen to be the representative of the wide range of  $[O\text{III}]$  line widths we measure in our sample. The data is shown in grey, the best-fitting parametric model in black, and the individual model components in orange. The broad  $H\beta$  centroid is used to measure the systemic redshift, and  $\Delta v$  is the velocity shift from the line rest-frame transition wavelength for  $H\beta$ . Below each fit we plot the data minus model residuals, scaled by the errors on the fluxes. **Resample model at higher resolution.**

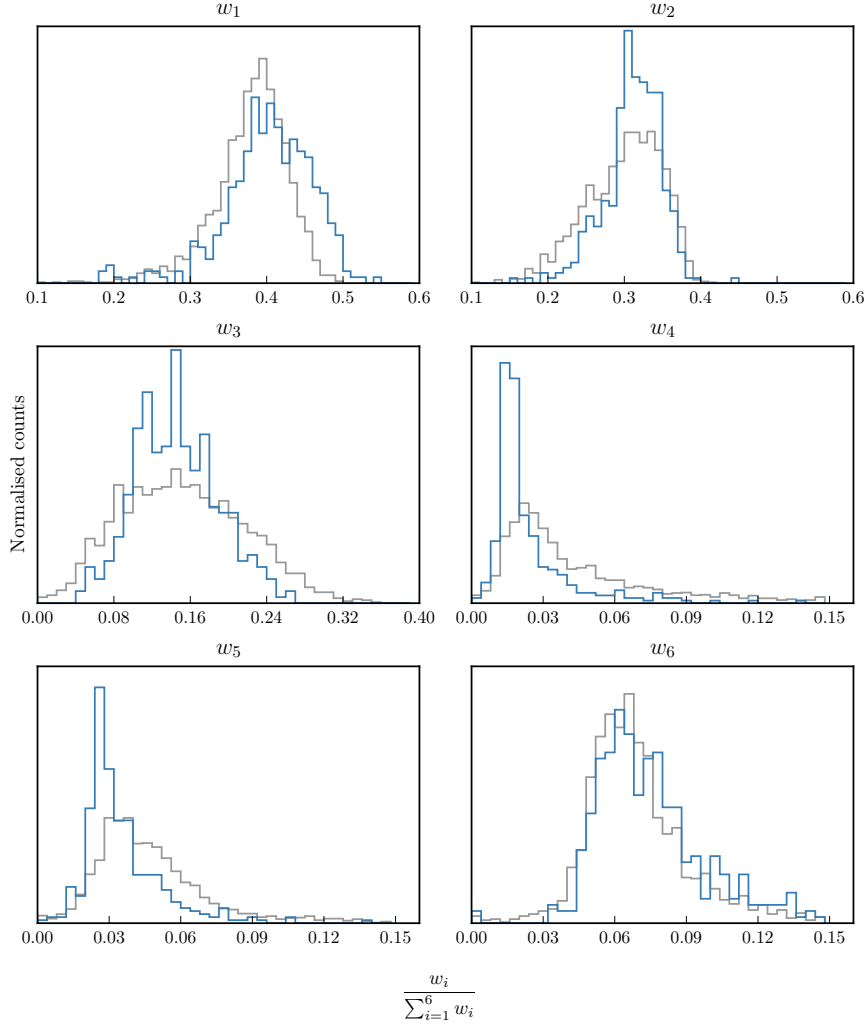


Figure 1.2: The relative weight in each of the six positive ICA components for the high-luminosity (blue) and low luminosity samples (grey). In the high-luminosity sample Fe II emission is stronger (component  $w_1$ ). The core [O III] emission is weaker (components  $w_4$ ,  $w_5$ ) but the strength of the blueshifted wing is the same ( $w_6$ ).

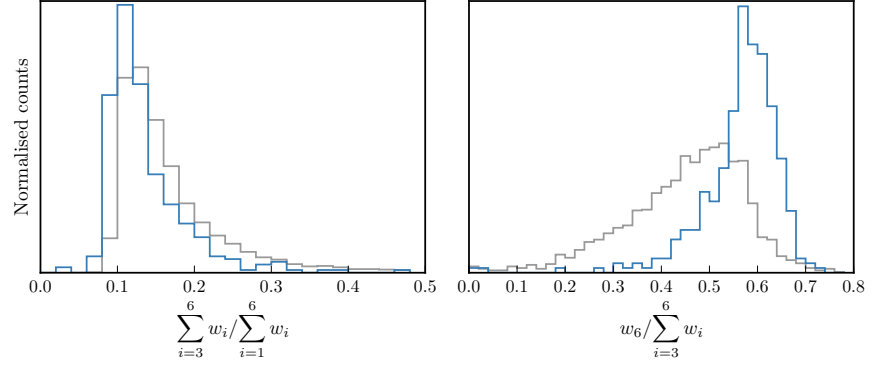


Figure 1.3: The relative weight in the three ICA components corresponding to [O III] emission (*left*) and the relative weight of the component most closely related to blueshifted [O III] emission relative to all three [O III] components (*right*). [O III] emission is weaker in the high-luminosity sample, but the relative contribution but the fractional contribution from the blueshifted component to the total [O III] emission is higher. Hence [O III] is weaker, broader, and more asymmetric in the high-luminosity sample. See Zakamska discussion.

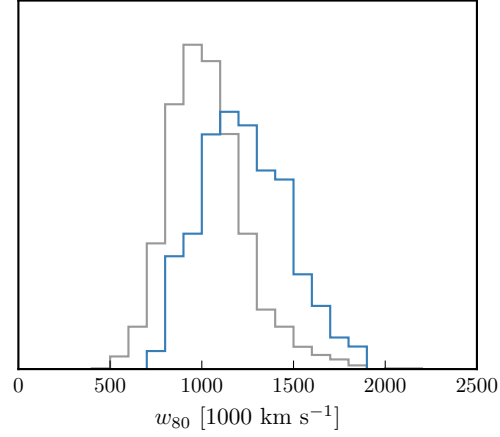


Figure 1.4: Comparison of [O III] velocity-widths in the high and low luminosity samples using the ICA component fits. If keep this need to explain in text how  $w_{80}$  is calculated from ICA component fits.



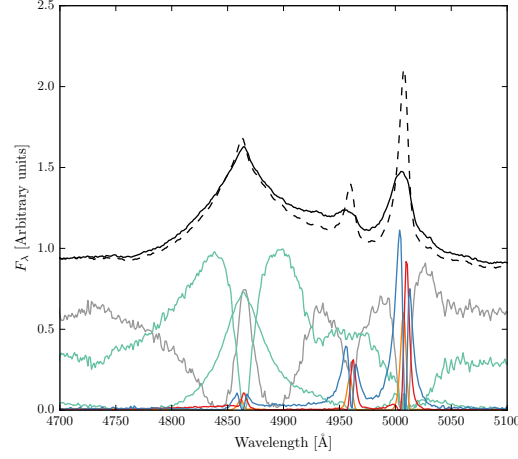


Figure 1.5: Black solid line is the median from the ICA fits to the high-luminosity sample. Black dashed line shows the median from the low-luminosity sample. The six positive ICA components are also shown.

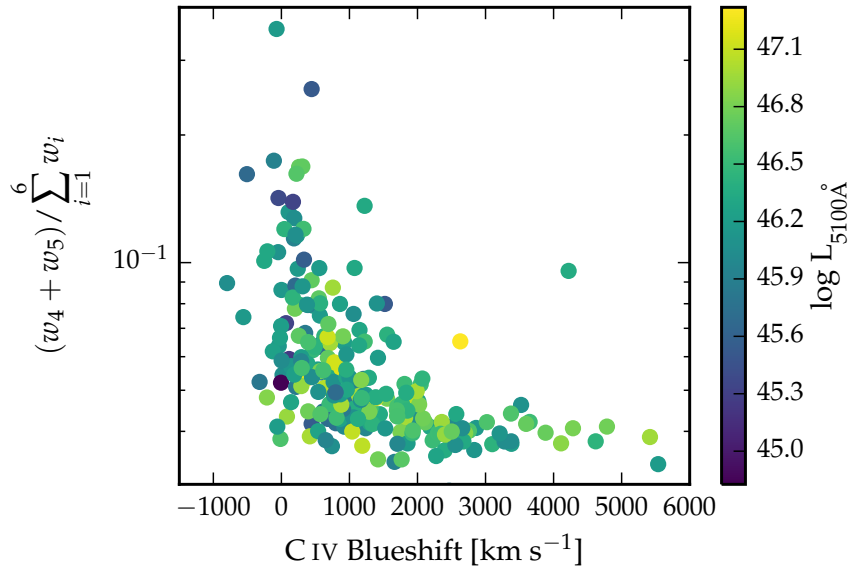


Figure 1.6: [O III] strength decreases as the C IV blueshift increases, I run in to problems comparing the C IV blueshift to the [O III] blueshift / velocity-width. See similar thing if I use [O III] EQW instead. Need to fix y ticks. Only showing the core components here. The C IV blueshift is now measured relative to the NIR ICA redshift. I think this trend is mostly being driven by the Eigenvector 1 correlations: as the blueshift increases the Fe II strength increases and the [O III] strength decreases. Doesn't appear to be driven by the luminosity. Is this tighter than EV1 trend shown with Fe/OIII strength by other authors? Is the AGN NLR absent in objects where outflows have reached kiloparsec scales, sweeping up the low-density material responsible for the [OIII]-emission?

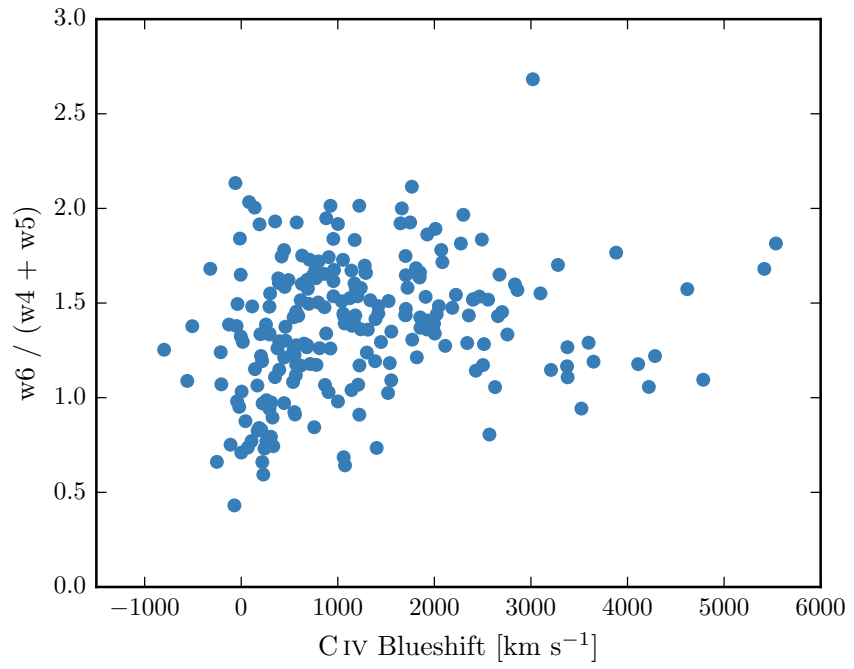


Figure 1.7: I think there is a trend here but at high blueshifts the OIII is undetected / very low S/N. Need to determin when we can believe OIII paramters. Why at low CIV blueshift is there a much bigger dynamic range than in [O III] blueshifts in Fig. 13. Is it just because we have more objects?

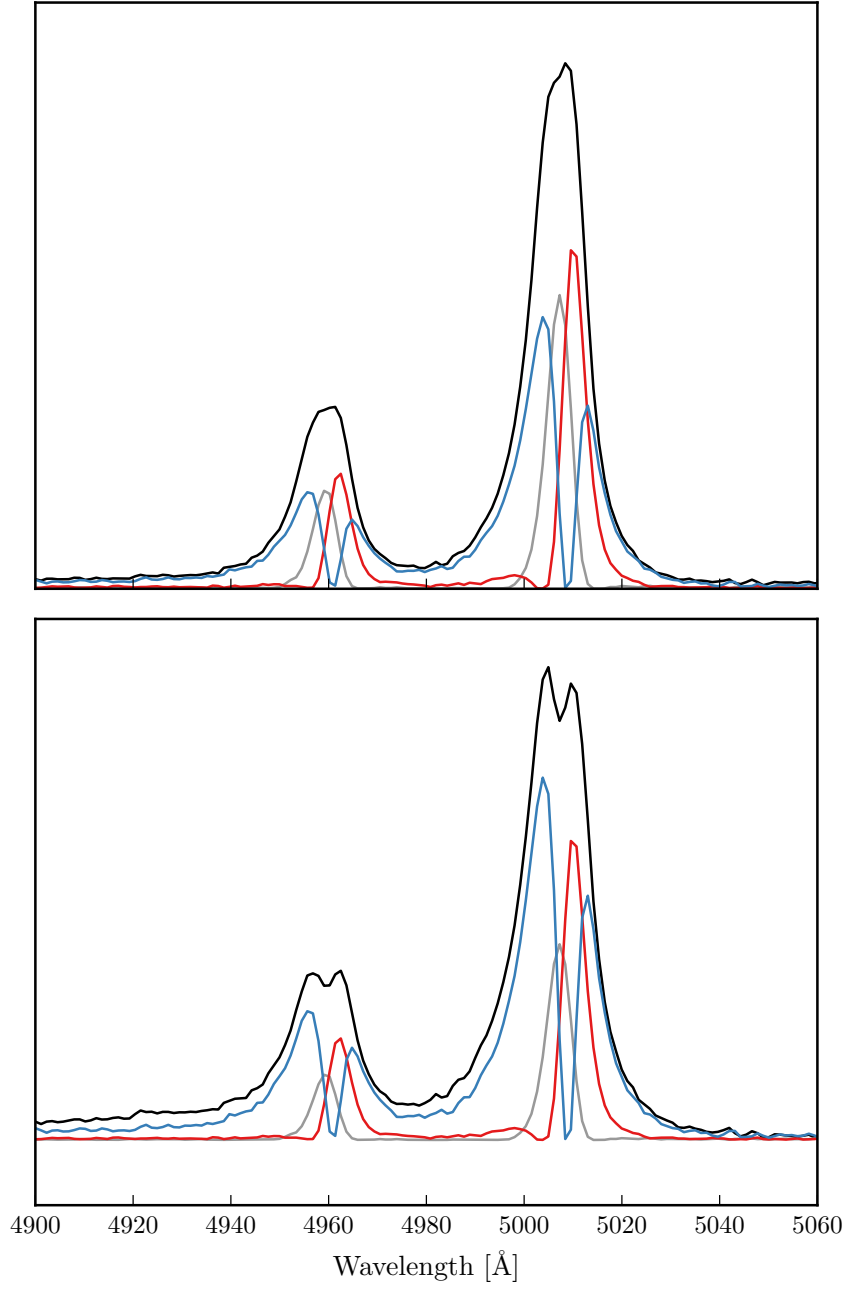


Figure 1.8: Comparison of median [O III] profiles from ICA fits to low- and high-luminosity samples.

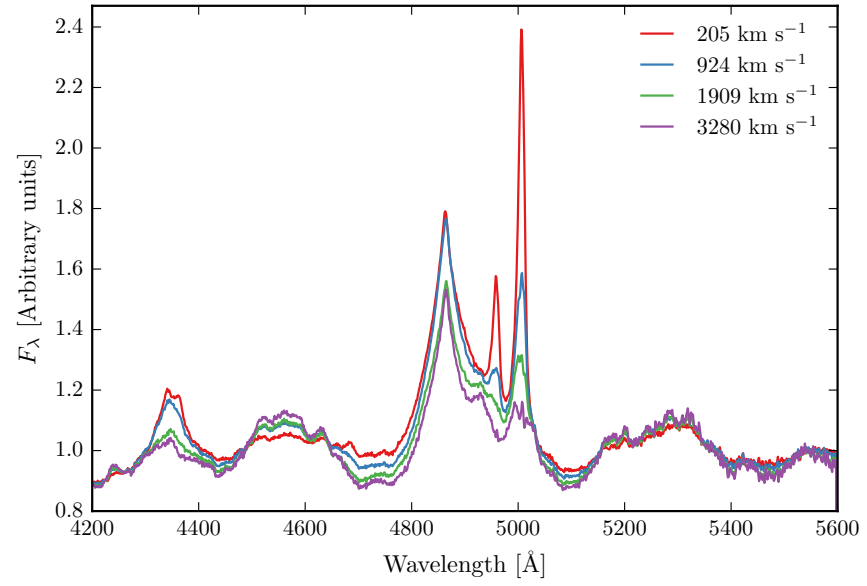


Figure 1.9: ICA median weights as a function of the CIV blueshift.

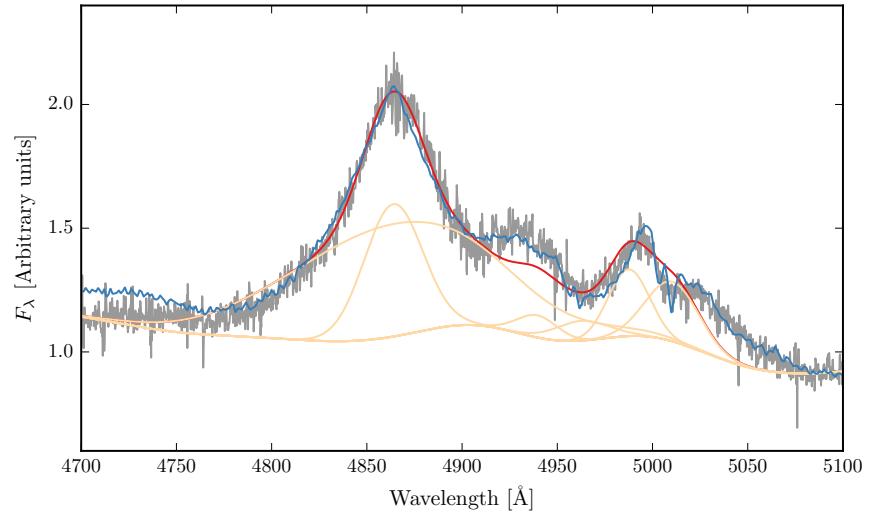


Figure 1.10: Example where poorly subtracting the iron can be confused with [O III].

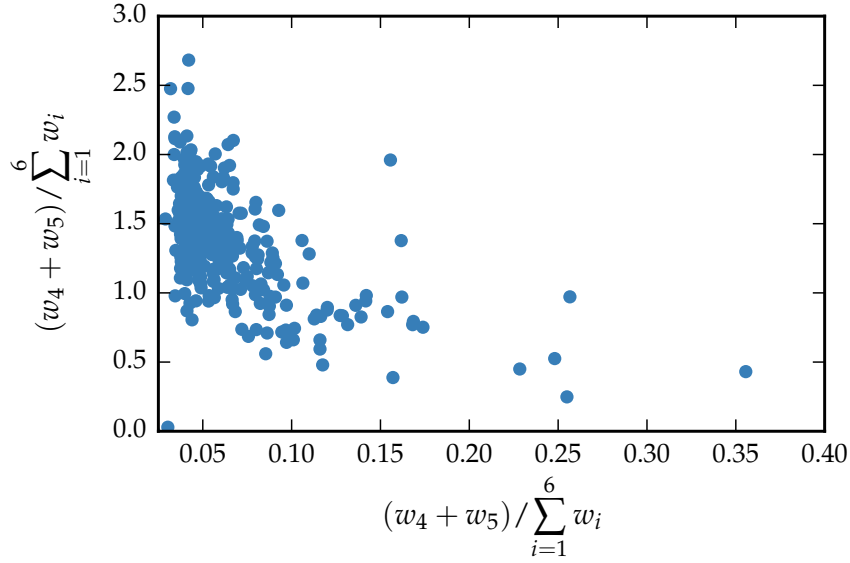


Figure 1.11: Zhang et al. 2011: Blueshift of [O III] correlates significantly with the EQW of the core. The more the peak of the line is blueshifted, the more the core component decreases dramatically, while the blue wing changes much less. We see this clearly. This is similar to behaviour of C IV? I.e. is there a mapping from this to the C IV space diagram? This would suggest that the mechanism producing the two correlations is the same. Consistent with the core coming from the canonical extended NLR where the gas is dominated by gravity of the bulge while the wing arises in an outflow. And C IV explained by wind. Suggests intimate connection between BLR and NLR.

quasars the [O III] emission can be clearly separated into a narrow component at the systemic redshift and a lower-amplitude, blueshifted broad component (e.g. Shen, 2016), often this decomposition is highly uncertain. Furthermore, often the S/N is not sufficient to statistically justify the addition of a second Gaussian component. Instead, we characterize the [O III] line profile using a number of non-parametric measures, which are commonly used in the literature (e.g. Zakamska and Greene, 2014; Zakamska et al., 2016). A normalised cumulative velocity distribution is constructed from the best-fitting model, from which the velocities below which 5, 10, 25, 50, 75, 90, and 95 per cent of the total flux accumulates can be read off. The width of the emission line can then be defined, for example, using  $w_{80} = v_{90} - v_{10}$ . The absolute asymmetry in the line profile  $A$  is defined as  $((v_{95} - v_{50}) - (v_{50} - v_5)) / (v_{95} - v_5)$  (Zakamska and Greene, 2014).

We also define the blueshift of the [O III] emission, which is a measure of the velocity shift of the profile from the expected position. This requires a measure of the observed line position, and an accurate measurement of the quasar systemic redshift. We use  $v_{10}$  to measure the location of the [O III] emission. Note that  $v_{50}$  is not suitable because when [O III] is low S/N we fit with single Gaussian.

**The line width measures are not at present corrected for instrumental broadening, but this can easily be done.**

### 1.3.2 Other flags

#### Flag 2

Low S/N. Includes some of the strong iron emitters.

#### Flag 3

74 objects where [O III] is undetected, although I don't have a rigorous definition of what this means. Merge with 2?

## 1.4 ICA COMPONENT FITS

What is the segue here? Sometimes Gaussians give poor fit? Not clear what is H $\beta$ , what is OIII, what is Fe? Show some examples of when the multi-Gaussian fits fail. Need to describe sample used in ICA component decomposition and briefly describe method (or refer to Allen & Hewett).

## 1.5 MEASURING THE QUASAR SYSTEMIC REDSHIFT

Explain flags Need to send paul redshifts

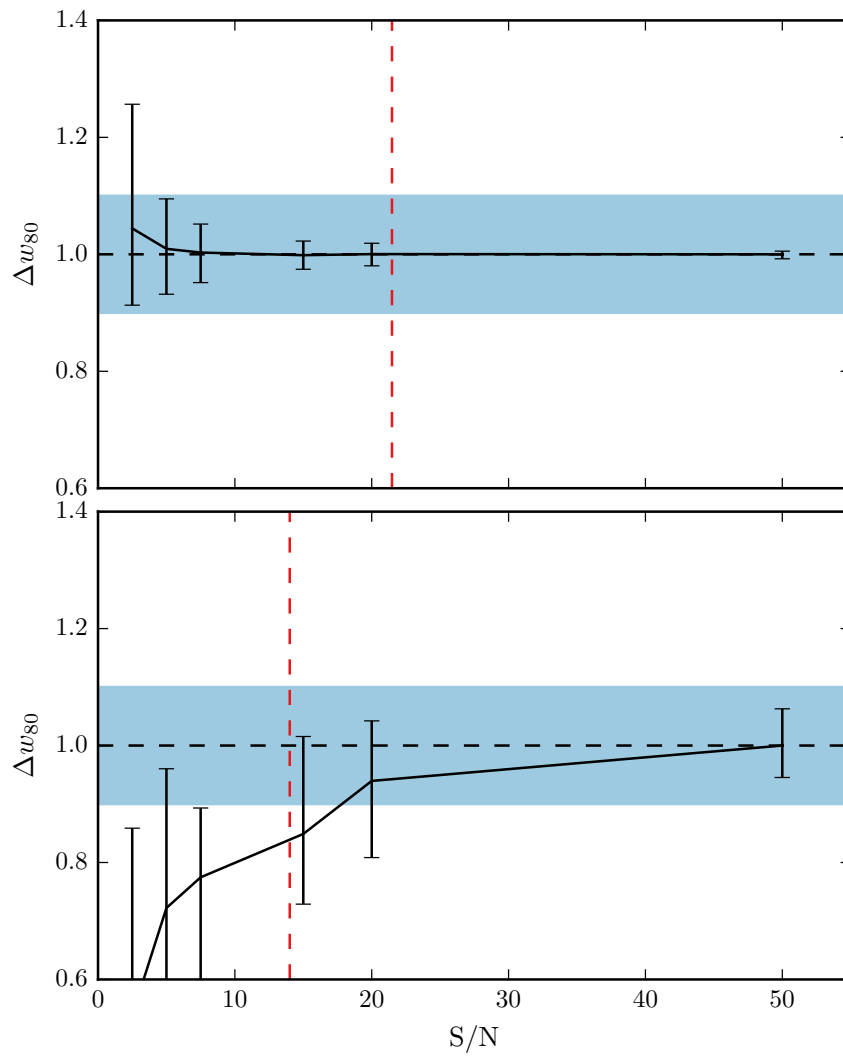


Figure 1.12

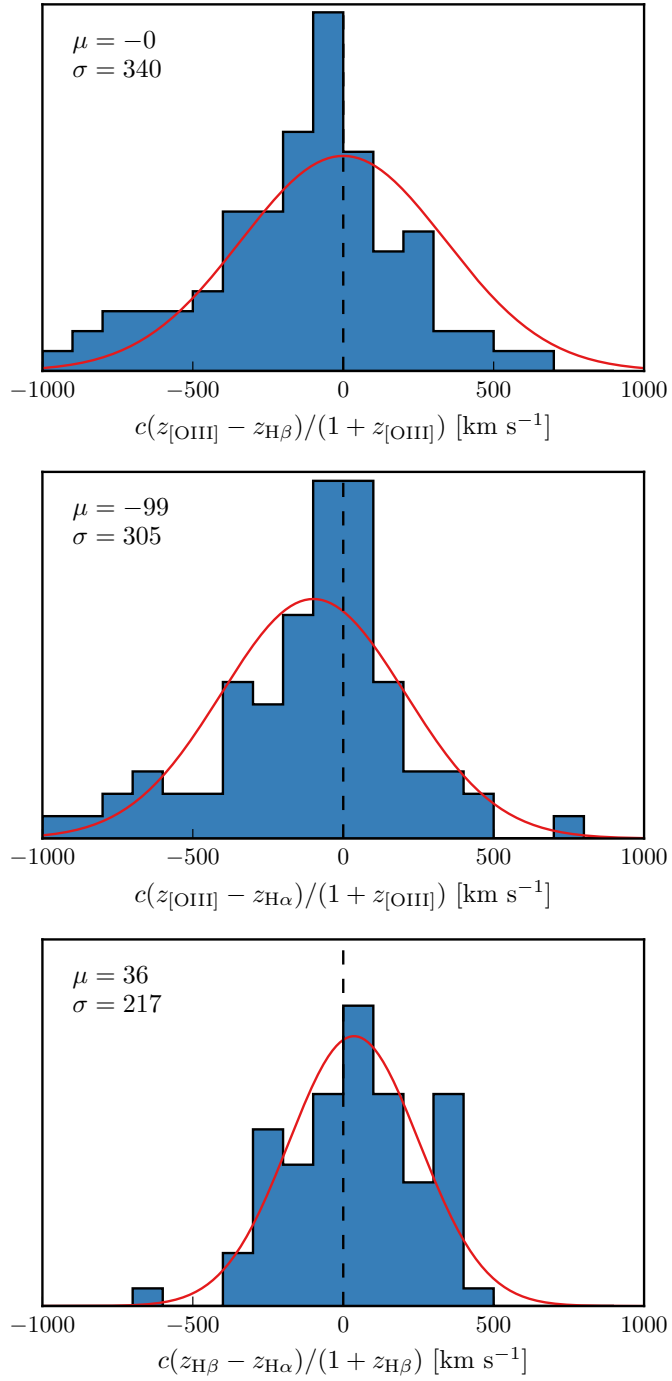


Figure 1.13: Redshift comparisons. Lots have been excluded from Ha/H $\beta$  so need to look at flags greater than one. What is the big peak? Gaussian fit to the first one has failed. Find out why these plots look different to ones in paper.



### 1.5.1 $H\alpha$

There are 224 quasars in our sample with spectra covering the  $H\alpha$  emission line. We discard seven of these from our sample because of very low S/N ( $<2.5$  measured in the  $H\alpha$  line), leaving 217. To measure the position of the line we fit a parameteric model, which is very similar to the model described in Paper I. The continuum emission is first modeled and subtracted using the procedure described in Paper I. We then test five different models with increasing degrees of freedom to model the  $H\alpha$  emission. The model we select is the simplest model for which the fractional change in the reduced chi-squared from the model with the lowest reduced chi-squared is less than ten per cent.

The models we test are: (1) a single broad Gaussian; (2) two broad Gaussians with identical velocity centroids; (3) two broad Gaussians with different velocity centroids; (4) two broad Gaussians with identical velocity centroids, and additional narrower Gaussians to model the narrow  $H\alpha$  emission, and the narrow components of  $[N\text{ II}]\lambda\lambda 6548, 6584$  and  $[S\text{ II}]\lambda\lambda 6717, 6731$ ; (5) two broad Gaussians with different velocity centroids, and additional narrower Gaussians. If used, the width and velocity of all narrow components are set to be equal in the fit, and the relative flux ratio of the two  $[N\text{ II}]$  components is fixed at the expected value of 2.96. The number of quasars fit by each model is: model 1 - 10; model 2 - 71; model 3 - 32; model 4 - 51; model 5 - 53. The redshift is then measured at the peak flux of the  $H\alpha$  model, including both the broad and narrow components of  $H\alpha$  if appropriate.

### 1.5.2 ICA

The only sensible way to measure the systemic redshift is using the NIR ICA fit.  $H\alpha$  and  $H\beta$  seem to give no systematic offset but large scatter, and they are often asymmetric, so should only use peak. And  $H\alpha$  isn't always available, and have other narrow components need to decompose.  $O\text{ III}$  peak is mostly fine to use, but then there are some objects where the whole line is blueshifted. And critically, at large CIV blueshifts the  $[O\text{ III}]$  emission is often undetected. Can show comparison of NIR ICA redshifts to... Optical ICA? Hewett & Wild?

Should emphasise that most people use  $[O\text{ III}]$  to get the most reliable systemic redshift. While this is fine at low luminosities, at high luminosities this can result in large errors (profile can be dominated by blueshifted component, Fe emission can be improperly subtracted, or  $[O\text{ III}]$  might not be detected at all. Publish ICA components with this paper?

Can also describe what I found trying to get redshifts from broad  $H\alpha$ ,  $H\beta$ ? (Narrow components generally very weak at these luminosities)

ties so can't be used.) Generally find no systematic errors but large ( $\sim 1000 \text{ km s}^{-1}$  scatter). Comparing NIR ICA to [O III] for the [O III] with high S/N I find small (few hundred  $\text{km s}^{-1}$ ) scatter.

Should publish [O III] redshifts with this paper for people to use.

#### 1.5.3 *Parameter uncertainties and upper limits*

Describe how uncertainties on best-fitting parameters were calculated.

In 78 quasars, or approximately 25 per cent of or sample, the [O III] is undetected, or detected with very low S/N. In this section we describe how upper limits on the [O III] equivalent width were calculated. Firstly, the best-fitting model comprising the continuum, Fe II, and H $\beta$  emission is subtracted from the spectra, leaving behind only emission due to [O III]. From this spectra we generate 100 mock spectra, where the flux at each wavelength is randomly drawn from a Normal distribution with a mean equal to the flux convolved with a Gaussian of width  $200 \text{ km s}^{-1}$  and a width equal to the known error. We then perform an error-weighted linear least-squares regression with an [O III] template derived from a fit to a very high S/N low redshift SDSS composite spectra. The equivalent width of the best-fitting model is recorded for each of the 100 realisations of the spectra. The error in the equivalent width is defined as the root-mean-square of these values.

Calculated uncertainties using Monte Carlo. Uncertainties on  $v_{10}$  are very large, which I think makes sense since the wing Gaussian will be appearing and disappearing, giving a large dispersion in  $v_{10}$ . Or regardless  $v_{10}$  is just very sensitive to the noise. Maybe I should be using  $v_{25}$  instead?

#### 1.5.4 *Absolute flux calibration of spectra and continuum luminosities*

Relative flux-calibration of the infrared spectra as a function of wavelength has been achieved, to  $\simeq 10$  per cent, through observations of appropriate flux standards. The absolute flux levels, however, can be in error by large factors due to variable atmospheric conditions combined with the narrow slit widths. For the majority of the quasars we have, therefore, established the absolute flux scale for each near-infrared spectrum using the same quasar SED-model fitting scheme employed in Paper I. Briefly, the SED-model was fit, with the normalisation and  $E(B-V)$  as free variables, to optical/infrared magnitudes, or SDSS/BOSS spectra (check order I do this.) This allows us to extrapolate from the optical when we do not have photometric data in the near-infrared. The spectra were then normalised to the SED model using a linear error-weighted least-squares regression in the the regions of the spectra covered by the H/K bands. The monochromatic contin-

uum luminosity at  $5100\text{\AA}$  was calculated directly from the normalised SED-model. **If this sounds strange can also calculate from fit to normalised spectra. Check if any missing normalisation / monochromatic luminosities.**

## 1.6 RESULTS FROM ICA FITS

Need to convince the reader that the ICA components approximately correspond to real components. Explain how non-parameteric measures derived from ICA reconstructions.

We find there is a decreasing symmetric component at high luminosities. Relates directly to Shen and Ho, (2014). A stable narrow line region is removed by the outflowing material. Shen and Ho, (2014) showed that the strength of the core [O III] component decreases with quasar luminosity and optical Fe II strength faster than the wing component, leading to overall broader and more blueshifted profiles as luminosity and Fe II strength (or C IV blueshift) increases.

## 1.7 LUMINOSITY/REDSHIFT-EVOLUTION OF [O III] PROPERTIES

In this section we look for any luminosity/redshift dependent changes in the [O III] line properties. To do this we extend the dynamic range of our samples in terms of both luminosity and redshift by supplementing our sample with quasars presented by Zakamska and Greene, (2014) and Harrison et al., (2016).

The Zakamska and Greene, (2014) objects are a sample of 568 obscured luminous quasars selected from SDSS (Reyes et al., 2008; Yuan, Strauss, and Zakamska, 2016). They are selected to have [O III] luminosities above  $10^{8.5} L_{\odot}$  and have a median redshift  $z = 0.397$ .

We also include 40 quasars at redshifts  $1.1 \leq z \leq 1.7$  from the KMOS AGN Survey at High redshift (KASHz) with [O III] line measurements.

We also have the same information for  $\sim 20\,000$  SDSS spectra from Mullaney et al., (2013).

In Figure 1.14 we show the [O III] velocity width as a function of the [O III] luminosity and the quasar redshift. The lack of any redshift-evolution between  $z = 0$  and  $z = 1.5$  was reported by Harrison et al., (2016). Our additional data suggests that this continues to  $z \sim 2.5$ . On the other hand, at fixed redshift, we see a significant correlation between the [O III] velocity width and the luminosity.

The fact that we don't see many broad lines in the Zakamska and Greene, (2014) objects even at luminosities  $> 43 \text{ erg/s}$  could be due to the fact that these are all type II quasars, whereas the sample presented in this paper are all type I. Mullaney et al., (2013) showed that the [O III] lines of type I quasars are typically broader than in type II quasars.

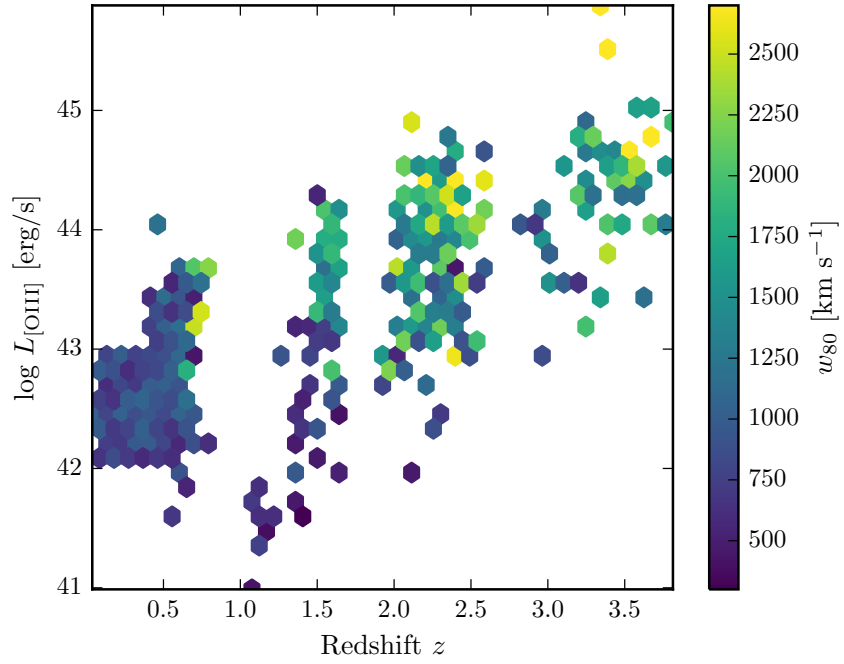


Figure 1.14: The [O III] velocity-width, characterised by  $w_{80}$ , as a function of the [O III] luminosity and the quasar redshift. The color of each hexagon denotes the mean  $w_{80}$  for the objects in that luminosity-redshift bin. We have supplemented our sample with low- $z$  objects from Zakamska and Greene, (2014) and medium ( $z \sim 1.5$ ) redshift objects from Harrison et al., (2016). If I keep this plot make sure its clear which points belong to which sample.

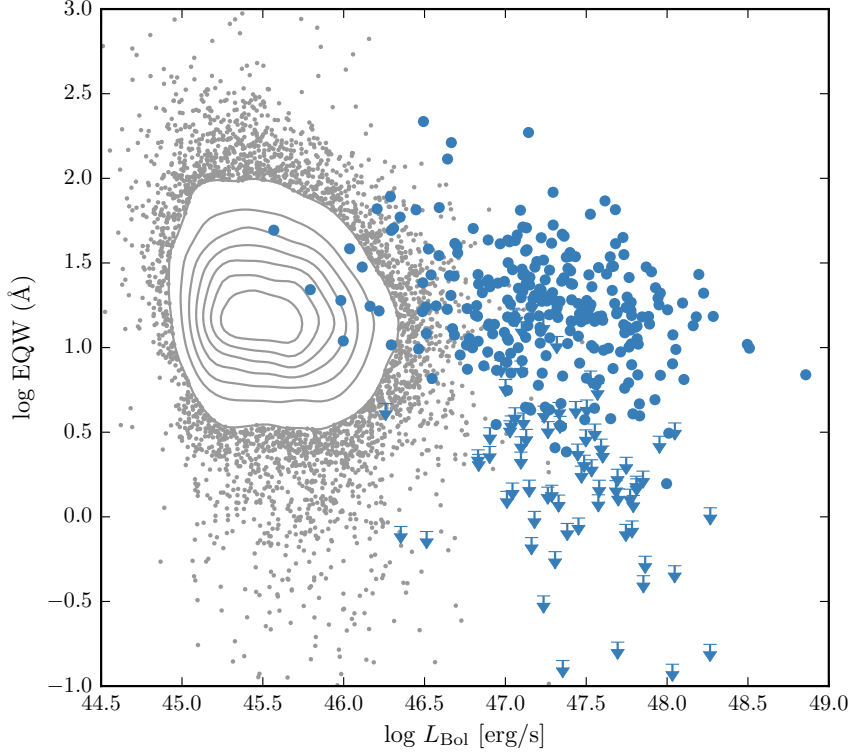


Figure 1.15: The [O III] EW as a function of the quasar bolometric luminosity for the sample presented in this paper (blue circles) and the low- $z$  SDSS sample (grey points and contours). Upper limits are denoted by the downward arrows.

Looking at the [O III] velocity width as a function of luminosity tells us about the physical drivers of the outflows observed in [O III]. The correlation with luminosity suggests that the highest velocity outflows are associated with the most luminous AGN. This has been reported for low-redshift AGN, for both ionized and molecular outflows (e.g. Westmoquette et al. 2012; Veilleux et al. 2013; Arribas et al. 2014; Ciccone et al. 2014; Hill & Zakamska 2014).

This suggests that the outflows are driven by radiative forces. On the other hand, Mullaney et al., (2013) find that once the correlation between the [O III] luminosity and the radio luminosity has been taken in to account, the [O III] velocity width is more strongly related to the radio luminosity of the AGN.

### 1.8 EQUIVALENT WIDTH

In Fig. 1.15 we show the [O III]5008 EW as a function of the quasar bolometric luminosity. Bolometric luminosity is estimated from the monochromatic continuum luminosity at 5100Å using the correction

factor given by Richards et al., (2006). For comparison, we also show the low- $z$  sample from Shen et al., (2011).

The equivalent width of [O III] has been found to strongly decrease as a function of redshift and/or luminosity (e.g. Brotherton, 1996; Netzer et al., 2004; Sulentic et al., 2004; Baskin and Laor, 2005).

The size of the narrow line region is roughly expected to scale as  $L^{0.5}$  (e.g. Netzer et al., 2004). However, for high luminosity quasars with strong [O III] this gives NLR sizes which are unreasonably large ( $\sim 100$  kpc; Netzer et al., 2004).

Netzer et al., (2004) found 1/3 of their high luminosity sample had very weak [O III], whereas quasars with weak [O III] are very rare for nearby AGN. We find a very similar fraction. Netzer et al., (2004) claim that for the population of strong [O III] emitters there is no reduction of EW with increasing source luminosity. On the other hand, there are many weak or no [O III] emitters at high luminosity that could give the impression that the line EQW decreases with increasing source luminosity.

#### 1.8.1 OIII outflows

Our best-fitting profiles show a strongly blue-asymmetric profile (Fig. 1.16), with a significant fraction of the total emission in a blue wing. The luminous blueshifted broad wing and the extremely broad profile reveals high-velocity outflowing ionized gas. This can be explained if the far-side of any outflowing gas, that is moving away from the line of sight, is obscured by dust in the host galaxies (e.g. Heckman et al. 1981; Vrtilik 1985). Observations at both low and high redshifts commonly observe this blueshifted component. Our results, and those of other authors, suggest that kpc-scale outflows in ionized gas are common among the most luminous high-redshift actively accreting SMBHs.

The situation is very different in nearby AGN, where the [O III] velocity width is dominated by the galactic potential and correlates well with the stellar velocity dispersion. HI, CO and absorption line measures of the host galaxy rest frame suggest that [O III] usually gives consistent results within 200 km/s (de Robertis 1985; Whittle 1985; Wilson & Heckman 1985; Condon et al. 1985; Stripe 1990; Alloin et al. 1992; Evans et al. 2001).

We see a correlation between the [O III] velocity width and blueshift. As the blueshift of the line increases it gets broader. This is consistent with Shen and Ho, (2014), where the strength of the narrow core is decreasing, leading to a broader and more blueshifted profile.

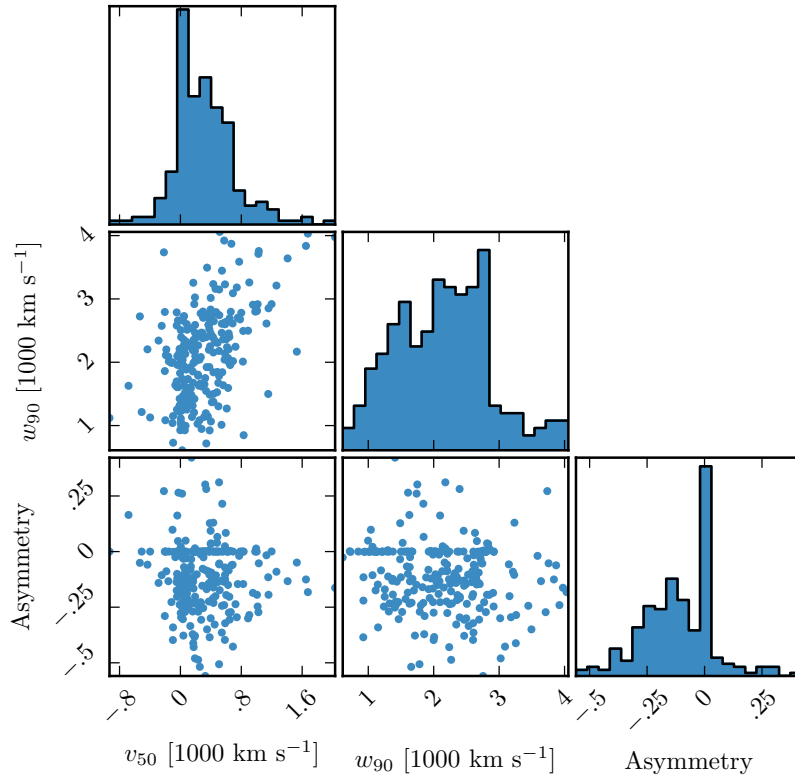


Figure 1.16: The distributions of and correlations between a subset of the non-parameteric measures we made of the best-fitting [O III] models.

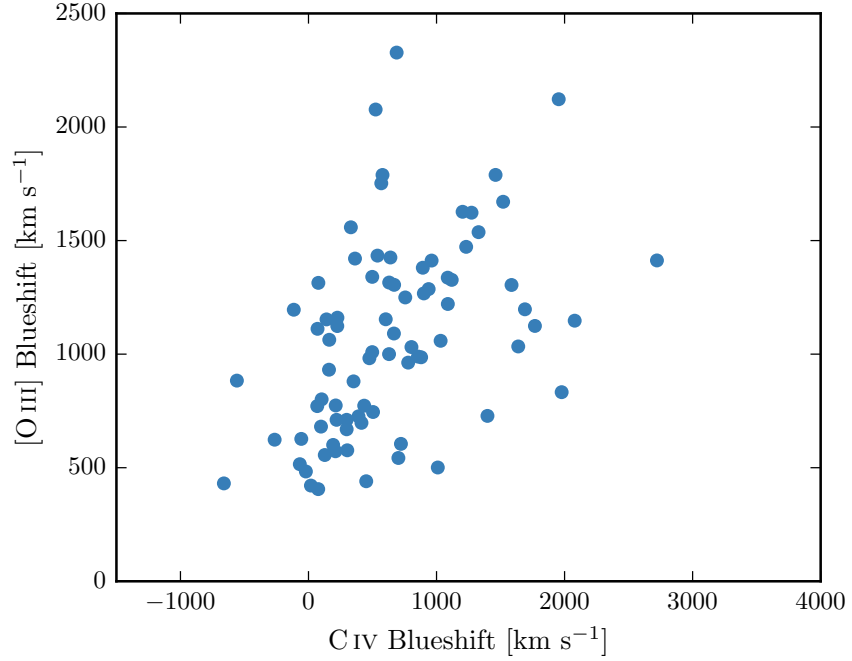


Figure 1.17: The relation between the blueshifts of C IV and [O III]. Equivalent to Fig 8. We use the H $\beta$  peak in this figure, which I think is responsible for some of the trend. However, we do see a correlation (albeit noisier) using the NIR ICA redshifts. Not a sensible to use the [O III] redshifts, since these become much more unreliable at the high C IV blueshift end (when [O III] is weaker: figure 7. Note that we are using  $v_{10}$  for the [O III] position and  $v_{50}$  for the C IV position. We can't use  $v_{50}$  for [O III] because sometimes we are using a single Gaussian, especially if the [O III] is weaker and we miss the broad component. Need to remake this plot / don't use at all because I don't believe some of the Gaussian fits to [O III], especially at high C IV blueshifts when [O III] is weak and Fe II is strong.) Only objects where fit with two components.



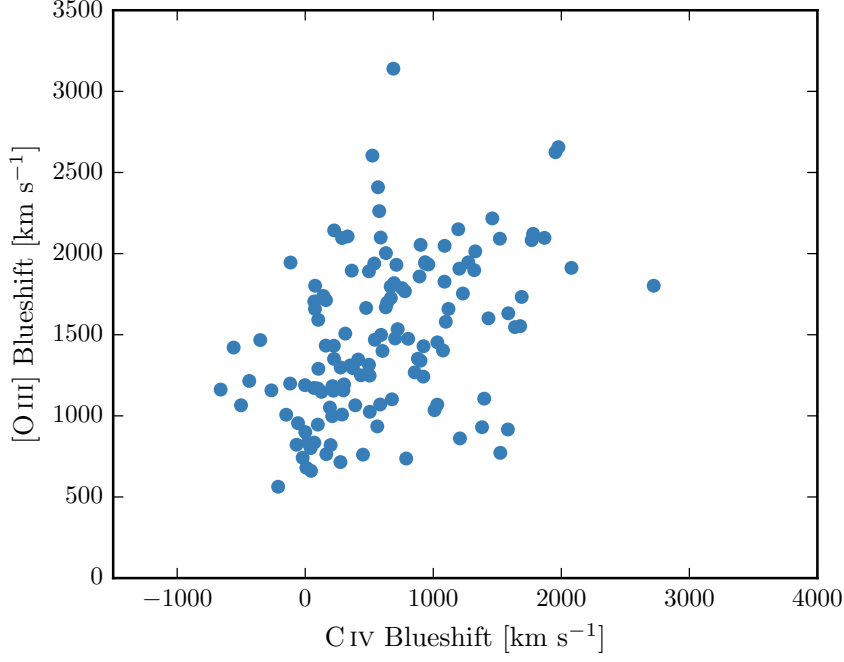


Figure 1.18

### 1.8.2 $[O\text{ III}]$ and $C\text{ IV}$ outflows are linked

As described in Paper I, we have searched for optical counterparts to our near-infrared spectra. Optical spectra are available for XXX quasars in our catalogue, and cover the broad  $C\text{ IV}$  doublet. As we described in Paper I and Coatman et al., (2016),  $C\text{ IV}$  is often blueshifted, which almost certainly signal the presence of strong outflows, most likely originating in a disc wind. In Paper I we demonstrated that the quasars in our sample cover the full range of  $C\text{ IV}$  blueshifts seen in the SDSS quasar population, which makes our sample unique in that it allows us to study properties of the quasar across the full parameter range.

The  $C\text{ IV}$  velocity centroid measurements are taken directly from paper I. We define the ‘location’ of the  $[O\text{ III}]$  emission using  $v_{10}$ , although the results are the same if  $v_{20}$ ,  $v_{50}$  etc. are used instead.

In Figure 1.17 we show the  $C\text{ IV}$  blueshifts against the  $[O\text{ III}]$  blueshifts. This comparison is done for a sub-sample of 146 objects where we have good measurements of the  $C\text{ IV}$ ,  $[O\text{ III}]$ , and  $H\beta$  (to measure the systemic redshift) profiles. Objects with  $S/N > 3$  are shown as blue filled circles and objects with  $S/N < 3$  as open grey circles. We calculated the median  $S/N$  per pixel in the best-fitting model for the  $[O\text{ III}]5008$  emission.

There is a clear and strong correlation. Similar correlations have been tentatively found in lower redshift quasars and AGN (Zamanov et al., 2002).

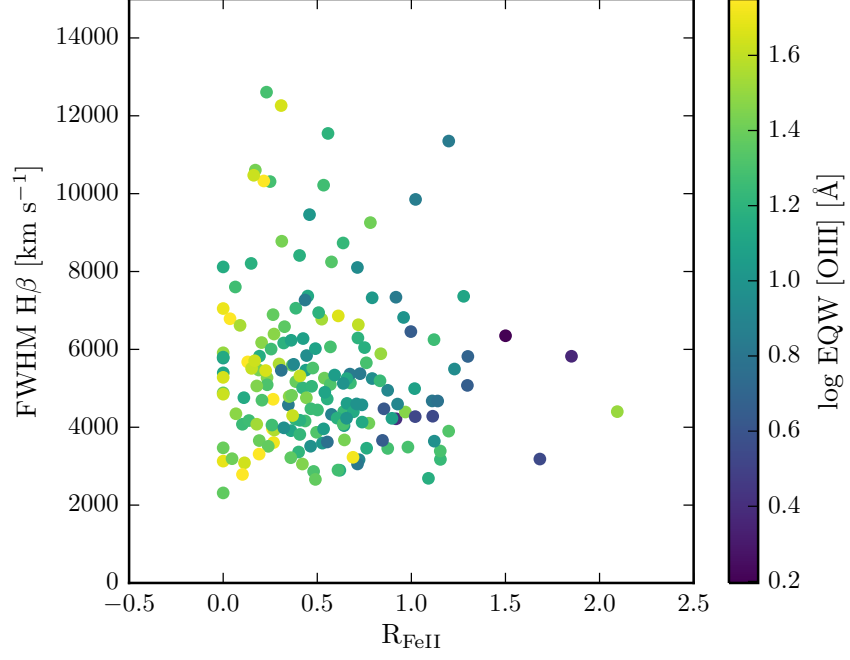


Figure 1.19: The [O III] EQW as a function of the H $\beta$  FWHM and the optical Fe II strength (EQW Fe II/ EQW H $\beta$  ).

The blueshifting of C IV is known to correlate with luminosity (Richards et al., 2011). In [O III], the blueshifted wing becomes relatively more prominent as the luminosity of the quasar increases (Shen and Ho, 2014). Therefore, it is plausible that the correlation between the C IV and [O III] blueshifts is a secondary effect that is driven by the correlation of each with the luminosity. In Figure ?? we color the data points by the luminosity, and no luminosity-dependent trends are apparent. We find that both the [O III] and C IV blueshifts are correlated with the luminosity, but that these correlations are much weaker than the correlation between the [O III] and C IV blueshifts.

### 1.9 EIGENVECTOR ONE CORRELATIONS

Because of this diversity, it is the dominant variable in the set of correlations making up EV1, which is believed to be linked to certain fundamental parameters of the accretion process. In Figure 1.19 we show the [O III] EQW as a function of the H $\beta$  FWHM and the optical Fe II strength. The optical Fe II strength is defined as the ratio of the Fe II and H $\beta$  EQW, where the Fe II EQW is measured between 4434 and 4684Å. These parameters form part of ‘eigenvector 1’ (EV1), the first eigenvector in a principal component analysis which originated from the work of Boroson and Green, (1992). In our sample, these parameters follow very similar correlations to what is observed at low- $z$

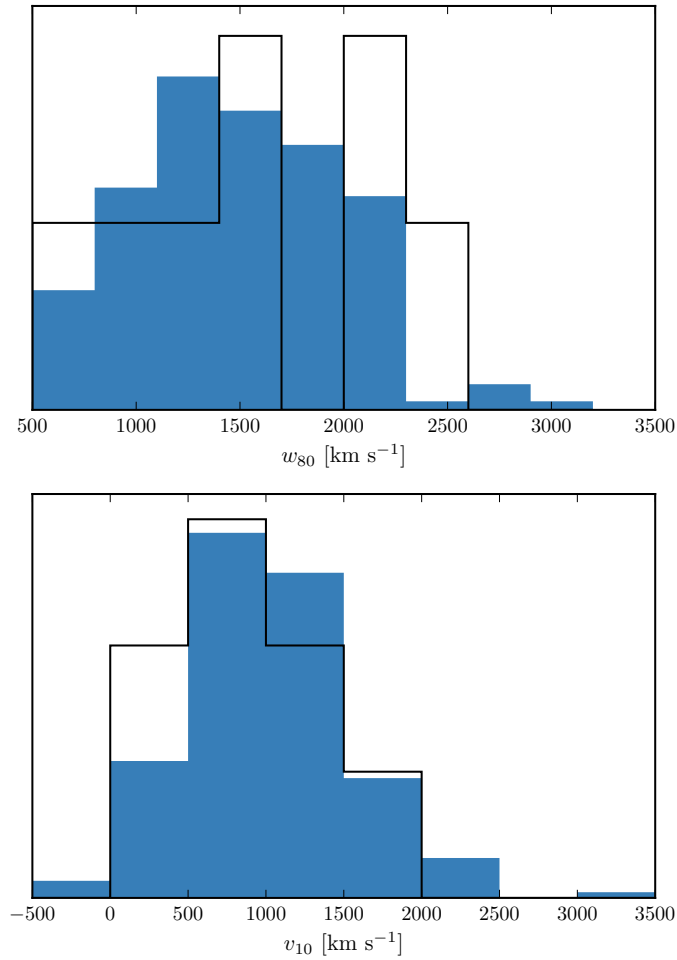


Figure 1.20: The distribution of  $w_{80}$  and  $v_{10}$  for the 19 BALs are compared to the distribution for the non-BALs. These look rubbish. Cumulative distributions instead? Try doing gaussian kernel density estimator

(e.g. Shen and Ho, 2014). In particular, the anti-correlation between the [O III] and Fe II EQWs.

Same as Shen, (2016), we confirm that the EV1 correlations hold at high luminosities/redshifts. See also Sulentic et al. 2004, 2006; Runnoe et al. 2013. Make sure it's clear that Shen, (2016) quasars make up a significant chunk of our sample.

#### 1.10 MAPPING EV1 TO CIV BLUESHIFT AND EQW

#### 1.11 SIGNAL TO NOISE TESTS

#### 1.12 BROAD ABSORPTION LINE QUASARS

19 quasars in our catalogue are classified as broad absorption line (BAL) quasars, using either the SDSS classification flags or the Allen et al., (2011) catalogue. We find that the BAL quasars have typically broader [O III] than the rest of the sample. Note that in the Zakamska et al., (2016) sample of very red quasars, the incidence of BALs is very high, and these objects have extremely broad [O III] profiles. A two-sided Kolmogorov-Smirnov statistic on the  $w_{80}$  distributions returned a p-value of 0.10. What does this mean? Try with different parameters? Histograms look rubbish so maybe just give the numbers.

#### 1.13 DISCUSSION

##### 1.13.1 *Type II quasars*

Implications of our findings on searches for high-redshift type 2 quasars. It could be that type II quasars exist. If you look at CIV/MgII the narrow line components are very weak. So the contribution from the narrow line region is very weak in luminous quasars, and you just won't see it even if the broad line region is obscured. Findings in this paper seem to suggest that the startic narrow line region is very weak in luminous quasars.