

# The first high-redshift Changing Look Quasars

Nicholas P. Ross<sup>1\*</sup>, Matthew Graham<sup>2</sup>, K. E. Saavik Ford<sup>3,4,5</sup>, Barry McKernan<sup>3,4,5</sup>  
and Daniel Stern<sup>6</sup>

<sup>1</sup>*Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, United Kingdom*

<sup>2</sup>*Cahill Center for Astronomy and Astrophysics, California Institute of Technology, Mail Code 249/17, 1200 E California Blvd, Pasadena CA 91125, USA*

<sup>3</sup>*Department of Science, BMCC, City University of New York, New York, NY 10007, USA*

<sup>4</sup>*Department of Astrophysics, Rose Center for Earth and Space, American Museum of Natural History, Central Park West at 79th Street, NY 10024, USA*

<sup>5</sup>*Graduate Center, City University of New York, 365 5th Avenue, New York, NY 10016, USA*

<sup>6</sup>*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Mail Stop 169-221, Pasadena, CA 91109, USA*

Accepted XXX. Received YYY; in original form ZZZ

## ABSTRACT

We report on three redshift  $z > 2$  quasars with dramatic changes in their C iv emission lines, the first ‘Changing-Look’ quasars at high redshift. This is also the first time the changing-look behaviour has been seen in a high-ionization emission line. SDSS J1205+3422, J1638+2827 and J2228+2201 show interesting behaviour in their observed optical light curves, and subsequent spectroscopy shows significant changes in the C iv broad emission line, with both line collapse and emergence being displayed in rest-frame timescales of  $\sim 240$ –1640 days. Where observed, the profile of the Ly $\alpha$ /N v emission complex also changes, and there is tentative evidence for changes in the Mg ii line. Although line measurements from the three quasars show large changes in the C iv line flux-line width plane, the quasars are not seen to be outliers when considered against the full  $z \sim 2$  quasar population in terms of (rest) Equivalent Width and FWHM properties. We put these observations in context with recent “state-change” models, but note that even in their ‘low-state’, the C iv CLQs are above  $\sim 10\%$  in Eddington luminosity.

**Key words:** accretion, accretion discs – surveys – quasars: general – quasars: individual: J1100-0053

## 1 INTRODUCTION

Luminous AGN, i.e. quasars, are now seen to significantly vary their energy output on timescales of weeks to months. This observation, and the subsequent mismatch in the expected “viscous” timescale, which for a  $\approx 10^7 M_\odot$  central supermassive black hole (SMBH) is  $\sim$ hundreds of years, was noted over 30 years ago (e.g. Alloin et al. 1985). However, with new photometric light-curve and repeat spectroscopic data, the desire for a deeper understanding of AGN accretion disk physics has been recently re-invigorated the field (e.g. Lawrence 2018; Antonucci 2018).

The optical continuum variability of quasars has been recognized since their first optical identification (e.g., Matthews & Sandage 1963; MacLeod et al. 2012). Dramatic changes in the broad emission lines (BELs) of quasars has only recently been identified (e.g., LaMassa et al. 2015). Samples of over 100 “Changing Look” quasars (CLQs) or “Changing State” quasars (CSQs) have now been assembled (e.g. MacLeod et al. 2019; Graham et al. 2019). The community uses both these terms as a cover for the underlying physics. For sake of argument, “Changing Look” quasars can potentially be

thought of as the extension to the BELs of quasar continuum variability (e.g., MacLeod et al. 2012) whereas the “Changing State” quasars (CSQs) have a ‘state-transition’ similar to that in Galactic X-ray binaries (Noda & Done 2018; Ruan et al. 2019). In this paper, we use the term ‘Changing Look’, as we are currently agnostic, and somewhat ignorant, to the underlying physical processes.

These CLQs have primarily been defined according to the (recombination) Balmer emission line properties with particular attention paid to the H $\beta$  emission line, observed from optical spectroscopy. Recent work (Guo et al. 2019; Homan et al. 2019) report on discoveries of Mg ii Changing-look AGN. However, current CLQ studies have been at redshifts  $z < 1$ .

While there have been a slew of studies on triply ionized carbon, i.e. C iv, these have tended to focus on broad absorption line quasars (BAL QSOs; see Table 1 Hemler et al. 2019) or the Baldwin Effect (BEff; Baldwin 1977; Bian et al. 2012; Jensen et al. 2016; Hamann et al. 2017)<sup>1</sup>. Dramatic changes in the collisionally excited

<sup>1</sup> As noted in Rakić et al. (2017), two different types of Baldwin effect are present in the literature: the *global* (or *ensemble*) Baldwin Effect, which is an anti-correlation between the EW of the emission line and the underlying continuum luminosity of *single-epoch* observations of a *large number* of

\* E-mail: npross@roe.ac.uk

broad emission line (BEL) of C IV (and indeed C III) have not to this point been seen.

Here, we report on three quasars which show dramatic changes in their C IV and C III broad emission line properties as well as in the underlying continuum. We claim these are the first examples of “Changing Look Quasars” at high ( $z > 1$ ) redshift. Moreover, these are the first cases for substantial changes of ions with high ionization potentials (I.P.’s  $> 2$  Rydberg), thus linking the ionizing photons to the energetic inner accretion disk, potentially by inverse Compton scattering of lower energy photons to higher energies. Furthermore, the measured rest-wavelengths of emission lines in quasar spectra, are known to vary from their nominal laboratory wavelengths especially for the high-ionization broad lines (e.g. Vanden Berk et al. 2001).

In this paper we use the wavelengths of 1548.202 and 1550.774 Å for the C IV doublet (Kramida et al. 2018). The 1548.202 and 1550.774 Å emission doublet is created by the  $2p^2P_0 - 2s^2S$  transition, split by total angular momentum  $J = 3/2$  and  $1/2$ , resulting in energies  $64,591 \text{ cm}^{-1}$  and  $64,484 \text{ cm}^{-1}$ , respectively (e.g. Moore 1993). The transition probabilities of the the 1548 and 1550 Å lines are  $A_{ki} = 2.65 \times 10^8$  and  $2.64 \times 10^8 \text{ s}^{-1}$ .

The ground state of carbon is  $1s^2 2s^2 2p^2$ . Using the NIST Atomic Spectra Database Ionization Energies Form for ionisation energies, we note 11.3 eV is the energy required for C I to dislodge one electron and become singly-ionised C II; 24.4 eV is then the (‘additional’) energy needed for singly-ionised C II to dislodge an additional electron, and become doubly-ionised C III, and 47.89 eV (3.519 Ry) is required for doubly-ionised C III become triply-ionised C IV. 64.49 eV (4.74 Ry) is the energy needed to ionize C IV itself. This energy corresponds to a thermal temperature of  $T \gtrsim 4 \times 10^5$ , implying a heating energy source of (soft) X-ray photons ( $k_B = 8.617 \times 10^{-5} \text{ eV/K}$ ). C III is the  $1s22s2p^3P^o$  to  $1s^22s^21S$  transition (with  $J = 1 \rightarrow 0$ ) resulting in an energy of  $52,390.75 \text{ cm}^{-1}$  and a transition probability of  $A_{ki} = 1.14 \times 10^2 \text{ s}^{-1}$  (Wiese et al. 1996).

C IV variability has been long studied, e.g., Baldwin (1977); Gaskell (1982); Gregory et al. (1982); Wilkes (1986); Espey et al. (1989, 1990); Zheng & Sulentic (1990); Corbin (1990, 1991); Weymann et al. (1991); Dimitrijevic & Sahal-Brechot (1992); Tytler & Fan (1992); Wills et al. (1993); Brotherton et al. (1994); Osmer et al. (1994); Laor et al. (1995); McIntosh et al. (1999); Nazaroza (2003).

Wilhite et al. (2006) examine the variability of a C IV sample of 105 quasars observed at multiple epochs by the Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002; Abazajian et al. 2009a). They find a strong correlation between the change in the C IV line flux and the change in the line width, but no correlations between the change in flux and changes in line center and skewness. These authors find that the relation between line flux change and line width change is consistent with a model in which a broad line base varies with greater amplitude than the line core. The C IV lines in these high-luminosity quasars appear to be less responsive to continuum variations than those in lower luminosity AGN. Wilhite et al. (2006) find no evidence for variability of the well known blueshift of the C IV line with respect to the low-ionization Mg II  $\lambda 2798$  line in the highest flux objects.

Richards et al. (2011) explored the BEL region in over 30,000  $z > 1.54$  SDSS quasars, concentrating on the properties of the C IV

emission line. We consider two well-known effects involving the C IV emission line: the anti-correlation between the C IV EQW and luminosity (i.e., the BEff) and the blueshifting of the peak of C IV emission with respect to the systemic redshift. These authors conclude that these two C IV parameters (EQW and blueshift) are capturing an important trade-off between “disk” and “wind” components in the disk-wind model of accretion disks (e.g., Murray et al. 1995; Elvis 2000; Proga et al. 2000), with one dominating over the other depending on the shape of the SED (Leighly 2004, strong C IV EQW indicates a more ionizing SED and large C IV blueshift indicating a less ionizing SED).

The Sloan Digital Sky Survey Reverberation Mapping Project (SDSS-RM; Shen et al. 2015) has a monitored  $\sim 350$  quasars with C IV. Noting the biases associated with C IV Emission Line Properties (e.g. increasing systematic offsets with decreasing signal-to-noise Denney et al. 2016), Grier et al. (2019) report significant time delays between the continuum and the C IV 1549 emission line in 52 quasars, and investigate the C IV radius-luminosity relationship.

C IV is also known to exhibit significant displacements to the blue and these ‘blueshifts’ almost certainly signal the presence of strong outflows. As a consequence, single-epoch virial black hole (BH) mass estimates derived from C IV velocity widths are known to be systematically biased compared to masses from the hydrogen Balmer lines. Coatman et al. (2017) use a large sample of 230 high-luminosity ( $L_{\text{Bol}} = 1045.5\text{--}1048 \text{ erg s}^{-1}$ ), redshift  $1.5 < z < 4.0$  quasars with both C IV and Balmer line spectra, we have quantified the bias in C IV BH masses as a function of the C IV blueshift. C IV BH masses are shown to be a factor of 5 larger than the corresponding Balmer-line masses at C IV blueshifts of  $3000 \text{ km s}^{-1}$  and are overestimated by almost an order of magnitude at the most extreme blueshifts,  $\gtrsim 5000 \text{ km s}^{-1}$ .

Sun et al. (2018) use the multi-epoch spectra of 362 quasars from the Sloan Digital Sky Survey Reverberation Mapping project to investigate the dependence of the blueshift of C IV relative to Mg II on quasar properties. We confirm that high-blueshift sources tend to have low C IV equivalent widths (EWs), and that the low-EW sources span a range of blueshift. Other high-ionization lines, such as He II, also show similar blueshift properties. The ratio of the line width (measured as both the full width at half maximum and the velocity dispersion) of C IV to that of Mg II increases with blueshift. Quasar variability enhances the connection between the C IV blueshift and quasar properties (e.g., EW). The variability of the Mg II line center (i.e., the wavelength that bisects the cumulative line flux) increases with blueshift. In contrast, the C IV line center shows weaker variability at the extreme blueshifts. Quasars with the high-blueshift C IV lines tend to have less variable continuum emission, when controlling for EW, luminosity, and redshift. Our results support the scenario that high-blueshift sources tend to have large Eddington ratios. Therefore, according to this study, the C IV or [He II] EW is not an accurate indicator of the Eddington ratio or quasar SED. Recent investigations also include Meyer et al. (2019) and Doan et al. (2019). Dyer et al. (2019) provide a detailed analysis of 340 quasars at high-redshift ( $1.62 < z < 3.30$ ) from the SDSS-RM project, which we will compare our results to.

The purpose of this paper is, for the first time, to access and report on the Changing-Look quasar phenomenon at high,  $z > 2$  redshift. By doing so, we move from the low-ionization energy Balmer emission line series to the high-ionization emission lines, in particular C IV  $\lambda 1549$ .

This paper is organised as follows. In Section 2, we describe our sample selection, catalogs and observational data sets. In Section

AGN and second, the *intrinsic* Baldwin effect, the same anti-correlation but in an *individual, variable* AGN (Pogge & Peterson 1992).

Object R.A. / deg Decl. / deg	Redshift	g-band magnitude	MJD	Date	Instrument	Exposure Time / seconds	SDSS Spectrum Plate-FiberID	Notes
J120544.7+342252.4 181.436164 +34.381229	2.068±0.0003 2.071	18.27	53498 58538 58693	2005-May-08 2019-Feb-24 2019-Jul-29	SDSS DBSP DBSP	8057 1800 2400	2089-427 — —	Average conditions
J163852.9+282707.7 249.720558 +28.452159	2.185±0.0004 2.186±0.0007 2.182	19.77	54553 55832 58583	2008-Mar-28 2011-Sep-28 2019-Apr-10	SDSS BOSS LRIS	4801 3600 1800	2948-614 5201-178 —	
J222818.7+220102.9 337.078194 +22.017478	2.217±0.0021 2.222±0.0004	19.97	56189 56960 58693	2012-Sep-19 2014-Oct-30 2019-Jul-29	BOSS BOSS DBSP	2700 4500 2400	6118-720 7582-790 —	eBOSS reobservation

**Table 1.** Details of our spectroscopic observations. Redshift and redshift errors from SDSS SkyServer for SDSS, BOSS and eBOSS spectra. Exposure times are from the `plate.fits` file. SDSS, BOSS and eBOSS spectra have  $R \sim 2,000$ . DBSP: Double Spectrograph on the Palomar 200-inch telescope. LRIS: Low Resolution Imaging Spectrometer on Keck I 10m telescope.

3, we present the high- $z$  quasars and report the line properties for the quasars at the observed epochs. We give a very brief theoretical discussion in Section 4. We present our Conclusions in Section 5. We report all magnitudes on the AB zero-point system (Oke & Gunn 1983; Fukugita et al. 1996) unless otherwise stated explicitly. For the WISE bands,  $m_{AB} = m_{Vega} + m$  where  $m = (2.699, 3.339)$  for WISE W1 at  $3.4\mu\text{m}$  and WISE W2 at  $4.6\mu\text{m}$ , respectively (Cutri et al. 2011). We adopt a flat  $\Lambda$ CDM cosmology with  $\Omega_\Lambda = 0.73$ ,  $\Omega_M = 0.27$ , and  $h = 0.71$  in order to be consistent with Hamann et al. (2017). As a guide this cosmology has a  $z = 2.000$  comoving radial distance of 5244.3 Mpc, a  $\sim 1.25\%$  difference compared to 5179.0 Mpc from  $\Omega_\Lambda = 0.70$ ,  $\Omega_M = 0.30$ , and  $h = 0.70$  that is used in Shen et al. (2011).

## 2 DATA

Our high- $z$  CLQs were identified as follows. We selected all 64,774 SDSS DR15 sources with  $z > 0.35$  classified as ‘QSO’, having at least two spectra separated by at least 100 days, and with a corresponding CRTS light curve. We fitted a damped random walk to the CRTS data via Gaussian process regression and the photometric magnitudes at the epochs of the SDSS spectra for a given source are predicted. Those where  $|\Delta V| > 0.3$  are then selected for visual inspection. Three quasars SDSS J120544.7+342252.4 (hereafter J1205+3422), SDSS J163852.93+282707.7 (hereafter J1638+2827) and SDSS J222818.76+220102.9 (hereafter J2228+2201), satisfied these selection criteria and showed interesting or dramatic emission line behaviour.

### 2.1 Spectra

An overview of our spectroscopic observations is given in Table 1. The spectra are from the SDSS (Stoughton et al. 2002; Abazajian et al. 2009b; Schneider et al. 2010), the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS Eisenstein et al. 2011; Dawson et al. 2013; Smee et al. 2013; Alam et al. 2015; Pâris et al. 2017) and the SDSS-IV Extended Baryon Oscillation Spectroscopic Survey (eBOSS; Dawson et al. 2016; Abolfathi et al. 2018; Pâris et al. 2018). These quasars were targetted via a range of techniques and algorithms (see Richards et al. 2002; Ross et al. 2012; Myers et al. 2015). The SDSS, BOSS and eBOSS data are supplemented by

spectra from the Low Resolution Imaging Spectrometer (LRIS) on the 10m Keck I telescope (Oke et al. 1995), and the Double Spectrograph (DBSP) instrument on the Palomar Hale 5m telescope.

### 2.2 Emission Line and Power-law slope measurements

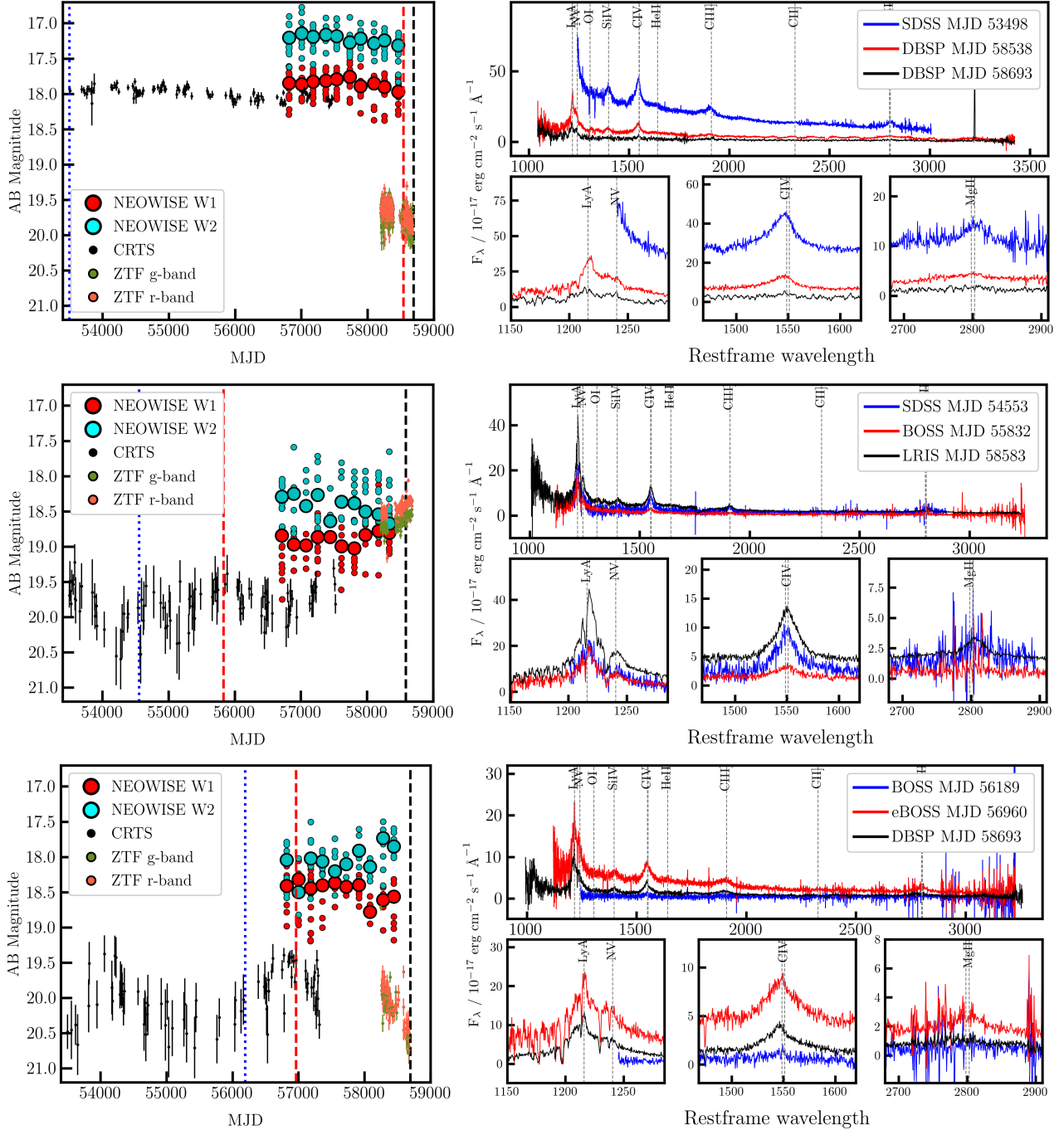
We use the measured quasar emission line properties from several catalogues: Shen et al. (2011), Hamann et al. (2017), Kozłowski (2017) and Calderone et al. (2017).

Shen et al. (2011) present a compilation of properties of the 105,783 quasars in the SDSS Data Release 7 (DR7) quasar catalog (DR7Q; Schneider et al. 2007). Shen et al. (2011) report non-zero C IV FWHM and EWs for approximately half (51,501) of the full DR7Q, and non-zero Mg II FWHM and EWs for 80% (84,183) of the DR7Q quasars. Measured line values using the methods and catalogue from Shen et al. (2011).  $M_1(z=2)$  is the Absolute  $i$ -band magnitude  $K$ -corrected to  $z=2$ ; Bolometric luminosity computed from the monochromatic luminosity at  $1350\text{\AA}$  using the spectral fits and bolometric corrections ( $BC = 3.81$ ) in Richards et al. (2006); Line luminosity, FWHM, rest-frame equivalent width, and their errors for the whole C IV profile. Power-law slope  $\alpha_\lambda$  for the continuum fit for C IV; Virial BH masses using calibrations of Vestergaard & Peterson (2006). Eddington ratio computed using the virial BH mass.

Calderone et al. (2017) present the Quasar Spectral Fitting (QSFIT) software package which among other quantities provides luminosity estimates as well as width, velocity offset and equivalent width of 20 emission lines, including C IV, C III] and Mg II. We attempt to process and fit all nine spectra using the latest version (v1.3.0) of the QSFIT online calculator and setting  $E(B-V) = 0.00$ .

Hamann et al. (2017) investigate in robust detail the UV continuum and the C IV (and N V  $\lambda 1238, 1242\text{\AA}$ ) emission lines for over 200,000 quasars in BOSS DR12Q (Pâris et al. 2017). The quasar redshift are limited to the range  $1.53 \leq z \leq 5.0$  so that C IV and the adjacent continuum are covered by BOSS. These measurements provide line profile information and flux ratios<sup>2</sup> Hamann et al. (2017) was focused on  $z \geq 2$  quasars and specifically their C IV properties in order to understand the high- $z$  ‘‘Extremely Red Quasar’’ population Ross et al. (2015); Zakamska et al. (2016); Perrotta et al. (2019);

<sup>2</sup> This emission-line catalog can be downloaded from here.



**Figure 1.** The three high- $z$  CLQ quasars; SDSS J1205+3422 (top), SDSS J1638+2827 (middle), SDSS J2228+2201 (bottom). The light curve data is present in the panels on the left hand side, with the spectral epoch observational timings given by the vertical lines. The spectra are on the right hand side, with zoom-in's on the Ly $\alpha$ -N v complex, the C iv line and the Mg ii line.

Zakamska et al. (2019). As such, these measurements can be taken as the ‘gold standard’ for C iv line measurement, though this is only for two out of our nine spectra.

When using the Shen et al. (2011) catalogue, we report line luminosity, FWHM, rest-frame equivalent width, and their errors for the whole Mg ii profile (this catalogue also quotes values for just the broad Mg ii component, but the differences for our objects is negligible). The line luminosities in Calderone et al. (2017) are given in units of  $10^{42}$  erg s $^{-1}$ , while the line luminosities in Shen

et al. (2011) are in units of log( $L$ ). We do not report the Shen et al. (2011) error on the line luminosity.

Power-law continuum slopes,  $\alpha$ , where  $f_{\lambda} \propto \lambda^{\alpha}$ , are also reported in these catalogues and from QSFit. We quote the most appropriate value given the emission line wavelength.

### 2.3 Multi-wavelength properties

Mid-infrared data (3.4 and 4.6  $\mu$ m) is available from the beginning of the Wide-field Infrared Survey Explorer (WISE) mission (2010

January; Wright et al. 2010) through the fifth-year of NEOWISE-R operations (2018 December; Mainzer et al. 2011). The WISE scan pattern leads to coverage of the full-sky approximately once every six months (a “sky pass”), but the satellite was placed in hibernation in 2011 February and then reactivated in 2013 October. Hence, our light curves have a cadence of 6 months with a 32 month sampling gap.

### 3 RESULTS

#### 3.1 Overall Spectral Evolution

Figure 1 presents the optical and infrared light curves for three high- $z$  CLQ quasars. Figure 1 also shows the spectra for each epoch, with the MJD of observation given by the dashed vertical lines in the light curves.

For J1205+3422, our spectral observations cover 5195 days observed, 1691 days in the rest-frame. For J1205+3422 is identified in SDSS as a bright  $g \approx 18.0$ , blue-sloped quasar with broad Si IV, C IV, C III] and Mg II observed in the initial spectrum (MJD 53498; 2005-May-08). C III] and C IV are seen to have large blueshifts of  $\approx 2600 \pm 150$  and  $\approx 1150 \pm 100$  km s $^{-1}$ , respectively. By the time the 2019 spectra were taken (MJD 58538, 2019-Feb-24 and MJD 58693 2019-Jul-29), however, the light curve has dropped by  $\sim 1.5$  magnitudes and the spectra are significantly less steep. While Ly $\alpha$  and N V are detectable in both the MJD 58538 and MJD 58693 DBSP spectra, C IV has all but disappeared in the MJD 58693 spectrum. The broad C III] emission has disappeared between the 2005 and 2019 spectra. *The changes in C IV and C III] going from broad emission to barely detectable have on the timescales of  $\approx 50$  days in the rest-frame.*

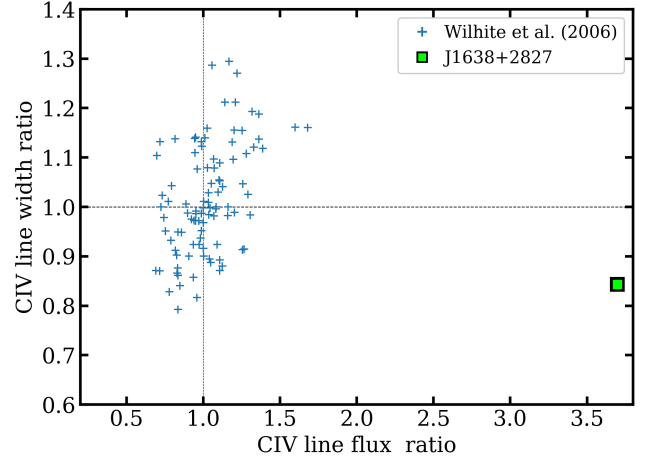
For J1638+2827, our spectral observations cover 4030 days observed, 1265 days in the rest-frame. Here, in the initial epoch spectrum, C IV is broad and bright, as is C III]. However, just over 400 days in the rest-frame later, the broad C IV and C III] BEL have faded, the continuum slope around 1400 Å has changed from  $\sim -1.48$  to  $\sim -2.25$ , but the Ly $\alpha$ /N V emission complex is very similar in shape and line flux intensity. Around 870 days in the rest-frame after the second spectral epoch, Ly $\alpha$ , N V, C IV, C III] and Mg II are all apparent and broad, with Mg II being seen for the first time at high signal-to-noise. The light curve is consistent with this spectral brightening, increasing from around  $\sim 19.5$ -20.5th magnitude to  $\sim 18.5$  in the optical band. An absorption feature between Ly $\alpha$  and N V is seen in all three spectral epochs.

For J2228+2201, our spectral observations cover 2504 days observed, 778 days in the rest-frame. Over the course of 240 days in the rest-frame, C IV and C III] both *emerge* as BELs and the standard UV/blue continuum slope increases in flux. Then, over the course of 538 days in the rest-frame, the broadline emission, while still very present, reduces in line flux the UV/blue continuum diminishes, though is still more luminous than the initial BOSS spectrum.

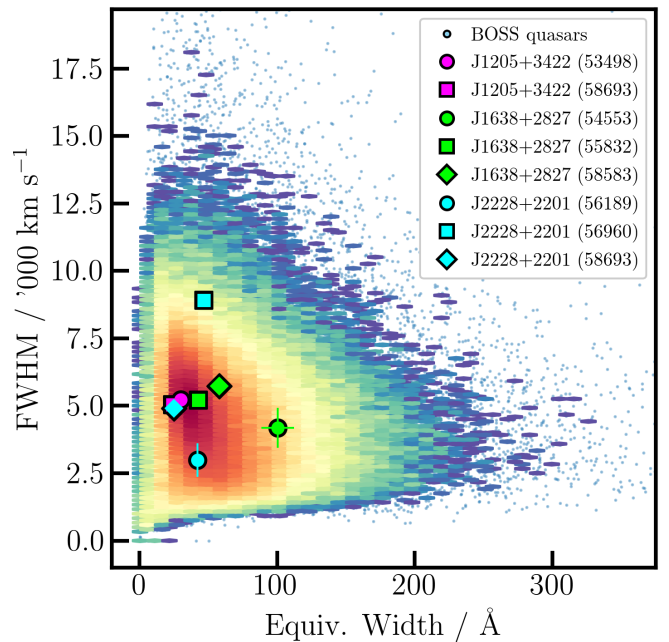
#### 3.2 Overall Spectral Evolution

Emission line measurements from the catalogues of Shen et al. (2011). Hamann et al. (2017), Kozłowski (2017) or the QSFIT routine of Calderone et al. (2017) are presented in Table 2. From Figure 2 there appears to be a strong correlation between the change in the line flux and the change in the line width. Figure 2 shows the epoch-to-epoch flux ratio versus the ratio of line widths.

The Balmer series in hydrogen is due to the recombination



**Figure 2.** The Change in C IV line width vs. line flux change. We compare our object J1638+2827 with the sample from Wilhite et al. (2006) with a sample of 105 quasars observed at multiple epochs by the SDSS. J1638+2827 is a substantial outlier in this parameter space.



**Figure 3.** The Rest Equivalent Width (REW) vs. Full Width Half Maximum (FWHM) of the C IV emission line in the BOSS DR12 quasar sample using the catalogue of Hamann et al. (2017). Note the REW logarithmic scaling.

cascade between different principal quantum numbers  $n$ , and the  $n = 2$  level (e.g., Seaton 1959a,b). Lower redshift  $z < 0.9$  CLQs have traditionally been identified via large changes in the H $\beta$  emission line. H $\beta$  emission is associated with a 2.55 eV energy difference. Thus we can place the high- $z$ , HIL C IV in context of Balmer H $\beta$  CLQs at lower- $z$ . C IV is one of the strongest collisionally excited lines in quasar spectra Hamann & Ferland (e.g. 1999). The line is most prominent at  $n_{\text{H}} \approx 10^{10}$  cm $^{-3}$  and  $\log U \sim 1.5$ , which are the canonical BELR parameters deduced over from early analysis of the C IV emission (Davidson & Netzer 1979). A dimensionless ionization parameter  $U \equiv \Phi(H)/cn_{\text{H}}$ , where  $c$  is the speed of light and  $n_{\text{H}}$  is the total hydrogen density ( $\text{H}^0 + \text{H}^+$ ).

Object	MJD	line	Line Lumin.	FWHM	$V_{\text{off}}$	E.W.	$\alpha_{\lambda}$	Catalogue
J1205+3422	53498	C iv	511±13	9593±287	1172±74	15.9±0.4	-1.64±0.01	QSFit
	53498	C iv	787	5230±219	1118±133	30.1±1.21	-1.47±0.08	Shen2011
	53498	C iv	403	5119 <sup>(a)</sup>	—	—	—	DR12 SAS
	53498	C iii]	441±10	14959±352 <sup>(b)</sup>	2616±147	25.10±0.59	-1.65±0.01	QSFit
	53498	C iii]	144	5119 <sup>(a)</sup>	—	—	—	DR12 SAS
	53498	Mg ii	327±20	4907±387	-274±419	26.66±1.65	-1.65±0.01	<sup>(d)</sup> QSFit
	53498	Mg ii	284	4730±314	-179±188	32±3.88	-1.87±0.06	Shen2011
	53948	Mg ii	130	5119 <sup>(a)</sup>	—	—	—	DR12 SAS
	58538	Ly $\alpha$	952±1.1	12242±15	-1679±6	165±0.2	—	QSFit
	58538	C iv	1037±5	>15000	983±40	—	—	QSFit
	58538	C iii]	167±0.9	>15000	2734±46	45±0.2	—	QSFit
	58538	Mg ii	216±1.4	13940±94	-465.2±38	88±0.6	—	QSFit
	58693	Ly $\alpha$	271±0.9	9637±52	-447±13	85.1±0.3	—	QSFit
	58693	C iv	52±0.9	5046±26	1053±17	24.0±0.2	—	QSFit
	58693	C iii]	59±0.9	10751±	1097±77	36±0.6	—	QSFit
	58693	Mg ii	69±1.5	14983±346	-190±134	72±1.6	—	QSFit
J1638+2827	54553	Ly $\alpha$	188	3207	—	—	—	DR12 SAS
	54553	C iv	257±13	4550±371	55±450	31.8±1.5	—	<sup>(d)</sup> QSFit
	54553	C iv	281	4181±736	680±133	100.5±12	-0.14±0.68	Shen2011
	54553	C iv	170	4537 <sup>(a)</sup>	—	—	—	DR12 SAS
	54553	C iii]	130±10	3852±402	-236±565	36.7±2.8	-1.47±0.20	<sup>(d)</sup> QSFit
	54553	C iii]	61	4537 <sup>(a)</sup>	—	—	—	DR12 SAS
	54553	Mg ii	139	4757±2224	-944±568	119±40	-1.49±0.54	Shen2011
	54553	Mg ii	69	4537 <sup>(a)</sup>	—	—	—	DR12 SAS
	55832	Ly $\alpha$	288±11	4444±243	-463±68	103.69±3.99	—	QSFit
	55832	Ly $\alpha$	234	4165.6 <sup>(a)</sup>	—	—	—	DR12 SAS
	55832	C iv	63±3	6052±250	-117±103	43.2±1.7	-2.25±0.05	QSFit
	55832	C iv	—	5210±226	—	42.8±2.0	-3.35	Ham17
	55832	C iv	46	5385 <sup>(a)</sup>	—	—	—	DR12 SAS
	55832	C iii]	15±5	11421±3654	>3000	14.8±4.5	-2.25±0.05	QSFit
	55832	C iii]	11	5385 <sup>(a)</sup>	—	—	—	DR12 SAS
	55832	Mg ii	13	5385 <sup>(a)</sup>	—	—	—	DR12 SAS
J2228+2201	58583	Ly $\alpha$	785±1	4956±4	-641±2	90±0.1	—	QSFit
	58583	C iv	311±1	5739±14	-167±6	58±0.1	—	QSFit
	58583	C iii]	52±0.8	3917.4 68.837	1514±127	124±2	—	QSFit
	58583	Mg ii	157±2	10565±129	-450±52	92±1	—	QSFit
	56189	C iv	—	2994±620	—	42.2±5.6	-1.59	Ham17
	56189	C iv	19	5218 <sup>(a)</sup>	—	—	—	DR12 SAS
	56189	C iii]	34±6	13748±2869	1851±1140	63±12	-0.46±0.21	QSFit
	56189	C iii]	7	5218 <sup>(a)</sup>	—	—	—	DR12 SAS
	56189	Mg ii	25±6	7253±1712	-931±708	51±10.95	-0.46±0.21	QSFit
	56189	Mg ii	13	5218 <sup>(a)</sup>	—	—	—	DR12 SAS
	56960	Ly $\alpha$	121±38	3580±673	-16±171	13.52±4.21	—	QSFit
	56960	C iv	229±4	8911±169	92±68	46.8±0.9	—	QSFit
	56960	C iii]	185±5	—	2701±225	47.75±1.29	—	QSFit
	56960	Mg ii	99±4	7312.6±340	188±137	50.75±2.21	—	QSFit
	58693	Ly $\alpha$	447±5	8133±93	613±130	56±0.6	—	QSFit
	58693	C iv	41±1	4914±>65	160±27	25±0.3	—	QSFit
	58693	C iii]	107±1.2	>15000	2422±67	—	—	QSFit
	58693	Mg ii	177±1.1	>15000	1000±2617	16±36	—	QSFit

**Table 2.** Line Measurement information for the nine epochs for the 3 quasars. Line Luminosity is in units of  $10^{42}$  erg s $^{-1}$ ; FWHM and  $V_{\text{off}}$  in km s $^{-1}$ , where positive values of  $V_{\text{off}}$  means the line is blueshifted. Equivalent widths are ÅShen11 is Shen et al. (2011). Ham17 is Hamann et al. (2017). DR12 SAS is the line measurement information from the SDSS DR12 Science Archive Server (SAS). <sup>(a)</sup>Emission lines of a common “width group”, in this case, C iv1549, [He ii] 1640, C iii] 1909 and Mg ii 2800 are constrained to have the same intrinsic velocity width in the SDSS spectral line fitting procedure (Bolton et al. 2012). Positive values of  $V_{\text{off}}$  means the line is blueshifted. Notes: QSFit does not fit the Mg ii line for J1638+2827 MJD 54553 or 55832. QSFit does not fit the C ivline for J2228+2201 MJD 56189. <sup>(d)</sup>Emission line modelled with two components. The different colours of text are merely for readability.

## 4 DISCUSSION

C iv probes the photoionization environment produced by the innermost disk, as indicated by RM time-delay measurements. In standard Shakura & Sunyaev (1973) thin disk models, large changes in the continuum flux are not permitted over short timescales due to the relatively long viscous time associated with such disks. Given the

observed short timescale continuum variations, it is not surprising that the Shakura & Sunyaev (1973) disk may fail on other fronts. The C iv variations observed in our sources...

This indicates they may comfortably fit into the sample of CIV variable QSOs explored by Dyer et al. (2019), and similar to those authors we suggest slim accretion disk models e.g., Abramowicz et al. (1988) or inhomogeneous disk models (e.g., Dexter & Agol



Object	MJD	$M_i$	$L_{\text{bol}}$	$M_{\text{BH}}$	$\eta_{\text{Edd}}$	Ref.
				Mg II	C IV	
J1205+3422	53498	-27.74	47.216 $\pm$ 0.004	9.55 $\pm$ 0.05	9.49 $\pm$ 0.04	Shen2011
	58538					
	58693					
J1638+2827	54553	-26.75	46.166 $\pm$ 0.04	9.03 $\pm$ 0.37	8.74 $\pm$ 0.15	Shen2011
	55832	-26.40	46.721 $\pm$ 0.073	9.34	9.13	Kol017
	58583					
J2228+2201	56189	-25.46	46.231 $\pm$ 0.073	9.45	8.73	Kol017
	56960					
	58693					

**Table 3.**  $\eta_{\text{Edd}}$  is the base 10 logarithm of the Eddington ratio. Shen11 is Shen et al. (2011). Kol17 is Kozłowski (2017). Measured line values using the methods and catalogue from Shen et al. (2011).  $M_i(z=2)$  is the Absolute  $i$ -band magnitude  $K$ -corrected to  $z=2$ ; Bolometric luminosity computed from the monochromatic luminosity at 1350Å using the spectral fits and bolometric corrections (BC = 3.81) in Richards et al. (2006); Line luminosity, FWHM, rest-frame equivalent width, and their errors for the whole C IV profile. Power-law slope  $\alpha_\lambda$  for the continuum fit for C IV; Virial BH masses using calibrations of Vestergaard & Peterson (2006). Eddington ratio computed using the virial BH mass.

2011) may provide viable explanations for our observations. I want to say a bit more here about the generic probe of photoionization vs shielding and conditions in the BL region but that will take more time.

This implies that the variable C IV in our sample arises through different emission mechanisms than is usual for high- $z$  quasar...

#### 4.1 The Baldwin Effect

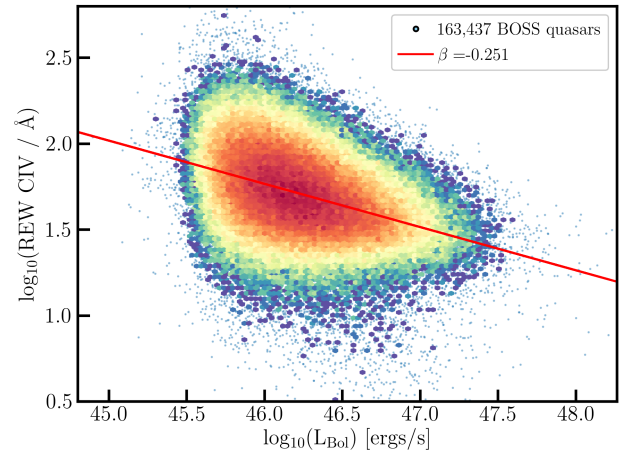
The variable properties of the rest-frame UV quasar emission lines have been long studied, with the global (or ensemble) Baldwin Effect (the anti-correlation between the EW of the emission line and the underlying continuum luminosity of single-epoch observations of a large number of AGN, first noted in Baldwin (1977). More recently, the intrinsic Baldwin effect, the same anti-correlation but in an individual, variable AGN. The variable properties of high- $z$  quasars, however, has been less well studied. Reasons for this include more massive systems will tend to have longer timescales with e.g.  $t_{\text{dyn}} = \sqrt{R^3/GM} \rightarrow t_{\text{dyn}} \sim M^2$  if e.g.  $R_{\text{Sch}} = 2GM/c^2$ .

The X-ray Baldwin Effect (e.g., Iwasawa & Taniguchi 1993)... Bachev et al. (2004) find a 10-fold decrease in EW C IV with Eddington ratio (decreasing from  $\sim 1$  to  $\sim 0.01$ ), while N V shows no change. These trends suggest a luminosity-independent “Baldwin effect” in which the physical driver may be the Eddington ratio. Ge et al. (2016) Broad emission lines is a prominent property of type I quasi-stellar objects (QSOs).

#### 4.2 Eddington ratios and State Changes

The broad UV and optical lines in quasars are most sensitive to the extreme ultraviolet (EUV) part of the spectral energy distribution (SED), with C IV (and indeed [He II] and N V) being at the higher energy end of the EUV distribution.

The soft X-ray excess is the excess of X-rays below 2 keV with respect to the extrapolation of the hard X-ray spectral continuum model is a very common feature among type 1 active galactic nuclei (AGN). Noda & Done (2018) note that The soft X-ray excess produces most of the ionizing photons, so its dramatic drop leads to the disappearance of the broad-line region, driving the “changing-look” phenomena. major difference is that radiation pressure should be much more important in AGNs, so that the sound speed is much faster than expected from the gas temperature. This spectral hardening appears similar to the soft-to-hard state transition in black hole binaries at  $L/L_{\text{Edd}} \sim 0.02$  (i.e.  $\eta_{\text{Edd}} \sim -1.7$ , where the



**Figure 4.** The Baldwin Plot. The bolometric luminosities are from Kozłowski (2017), while the REW measurements are from Hamann et al. (2017).

inner disc evaporates into an advection dominated accretion flow, while the overall drop in luminosity appears consistent with the hydrogen ionization disc instability. Crucially Noda & Done (2018) make the prediction that all changing-look AGNs are similarly associated with the state transition at  $L/L_{\text{Edd}} \sim$  a few per cent. Jiang et al. (2014, 2016, 2019b). Jiang et al. (2019a) use global three dimensional radiation magneto-hydrodynamic simulations to study the properties of inner regions of accretion disks around a  $5 \times 10^8 M_{\odot}$  black hole with mass accretion rates reaching 7% and 20% of the Eddington value.

We investigate this reporting the Eddington ratios of the three quasars in Table 3.

#### 4.3 Variability around billion solar mass black holes

The Event Horizon Telescope (EHT) mapped the central compact radio source of the elliptical galaxy M87 at 1.3 mm (Event Horizon Telescope Collaboration 2019a,b,c,d,e,f).

The EHT observations confirm the observed 1.3mm asymmetric ring emission is consistent with predictions of strong gravitational lensing of synchrotron emission from a hot plasma orbiting near the black hole event horizon (Event Horizon Telescope Collaboration 2019e).

EHT2017 data includes tracks from four separate days of observing; each day is  $2.8 r_g c^{-1}$  (?) timescale is short compared to the decorrelation timescale of simulated images, which is  $\sim 50 r_g c^{-1}$ , and smaller than the light-crossing time of the source plasma.

For M87,  $M_{M87^*} = (6.5 \pm 0.7) \times 10^9 M_\odot$ ,

$$R_s = 2r_g = 2GM/c^2 = 9.598 \times 10^{12} \text{m}. \quad (1)$$

giving a *light crossing timescale* of  $t_{\text{lt}} = R_s/c = 32015 \text{secs}$  (0.37 days).

## 5 CONCLUSIONS

In this paper we have reported on three redshift  $z > 2$  quasars with dramatic changes in their C IV emission lines, the first ‘Changing-Look’ quasars at high redshift. This is also the first time the changing-look behaviour has been seen in a high-ionization emission line.

- SDSS J1205+3422, J1638+2827 and J2228+2201 show interesting behaviour in their observed optical light curves, and subsequent spectroscopy shows significant changes in the C IV broad emission line, with both line collapse and emergence being displayed in rest-frame timescales of  $\sim 240$ – $1640$  days.
- Where observed, the profile of the Ly $\alpha$ /N V emission complex also changes, and there is tentative evidence for changes in the Mg II line.
- Although line measurements from the three quasars show large changes in the C IV line flux-line width plane, the quasars are not seen to be outliers when considered against the full  $z > 2$  quasar population in terms of (rest) Equivalent Width and FWHM properties.
- We put these observations in context with recent ‘state-change’ models, but note that even in their ‘low-state’, the C IV CLQs are above  $\sim 10\%$  in Eddington luminosity.

Etiā mollis viverra nisi eget aliquet. Aliquam erat volutpat. Vivamus tristique, nisl eu malesuada semper, libero tortor convallis elit, a scelerisque orci nisi lacinia turpis. In lacinia ultrices volutpat. Proin ultrices luctus tellus, in placerat eros tincidunt id. Ut varius iaculis quam in consequat. Nulla nec orci est, sit amet Aliquam ac metus nec odio tempus pharetra sed nec diam. Sed eget arcu nulla. Etiā elementum ultrices ligula, at iaculis libero feugiat bibendum. Suspendisse potenti. Nam pharetra adipiscing euismod. Quisque imperdiet dignissim odio, sed volutpat justo tincidunt eu. Nunc vehicula pharetra suscipit. Integer aliquet pretium ipsum vel ultrices. Nam rutrum nibh ac quam pulvinar molestie.

### Availability of Data and computer analysis codes

All materials, databases, data tables and code are fully available at: [https://github.com/d80b2t/CIV\\_CLQs](https://github.com/d80b2t/CIV_CLQs).

## ACKNOWLEDGEMENTS

NPR acknowledges support from the STFC and the Ernest Rutherford Fellowship scheme.

We thank:

- Andy Lawrence, Mike Hawkins and David Homan for useful discussion.

This paper heavily used TOPCAT (v4.4) (Taylor 2005, 2011). This research made use of *Astropy*, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013; The Astropy Collaboration et al. 2018).

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III web site is <http://www.sdss3.org/>. SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, and NEOWISE, which is a project of the Jet Propulsion Laboratory/California Institute of Technology. WISE and NEOWISE are funded by the National Aeronautics and Space Administration. No animals were harmed in the production of this paper, but there was a large spider in NPRs apartment that ‘‘vanished’’.

## REFERENCES

- Abazajian K. N., et al., 2009a, *ApJS*, 182, 543  
 Abazajian K. N., et al., 2009b, *ApJS*, 182, 543  
 Abolfathi et al., 2018, *ApJS*, 235, 42  
 Abramowicz M. A., Czerny B., Lasota J. P., Szuszkiewicz E., 1988, *ApJ*, 332, 646  
 Alam S., et al., 2015, preprint, (arXiv:1501.00963)  
 Alloin D., Pelat D., Phillips M., Whittle M., 1985, *ApJ*, 288, 205  
 Antonucci R., 2018, *Nature Astronomy*, 2, 504  
 Astropy Collaboration et al., 2013, *Astron. & Astrophys.*, 558, A33  
 Bachev R., Marziani P., Sulentic J. W., Zamanov R., Calvani M., Dultzin-Hacyan D., 2004, *ApJ*, 617, 171  
 Baldwin J. A., 1977, *ApJ*, 214, 679  
 Bian W.-H., Fang L.-L., Huang K.-L., Wang J.-M., 2012, *MNRAS*, 427, 2881  
 Bolton A. S., et al., 2012, *AJ*, 144, 144  
 Brotherton M. S., Wills B. J., Steidel C. C., Sargent W. L. W., 1994, *ApJ*, 423, 131  
 Calderone G., et al., 2017, *MNRAS*, 472, 4051  
 Coatman L., Hewett P. C., Banerji M., Richards G. T., Hennawi J. F., Prochaska J. X., 2017, *MNRAS*, 465, 2120  
 Corbin M. R., 1990, *ApJ*, 357, 346  
 Corbin M. R., 1991, *ApJ Lett.*, 371, L51  
 Cutri R. M., et al., 2011, Technical report, Explanatory Supplement to the WISE Preliminary Data Release Products  
 Davidson K., Netzer H., 1979, *Reviews of Modern Physics*, 51, 715  
 Dawson K., et al., 2013, *AJ*, 145, 10  
 Dawson K. S., Kneib J.-P., et al., 2016, *AJ*, 151, 44  
 Denney K. D., et al., 2016, *ApJS*, 224, 14  
 Dexter J., Agol E., 2011, *ApJ Lett.*, 727, L24  
 Dimitrijevic M. S., Sahal-Brechot S., 1992, *A&AS*, 96, 613



- Doan A. N., et al., 2019, in American Astronomical Society Meeting Abstracts #233, p. 242.23
- Dyer J. C., Dawson K. S., du Mas des Bourboux H., Vivek M., Bizyaev D., Oravetz A., Pan K., Schneider D. P., 2019, *ApJ*, 880, 78
- Eisenstein D. J., Weinberg D. H., et al., 2011, *AJ*, 142, 72
- Elvis M., 2000, *ApJ*, 545, 63
- Espey B. R., Carswell R. F., Bailey J. A., Smith M. G., Ward M. J., 1989, *ApJ*, 342, 666
- Espey B. R., Carswell R. F., Bailey J. A., Smith M. G., Ward M. J., 1990, *ApJ*, 354, 763
- Event Horizon Telescope Collaboration 2019a, *ApJ Lett.*, 875, L1
- Event Horizon Telescope Collaboration 2019b, *ApJ Lett.*, 875, L2
- Event Horizon Telescope Collaboration 2019c, *ApJ Lett.*, 875, L3
- Event Horizon Telescope Collaboration 2019d, *ApJ Lett.*, 875, L4
- Event Horizon Telescope Collaboration 2019e, *ApJ Lett.*, 875, L5
- Event Horizon Telescope Collaboration 2019f, *ApJ Lett.*, 875, L6
- Fukugita M., Ichikawa T., Gunn J. E., Doi M., Shimasaku K., Schneider D. P., 1996, *AJ*, 111, 1748
- Gaskell C. M., 1982, *ApJ*, 263, 79
- Ge X., Bian W.-H., Jiang X.-L., Liu W.-S., Wang X.-F., 2016, *MNRAS*, 462, 966
- Graham M. J., et al., 2019, arXiv e-prints, p. arXiv:1905.02262
- Gregory S., Ptak R., Stoner R., 1982, *ApJ*, 261, 30
- Grier C. J., et al., 2019, arXiv e-prints, p. arXiv:1904.03199
- Guo H., Sun M., Liu X., Wang T., Kong M., Wang S., Sheng Z., He Z., 2019, *ApJ Lett.*, 883, L44
- Hamann F., Ferland G., 1999, *ARA&A*, 37, 487
- Hamann F., et al., 2017, *MNRAS*, 464, 3431
- Hemler Z. S., et al., 2019, *ApJ*, 872, 21
- Homan D., Macleod C. L., Lawrence A., Ross N. P., Bruce A., 2019, arXiv e-prints, p. arXiv:1910.11364
- Iwasawa K., Taniguchi Y., 1993, *ApJ Lett.*, 413, L15
- Jensen T. W., et al., 2016, *ApJ*, 833, 199
- Jiang Y.-F., Stone J. M., Davis S. W., 2014, *ApJ*, 796, 106
- Jiang Y.-F., Davis S. W., Stone J. M., 2016, *ApJ*, 827, 10
- Jiang Y.-F., Blaes O., Stone J., Davis S. W., 2019a, arXiv e-prints, p. arXiv:1904.01674v1
- Jiang Y.-F., Stone J. M., Davis S. W., 2019b, *ApJ*, 880, 67
- Kozłowski S., 2017, *ApJS*, 228, 9
- Kramida A., Ralchenko Y., Reader J., NIST ASD Team 2018, doi:10.18434/T4W30F,
- LaMassa S. M., et al., 2015, *ApJ*, 800, 144
- Laor A., Bahcall J. N., Jannuzi B. T., Schneider D. P., Green R. F., 1995, *ApJS*, 99, 1
- Lawrence A., 2018, *Nature Astronomy*, 2, 102
- Leighly K. M., 2004, *ApJ*, 611, 125
- MacLeod C. L., et al., 2012, *ApJ*, 753, 106
- MacLeod C. L., et al., 2019, *ApJ*, 874, 8
- Mainzer A., et al., 2011, *ApJ*, 731, 53
- Matthews T. A., Sandage A. R., 1963, *ApJ*, 138, 30
- McIntosh D. H., Rix H. W., Rieke M. J., Foltz C. B., 1999, *ApJ Lett.*, 517, L73
- Meyer R. A., Bosman S. E. I., Ellis R. S., 2019, arXiv e-prints,
- Moore C. E., 1993, *Tables of Spectra of Hydrogen, Carbon, Nitrogen, and Oxygen Atoms and Ions*
- Murray N., Chiang J., Grossman S. A., Voit G. M., 1995, *ApJ*, 451, 498
- Myers A. D., et al., 2015, *ApJS*, 221, 27
- Nazarova L. S., 2003, *Astronomical and Astrophysical Transactions*, 22, 681
- Noda H., Done C., 2018, *MNRAS*, 480, 3898
- Oke J. B., Gunn J. E., 1983, *ApJ*, 266, 713
- Oke J. B., et al., 1995, *PASP*, 107, 375
- Osmer P. S., Porter A. C., Green R. F., 1994, *ApJ*, 436, 678
- Pâris I., Petitjean P., Ross N. P., et al., 2017, *Astron. & Astrophys.*, 597, A79
- Pâris I., et al., 2018, *Astron. & Astrophys.*
- Perrotta S., Hamann F., Zakamska N. L., Alexandroff R. M., Rupke D., Wylezalek D., 2019, *MNRAS*, 488, 4126
- Pogge R. W., Peterson B. M., 1992, *AJ*, 103, 1084
- Proga D., Stone J. M., Kallman T. R., 2000, *ApJ*, 543, 686
- Rakić N., La Mura G., Ilić D., Shapovalova A. I., Kollatschny W., Rafanelli P., Popović L. Č., 2017, *Astron. & Astrophys.*, 603, A49
- Richards G. T., et al., 2002, *AJ*, 123, 2945
- Richards G. T., et al., 2006, *ApJS*, 166, 470
- Richards G. T., et al., 2011, *AJ*, 141, 167
- Ross N. P., et al., 2012, *ApJS*, 199, 3
- Ross N. P., et al., 2015, *MNRAS*, 453, 3932
- Ruan J. J., Anderson S. F., Eracleous M., Green P. J., Haggard D., MacLeod C. L., Runnoe J. C., Sobolewska M. A., 2019, arXiv e-prints, p. arXiv:1903.02553v1
- Schneider D. P., et al., 2007, *AJ*, 134, 102
- Schneider D. P., et al., 2010, *AJ*, 139, 2360
- Seaton M. J., 1959a, *MNRAS*, 119, 81
- Seaton M. J., 1959b, *MNRAS*, 119, 90
- Shakura N. I., Sunyaev R. A., 1973, *Astron. & Astrophys.*, 24, 337
- Shen Y., et al., 2011, *ApJS*, 194, 45
- Shen Y., et al., 2015, *ApJS*, 216, 4
- Smee S. A., et al., 2013, *AJ*, 146, 32
- Stoughton C., et al., 2002, *AJ*, 123, 485
- Sun M., Xue Y., Richards G. T., Trump J. R., Shen Y., Brandt W. N., Schneider D. P., 2018, *ApJ*, 854, 128
- Taylor M. B., 2005, in Shopbell P., Britton M., Ebert R., eds, *Astronomical Society of the Pacific Conference Series Vol. 347, Astronomical Data Analysis Software and Systems XIV*. p. 29
- Taylor M., 2011, *TOPCAT: Tool for Operations on Catalogues And Tables, Astrophysics Source Code Library (ascl:1101.010)*
- The Astropy Collaboration et al., 2018, preprint, (arXiv:1801.02634v2)
- Tytler D., Fan X.-M., 1992, *ApJS*, 79, 1
- Vanden Berk D. E., et al., 2001, *AJ*, 122, 549
- Vestergaard M., Peterson B. M., 2006, *ApJ*, 641, 689
- Weymann R. J., Morris S. L., Foltz C. B., Hewett P. C., 1991, *ApJ*, 373, 23
- Wiese W. L., Fuhr J. R., Deters T. M., 1996, *Journal of Physical and Chemical Reference Data*, 532
- Wilhite B. C., Vanden Berk D. E., Brunner R. J., Brinkmann J. V., 2006, *ApJ*, 641, 78
- Wilkes B. J., 1986, *MNRAS*, 218, 331
- Wills B. J., Brotherton M. S., Fang D., Steidel C. C., Sargent W. L. W., 1993, *ApJ*, 415, 563
- Wright E. L., et al., 2010, *AJ*, 140, 1868
- York D. G., et al., 2000, *AJ*, 120, 1579
- Zakamska N. L., et al., 2016, *MNRAS*, 459, 3144
- Zakamska N. L., et al., 2019, *MNRAS*, 489, 497
- Zheng W., Sulentic J. W., 1990, *ApJ*, 350, 512

This paper has been typeset from a  $\mathrm{T}_{\mathrm{E}}\mathrm{X}/\mathrm{L}^{\mathrm{A}}\mathrm{T}_{\mathrm{E}}\mathrm{X}$  file prepared by the author.