Prescriptions for Correcting Ultraviolet-based Redshifts for Luminous Quasars at High Redshift

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Received 2019 October 31; revised 2020 January 21; accepted 2020 February 17; published 2020 April 8

Abstract

High-redshift quasars typically have their redshift determined from rest-frame ultraviolet (UV) emission lines. However, these lines, and more specifically the prominent C IV λ1549 emission line, are typically blueshifted yielding highly uncertain redshift estimates compared to redshifts determined from rest-frame optical emission lines. We present near-infrared spectroscopy of 18 luminous quasars at 2.15 < z < 3.70 that allows us to obtain reliable systemic redshifts for these sources. Together with near-infrared spectroscopy of an archival sample of 44 quasars with comparable luminosities and redshifts, we provide prescriptions for correcting UV-based redshifts. Our prescriptions reduce velocity offsets with respect to the systemic redshifts by ∼140 km s⁻¹ and reduce the uncertainty on the UV-based redshift by ∼25% with respect to the best method currently used for determining such values. We also find that the redshifts determined from the Sloan Digital Sky Survey Pipeline for our sources suffer from significant uncertainties, which cannot be easily mitigated. We discuss the potential of our prescriptions to improve UV-based redshift corrections given a much larger sample of high-redshift quasars with near-infrared spectra.

Unified Astronomy Thesaurus concepts: Galaxy distances (590); Quasars (1319); Active galactic nuclei (16)

1. Introduction

The best practical indicators for a quasar’s systemic redshift (z.sys) lie in the rest-frame optical band, particularly the prominent [O III] λ5007, Mg II λ2800, and the Balmer emission lines (e.g., Boroson 2005; Shen et al. 2016). However, at high-redshift (z ≃ 0.8), ∼10⁷ quasars typically have their z.sys values determined from rest-frame ultraviolet (UV) spectra since only 0.1% of these quasars have corresponding rest-frame optical information from near-infrared (NIR) spectra (e.g., Schneider et al. 2010; Pâris et al. 2017, 2018). Unfortunately, the UV-based z.sys estimates are highly inaccurate and imprecise given that the UV emission lines are usually blueshifted by up to ≈3000 km s⁻¹ (e.g., Gaskell 1982; Tytler & Fan 1992; Gibson et al. 2009; Shen et al. 2016). Mitigating these biases requires identifying robust corrections to UV-based redshifts.

Reliable redshift estimates are needed for multiple purposes. For example, accurate redshift estimates provide information on the kinematics of the outflowing material in the vicinity of a supermassive black hole, which likely impacts the star formation rate in the quasar’s host galaxy (e.g., Hopkins & Elvis 2010). Additionally, various cosmological studies utilize conversions between redshift differences and distances (e.g., Hogg 1999; Zhao et al. 2019). In this context, a velocity offset of 500 km s⁻¹ corresponds to a comoving distance of ≈5 h⁻¹ Mpc at z = 2.5, which can impact our understanding of, e.g., quasar clustering as velocity offsets can be misinterpreted to be distances in the redshift direction (e.g., Font-Ribera et al. 2013; Prochaska et al. 2013).

The Sloan Digital Sky Survey (SDSS; York et al. 2000) provides observed-frame optical spectra and redshifts for hundreds of thousands of quasars. The redshifts determined for these quasars stem from a cross-correlation by a composite quasar template spectrum provided by Vanden Berk et al. (2001).

However, these estimates become increasingly uncertain in high-redshift quasars because mostly rest-frame UV emission lines are present in the optical band. The first meaningful correction to these UV-based redshifts was achieved by Hewett & Wild (2010, hereafter HW10). They achieved this by introducing a two-part linear relation between the absolute magnitude and redshift of quasars. A more recent improvement to the HW10 method was achieved by Mason et al. (2017, hereafter M17), by comparing [O III]-based z.sys values with the spectral properties of the C IV λ1549 emission line for 45 quasars with z ≃ 2.2.

In this work, we expand on the M17 method by adding high-quality NIR spectra of 18 quasars at 2.15 < z < 3.70. We perform multiple regression analyses and provide improved prescriptions for correcting a variety of UV-based redshifts when the C IV line is available in the spectrum. This paper is organized as follows. In Section 2, we describe our sample selection, observations, and data analysis. In Section 3, we present our spectroscopic measurements, and in Section 4 we discuss our results. Our conclusions are presented in Section 5. Throughout this paper, we compute luminosity distances using $H_0 = 70$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ (e.g., Spergel et al. 2007).

2. Sample Selection, Observations, and Data Analysis

We have selected a sample of 18 quasars for our investigation based upon the following criteria:

1. Availability of a flux-calibrated optical spectrum from the SDSS recorded in the Data Release 10 quasar catalog (Pâris et al. 2014).
2. Brightness in the range $m_i < 18.5$ in order to keep the signal-to-noise ratio (S/N) of the H β region of the respective NIR spectrum, obtained with a 3.8 m telescope, at ≃40.
| Quasar | $z$ | $z_{\text{em}}^a$ | $z_{\text{sys}}^b$ | $H'$ | $K'$ | Observation Date | Net Exposure |
|--------|-----|----------------|-------------------|------|------|-------------------|--------------|
| SDSS J013435.67−093102.9 | 2.225 | 1 | 2.214 | 14.8 | 13.6 | 2016 Aug 25 | 2880 |
| SDSS J014850.64−090712.8 | 3.303 | 1 | 3.329 | 16.7 | 15.5 | 2016 Sep 19 | 4800 |
| SDSS J073607.63+220758.9 | 3.464 | 2 | 3.445 | 16.1 | 14.9 | 2016 Sep 20 | 3840 |
| SDSS J142243.02 | ... | ... | ... | ... | ... | 2016 Sep 22 | 3840 |
| SDSS J153750.10+201035.7 | 3.413 | 3 | 3.413 | 15.7 | 15.4 | 2016 Sep 22 | 3840 |
| SDSS J153830.55+085517.0 | 3.563 | 1 | 3.550 | 15.6 | 14.6 | 2016 Sep 19 | 1920 |
| SDSS J154359.43+535903.1 | 3.279 | 1 | 3.264 | 15.0 | 14.2 | 2016 Sep 21 | 2880 |
| SDSS J154446.33+412035.7 | 3.551 | 1 | 3.567 | 15.6 | 15.5 | 2016 Sep 20 | 3840 |
| SDSS J154938.71+124509.1 | 2.377 | 4 | 2.369 | 14.5 | 13.5 | 2016 Sep 5 | 1920 |
| SDSS J155013.64+200154.5 | 2.196 | 1 | 2.188 | 15.1 | 14.2 | 2016 Sep 19 | 2400 |
| SDSS J160222.72+084538.4 | 2.276 | 1 | 2.275 | 15.0 | 14.0 | 2016 Sep 6 | 2880 |
| SDSS J163300.13+362904.8 | 3.575 | 1 | 3.570 | 15.5 | 15.1 | 2016 Sep 22 | 2640 |
| SDSS J165137.52+400218.9 | 2.342 | 1 | 2.338 | 15.0 | 13.7 | 2016 Sep 6 | 2880 |
| SDSS J172327.85+385951.8 | 3.390 | 2 | 3.367 | 16.0 | 15.3 | 2016 Sep 19 | 3840 |
| SDSS J210524.47+000407.3 | 2.307 | 1 | 2.344 | 14.7 | 13.8 | 2016 Aug 26 | 1920 |
| SDSS J212346.46−000502.9 | 2.268 | 1 | 2.270 | 14.6 | 13.9 | 2016 Sep 5 | 1920 |
| SDSS J221506.02+151208.5 | 3.285 | 2 | 3.284 | 16.4 | 15.2 | 2016 Aug 26 | 3840 |
| SDSS J235808.54+012507.2 | 3.401 | 2 | 3.389 | 14.7 | 13.8 | 2016 Aug 26 | 2880 |

Notes.

- (1) HW10; (2) Chen et al. (2014); (3) Richards et al. (2009); (4) Hutchings et al. (2006).
- Unless otherwise noted, the systemic redshift was obtained from the peak of the [O III] λ5007 emission line, where available, as explained in the text. Uncertainties on these values, discussed in Section 2.1, average ~150 km s⁻¹.
- Vega-based magnitudes were obtained from 2MASS.
- Indicates a BAL quasar.
- Systemic redshift was determined from $\lambda_{\text{peak}}$ of the H/β emission line.
- Systemic redshift was determined from $\lambda_{\text{peak}}$ of the Mg II emission line from the SDSS spectrum of the source.

3. Redshift within one of the following intervals, 2.15 < $z$ < 2.65 and 3.20 < $z$ < 3.70, in which, at a minimum, the H/β and [O III] lines can be modeled accurately within one of the NIR transmission windows in the H or K bands.

Spectroscopic observations of this sample were performed at the United Kingdom Infrared Telescope (UKIRT) on Maunakea, Hawaii. The observation log and quasar basic properties appear in Table 1.

We utilized the UKIRT Imager-Spectrometer with a slit width of 0.24 to maximize the resolution at the expense of potentially higher slit losses. During these observations, the telescope was nodded in an ABBA pattern in order to obtain primary background subtraction. The broad band B2 filter was used in order to obtain a wavelength range of approximately 1.395–2.506 μm, spanning the H and K bands as necessary. The dispersion for these observations was 10.9 Å pixel⁻¹ with a spectral resolution of $R \sim 448$. Standard stars of spectral type G and F were observed on each night alongside the quasar in order to remove the telluric features that are present in the quasars’ spectra.

The two-dimensional spectra of the quasars and the standard stars were obtained using standard IRAF routines. Each of the objects was initially pair subtracted in order to remove most of the background noise. Then, both the positive and negative residual peaks were analyzed and averaged together. During the analysis, wavelength calibration was achieved using argon arc lamps. The hydrogen features in each standard star were removed prior to removing the telluric features from the quasars’ spectra.

Removal of the telluric features and the instrumental response from the quasar spectra was done by dividing these spectra by their respective standard star spectra. Then, any remaining cosmic ray signatures on the quasar spectra were carefully removed. Finally, flux-calibrated, quasar spectra were obtained by multiplying these data by blackbody curves with temperatures corresponding to the spectral types of the telluric standards and by a constant factor that was determined by comparing the $H$, for 2.15 < $z$ < 2.65, or $K$, for 3.20 < $z$ < 3.70, band magnitudes from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) to the integrated flux across the respective band using the flux conversion factors from Table A.2 of Bessell et al. (1998). We do not rely on the telluric standards for the purpose of flux calibration given the relatively narrow slit and the differences in atmospheric conditions between the observations of the quasars and their respective standard stars. For each source, we utilized their SDSS spectrum to verify that the combined SDSS and UKIRT spectra are consistent with a typical quasar optical-UV continuum of the form $f_\nu \propto \nu^{α}$ (Vanden Berk et al. 2001). By comparing the flux densities at the rest-frame wavelength of 5100 Å to the flux densities at the rest-frame wavelength in the region of 2000–3500 Å, dependent on the redshift, in the SDSS spectrum of each source, we verified that the differences

4 This redshift interval ensures spectral coverage also of the Hα emission line in the K band.
5 The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatory, which is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.
between the two values were within 30%, indicating, at most, only modest flux variations. Such variations, over a temporal baseline of $\sim$6 yr in the rest-frame, are not atypical for such luminous quasars, even if most of these variations are intrinsic as opposed to measurement errors (see, e.g., Kaspi et al. 2007).

### 2.1. Fitting of the UKIRT Spectra

In order to fit the H\textsb{\small \beta} and H\alpha spectral regions, we used a model consisting of a local, linear continuum, which is a good approximation to a power-law continuum given the relatively narrow spectral band, a broadened Boroson & Green (1992) Fe II emission template, and a multi-Gaussian fit to the emission lines. The Fe II template was broadened by a FWHM value that was free to vary between 2000 and 10000 km s$^{-1}$ and, along with the linear continuum, was removed to more accurately fit the H\textsb{\small \beta} and [O III] emission lines. The chosen FWHM to broaden the Fe II template was determined with a least squares analysis.

We fit the H\textsb{\small \beta} line using two independent Gaussians, constrained by the width and height of the emission line, simultaneously with one Gaussian for each of the [O III] emission lines. The Gaussians assigned to the [O III] emission lines have identical widths and their intensity ratio was fixed to $I$ ([O III] $\lambda$5007)/$I$([O III] $\lambda$4959) = 3. The wavelengths of the two [O III] components were fixed to the ratio 5007/4959. For the available H\alpha features, two Gaussians were fit after a linear continuum was fit and subtracted around the emission line. We do not detect any [N II] emission lines while fitting this region, mainly given our low spectral resolution. The Gaussians were constrained so that the line peak would lie within 1500 km s$^{-1}$ from the wavelength that corresponded to the maximum of the emission line region, the widths could range from 0 to 15,000 km s$^{-1}$, and the flux density was restricted to lie within 0 and twice the maximum value of the emission line.

To estimate the uncertainties on the FWHM and rest-frame equivalent width (EW) of the emission lines, we performed the fitting by adjusting the placement of the continuum according to the noise level in the continuum (see, e.g., Shenner & Lieber 2015). Namely, by adjusting the local linear continuum between extremes of the noise around each emission line, we were able to derive an estimate for uncertainties on the FWHM and EW values. For all but two of the sources, the uncertainties on the values of FWHM and EW in the H\textsb{\small \beta} region are on the order of $\sim$5$\%$–15$. For SDSS J014850.64$-$090712.8 and SDSS J163300.13$+$362904.8, these uncertainties are on the order of $\sim$40$. Similarly, the uncertainties on the FWHM and EW values for the H\alpha emission line are up to $\sim$5$\%$.

The uncertainties on the wavelengths of the peaks of all the emission lines are up to $\sim$300 km s$^{-1}$. The majority of this uncertainty arises from the resolution of our spectrograph, however, our choice of a narrow slit was used to combat this. The uncertainty introduced from the pixel-wavelength calibration is minimal, averaging $\sim$5 km s$^{-1}$. The narrow [O III] $\lambda$5007 emission line provided our most accurate redshift estimates, having uncertainties on wavelength measurements averaging $\sim$150 km s$^{-1}$. The wavelength uncertainties were determined by evaluating our S/N and repeated measurements of each of the emission lines.

Basic spectral properties resulting from those fits are reported in Table 2. Columns (2), (3), and (4) provide the FWHM, EW, and the observed-frame wavelength of the peak (${\lambda}$peak) of the H\textsb{\small \beta} line, respectively. Columns (5)–(7) and (8)–(10) provide similar information for the [O III] $\lambda$5007 and H\alpha emission lines, respectively. The fits for the H\textsb{\small \beta} and [O III] emission lines appear in Figure 1, and the fits for the H\alpha emission line appear in Figure 2.

| Quasar (1)         | FWHM$_{\textsb{\beta}}$ (km s$^{-1}$) (2) | EW$_{\textsb{\beta}}$ (\AA) (3) | $\lambda_{\text{peak}}$ H\textsb{\small \beta} (\AA) (4) | FWHM$_{\textsb{\text{[O III]}}}$ (km s$^{-1}$) (5) | EW$_{\textsb{\text{[O III]}}}$ (\AA) (6) | $\lambda_{\text{peak}}$ [O III] (\AA) (7) | FWHM$_{\textsb{\text{H$\alpha$}}}$ (km s$^{-1}$) (8) | EW$_{\textsb{\text{H$\alpha$}}}$ (\AA) (9) | $\lambda_{\text{peak}}$ H$\alpha$ (\AA) (10) |
|-------------------|------------------------------------------|---------------------------------|-----------------------------------------------|------------------------------------------|---------------------------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|
| SDSS J013435.67$-$093102.9 | 4438                           | 99.7                           | 15656                                         | 1625                           | 14.6                           | 16091                          | 2882                           | 444                             | 21125                           |
| SDSS J014850.64$-$090712.8 | 4716                           | 33.7                           | 21035                                         | 1513                           | 4.3                            | 21680                          | ...                            | ...                             | ...                             |
| SDSS J073607.63$+$220758.9 | 6876                           | 94.3                           | 21625                                         | 1640                           | 31.6                           | 22256                          | ...                            | ...                             | ...                             |
| SDSS J142243.02$+$441721.2 | 4563                           | 39.9                           | 22607                                         | ...                            | ...                            | ...                            | ...                            | ...                             | ...                             |
| SDSS J153750.10$+$201035.7 | 5107                           | 69.5                           | 21516                                         | 1613                           | 14.6                           | 22094                          | ...                            | ...                             | ...                             |
| SDSS J153830.55$+$055170.0 | 5512                           | 70.8                           | 22161                                         | 3192                           | 26.1                           | 22782                          | ...                            | ...                             | ...                             |
| SDSS J154359.43$+$535903.1 | 8301                           | 54.3                           | 16495                                         | 1835                           | 28.6                           | 16843                          | 7495                           | 543                             | 22171                           |
| SDSS J154446.33$+$42035.7 | 7235                           | 132.4                          | 22202                                         | ...                            | ...                            | ...                            | ...                            | ...                             | ...                             |
| SDSS J154938.71$+$124509.1 | 5495                           | 42.4                           | 16408                                         | 1544                           | 15.4                           | 16866                          | 5550                           | 374                             | 22139                           |
| SDSS J155013.64$+$200154.5 | 6539                           | 61.9                           | 15544                                         | 1325                           | 7.5                            | 15960                          | 5178                           | 391                             | 20962                           |
| SDSS J160222.72$+$084353.8 | 6676                           | 122.3                          | 15951                                         | 2387                           | 19.5                           | 16398                          | 5629                           | 586                             | 21517                           |
| SDSS J163300.13$+$362904.8 | 4876                           | 57.8                           | 22297                                         | 3768                           | 24.6                           | 22884                          | ...                            | ...                             | ...                             |
| SDSS J165137.52$+$400218.9 | 4405                           | 65.6                           | 16234                                         | 957.8                          | 18.5                           | 16713                          | 4380                           | 377                             | 21920                           |
| SDSS J172237.85$+$385951.8 | 5938                           | 67.9                           | 21300                                         | 3028                           | 13.9                           | 21866                          | ...                            | ...                             | ...                             |
| SDSS J201024.47$+$000407.3 | 5331                           | 25.3                           | 16256                                         | ...                            | ...                            | 4530                           | 281                            | 21975                           |
| SDSS J223239.46$+$050502.9 | 4500                           | 48.1                           | 15929                                         | ...                            | ...                            | 4084                           | 319                            | 21540                           |
| SDSS J221506.02$+$151208.5 | 4059                           | 100.0                          | 20829                                         | 956.9                          | 61.7                           | 21450                          | ...                            | ...                             | ...                             |
| SDSS J235808.54$+$012507.2 | 3702                           | 63.3                           | 21397                                         | 2652                           | 11.6                           | 21974                          | ...                            | ...                             | ...                             |

Notes.

a Corresponding to the [O III] $\lambda$5007 component.
b SDSS J073607.63$+$220758.9 was observed on two different nights, as denoted in Table 1, and, therefore, we present the values stemming from the stacked spectrum.
Figure 1. NIR spectra of $2.15 < z < 3.70$ quasars. The spectrum in each panel is given by a thin solid line. The fit to each individual feature, Fe II, H$\beta$, and [O III] where applicable, and the linear continuum are indicated by dashed lines. The overall fit to each spectrum is given by the bold solid line.
2.2. Spectral Fitting of the C IV Emission Lines

In order to provide corrections to the UV-based redshifts of our sources, we fit the C IV emission lines present in their SDSS spectra. These fits appear in Figure 3. As suggested in M17, the parameters needed for the correction of the UV-based redshifts are the FWHM and EW of the C IV line, as well as the monochromatic luminosity of the continuum at a rest-frame wavelength of 1350 Å.

The C IV emission line was fit with a local, linear continuum and two independent Gaussians under the same constraints as we report for the Hβ and Hα emission lines. The spectral properties resulting from this fitting procedure are reported in Table 3. The uncertainties in each of these measurements were determined by the same method used when evaluating the rest-frame optical emission line uncertainties. Along with this fit, the continuum luminosity, $L_{1350}$, has also been derived by measuring the continuum flux density at rest-frame λ1350 Å and employing our chosen cosmology. These values also appear in Table 3.

![Figure 2](image_url)  
Figure 2. NIR spectra of 2.15 < z < 2.65 quasars. The spectrum in each panel is given by a thin solid line. The fit to the Hα line and linear continuum are indicated by dashed lines. The overall fit to each spectrum is given by the bold solid line.

3. Results

Combined with the sources in M17, we have a total of 63 objects in our sample, of which, six of our UKIRT objects were excluded from further analysis due to broad absorption line (BAL) identification: these are noted in Table 1. We then remove an additional BAL quasar, SDSS J014049.18−083942.5, from the sample in M17. Furthermore, we have excluded SDSS J013435.67−093102.9 from our sample given that it is a lensed quasar and its rest-frame UV spectrum is severely attenuated by the foreground lensing galaxy (see, e.g., Ofek et al. 2006).

Measurements of the C IV emission line for 52 out of the 55 sources in our combined sample are available in Shen et al. (2011). The C IV FWHM and EW measurements we obtained for 40 of these sources agree to within ~20% with those from

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6 Five of these sources are based on BAL quasar identification from Shen et al. (2011). SDSS J073607.63+220758.9 was identified as a BAL quasar following our visual inspection of its SDSS spectrum.
Shen et al. (2011) similarly, measurements of 10 of these sources agree to within ~65%. Generally, these discrepancies are inversely proportional to the S/N of the SDSS spectra and are larger in the presence of narrow absorption lines. The spectra for SDSS J025438.36+002132.7 and SDSS J153725.35014650.3 had extremely poor S/N, resulting in discrepancies of 108% and 53% for FWHM, and 57% and 210% for EW, respectively, between our measured values and the ones reported in Shen et al. (2011). The differences between the $\Delta \nu_{\text{C IV}}$ values we use and those used by M17 are rather small, and using the latter values do not change our results significantly.

A multiple regression analysis has been performed on the velocity offsets and the C IV emission line properties such that:

$$\Delta v (\text{km s}^{-1}) = \alpha \log_{10}(\text{FWHM}_{\text{C IV}}) + \beta \log_{10}(\text{EW}_{\text{C IV}}) + \gamma \log_{10}(L_{1350}),$$

where $\Delta v$ is the velocity offset and $\alpha$, $\beta$, and $\gamma$ are the coefficients associated with our regression analysis. The velocity offset created by each redshift derivation method was determined by the following equation

$$\Delta v = c \left( \frac{\nu_{\text{meas}} - \nu_{\text{sys}}}{1 + \nu_{\text{sys}}} \right),$$

where $\nu_{\text{meas}}$ is the redshift derived using various methods and reported in the studies indicated below. In order to derive the most reliable redshift correction, four regressions were performed using the following parameters from Equation (1):

1. $\log_{10}(\text{FWHM}_{\text{C IV}})$, $\log_{10}(\text{EW}_{\text{C IV}})$
2. $\log_{10}(\text{FWHM}_{\text{C IV}})$, $\log_{10}(L_{1350})$
3. $\log_{10}(\text{EW}_{\text{C IV}})$, $\log_{10}(L_{1350})$
4. all three parameters.

In total, this regression analysis was performed on redshifts determined from: (1) the measured line peak of the C IV emission line, (2) HW10, and (3) the SDSS pipeline. The coefficients, errors, and confidence statistics from Equation (1), determined in each of these cases, are reported in Table 6. For the confidence
statistics, we report the $t$-value (e.g., Sheskin 2007) to determine the importance of each individual parameter.

The residuals of the velocity offsets after each correction have been determined and analyzed, and basic statistics resulting from these residuals are listed in Table 7. The residuals before and after correction are presented in Figure 4. The residual distributions show the significant reduction in the velocity offsets before and after each correction. The corrected velocity offsets for C IV- and HW10-based redshifts are closer to zero than the corrected velocity offsets for the SDSS pipeline-based redshift, representative of the larger $\sigma$ value associated with SDSS pipeline redshift estimates. From evaluating the best-fitting coefficients and statistics reported for each correction, we determined the correction that we consider to provide the most reliable results. This correction has been emphasized in bold face in the text.

Figure 3. C IV fits of all 55 quasars used in the regression analysis. The spectrum and fit to the C IV emission line in each panel are given by a thin solid line. The linear continuum is indicated by a dashed line. The overall fit to each spectrum is given by the bold solid line.

Rest-Frame Wavelength [Å]
3.1. SDSS J142243.02 +441721.2 and SDSS J115954.33 +201921.1

SDSS J142243.02 +441721.2 from our UKIRT sample has significantly larger velocity offsets compared to the rest of the combined sample. The velocity offsets determined from C IV, HW10, and the SDSS pipeline are $-5097$ km s$^{-1}$, $-7740$ km s$^{-1}$, and $-16384$ km s$^{-1}$, respectively. The latter velocity offset stems from a misidentification of spectral features in the SDSS spectrum of the source as manifested by the SDSS pipeline products. The SDSS pipeline redshift for this source is $z = 3.396$ while the SDSS visual inspection value is $z = 3.615$. The disparity between these estimates confirms the misidentification of the emission lines by the SDSS pipeline. Because the velocity offsets for this source had a significant impact on the regression analysis and may be misleading, we have provided the results of the regression analysis with and without this object in Table 7.

The velocity offset of SDSS J115954.33 +201921.1 from the M17 sample, with respect to the redshift determined by the SDSS Pipeline is $-10,642$ km s$^{-1}$, which is significantly larger than the respective values of the combined sample, excluding SDSS J142243.02 +441721.2. SDSS J115954.33 +201921.1 was also removed from the SDSS pipeline regression as discussed further in Section 4. Here too, the disparity between the SDSS pipeline redshift value ($z = 3.330$) and the respective visual inspection value ($z = 3.425$) indicates a misidentification of spectral features by the SDSS pipeline.

4. Discussion

The results of our multiple regression analysis indicate that the most reliable redshift is obtained by correcting the HW10-based redshift employing the FWHM and EW of the C IV line, the monochromatic luminosity at a rest frame of 1350 Å, and the respective coefficients listed under the fourth correction to the HW10 method from Table 6. Using this correction, and removing SDSS J142243.02 +441721.2 from the analysis (see Section 3.1), we were able to reduce the uncertainty on the redshift determination from 731 to 543 km s$^{-1}$, yielding an improvement of $\sim 25\%$ with respect to the HW10-based redshifts; similarly, the mean systematic offset of the redshift determination is reduced from $-137$ to $+1$ km s$^{-1}$ (see Table 7). For comparison, utilizing only the M17 sample of 44 sources, the uncertainty on the HW10-based redshifts is reduced by $\sim 20\%$. The addition of the five sources from our UKIRT sample that have HW10-based redshifts, comprising a $\sim 10\%$ increase in the number of sources with respect to the M17 sample, therefore helped to further reduce the uncertainty on the HW10-based redshifts from $\sim 20\%$ to $\sim 25\%$. We anticipate that by utilizing a more representative of several hundred high-redshift quasars, we will be able to further improve these uncertainties significantly and the results will become increasingly less biased to small number statistics (e.g., B. Matthews et al. 2020, in preparation).

We note that, when we include the source with the highly discrepant $\Delta v_{\text{CIV}}$ value, SDSS J142243.02 +441721.2, in the regression analysis, the best redshift estimates are obtained from the corrected C IV-based redshifts (see Table 7). In this case, the mean systematic redshift offsets reduces from $-1023$ to $-8$ km s$^{-1}$ and the uncertainty on the redshifts’ determination decreases from 1135 to 746 km s$^{-1}$ (a $\sim 34\%$ improvement).

As it is apparent, even with this sample of 55 quasars, the methods to determine redshift using rest-frame UV features provide uncertainties as large as $\approx 500$–700 km s$^{-1}$. As reported in the first row of each section of Table 7, the uncorrected redshift determinations are significantly inaccurate and imprecise. C IV-based redshifts have a mean systematic offset of $\sim 1000$ km s$^{-1}$ (a blueshift) and a similar value for $\sigma$ (the standard deviation). The HW10 method further improves these C IV-based redshifts

| Quasar (1) | $z_{\text{CIV}}^a$ (2) | $\Delta v$ (km s$^{-1}$) (3) | $z_{\text{peak}}^b$ (4) | $\Delta v$ (km s$^{-1}$) (5) | $z_{\text{HW10}}^c$ (6) | $\Delta v$ (km s$^{-1}$) (7) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SDSS J013435.67 +093102.9 | 2.214 | ... | ... | 2.225 | 1029 |
| SDSS J014850.64 +090712.8 | 3.274 | -3786 | 3.290 | -2691 | 3.303 | -1796 |
| SDSS J073607.63 +220758.9 | 3.436 | -607 | 3.464 | 1285 | ... | ... |
| SDSS J142243.02 +441721.2 | 3.572 | -5097 | 3.397 | -16384 | 3.531 | -7740 |
| SDSS J153750.10 +201035.7 | 3.405 | -544 | ... | ... | ... | ... |
| SDSS J153830.55 +085517.0 | 3.535 | -989 | 3.537 | -856 | 3.563 | 858 |
| SDSS J154359.43 +535903.1 | 2.365 | 89 | 2.370 | 536 | 2.379 | 1341 |
| SDSS J154446.33 +412035.7 | 3.520 | -3087 | 3.569 | 131 | 3.551 | -1049 |
| SDSS J154938.71 +124509.1 | 2.378 | 801 | 2.355 | -1244 | ... | ... |
| SDSS J155013.64 +200154.5 | 2.190 | 188 | 2.194 | 565 | 2.196 | 754 |
| SDSS J160222.72 +084538.4 | 2.270 | -458 | ... | ... | 2.276 | 92 |
| SDSS J163300.13 +362904.8 | 3.562 | -525 | 3.538 | -2093 | 3.575 | 328 |
| SDSS J165137.52 +400218.9 | 2.339 | 90 | 2.341 | 270 | 2.342 | 360 |
| SDSS J172237.85 +385951.8 | 3.350 | -1168 | 3.390 | 1584 | ... | ... |
| SDSS J201052.47 +000407.3 | 2.293 | -4575 | ... | ... | 2.307 | -3301 |
| SDSS J212329.46 +050529.2 | 2.255 | -1376 | 2.233 | -3395 | 2.269 | -92 |
| SDSS J221756.02 +151208.5 | 3.285 | 70 | 3.284 | 0 | ... | ... |
| SDSS J233808.54 +012507.2 | 3.366 | -1572 | 3.400 | 753 | ... | ... |

Notes.

- $a$ Redshifts determined from the $\lambda_{\text{peak}}$ reported in Column (8) of Table 3.
- $b$ Acquired from P18.
- $c$ Acquired from HW10.
by reducing the systematic offsets by $\sim 900 \, \text{km} \, \text{s}^{-1}$ and $\sigma$ by $\sim 300 \, \text{km} \, \text{s}^{-1}$. Our prescription further reduces the systematic offset by an additional $\sim 100 \, \text{km} \, \text{s}^{-1}$ and reduces $\sigma$ by an additional $\sim 200–300 \, \text{km} \, \text{s}^{-1}$. Using the SDSS pipeline redshift estimate, determined from a principal component analysis on multiple features of a spectrum simultaneously (e.g., Bolton et al. 2012), the mean systematic velocity offset for our combined sample is the largest and extends beyond 1000 $\, \text{km} \, \text{s}^{-1}$ with a standard deviation of 1324 $\, \text{km} \, \text{s}^{-1}$. Overall, albeit utilizing a smaller combined sample with respect to the samples we use for C IV- and HW10-based redshifts, the redshifts determined from the SDSS pipeline provide the least reliable results (see Table 7). Our best correction applied to these redshifts improves the mean systematic velocity offset by $\sim 1000 \, \text{km} \, \text{s}^{-1}$, similar to the improvement achieved for C IV-based redshifts, but yields only a modest improvement in $\sigma$ which remains large.

In order to test the validity of our method, we have performed the same regression described in the text on the M17 sources ($\sim 80\%$ of our combined sample) and applied it to the remaining sources acquired from UKIRT. The C IV velocity offsets were used in the regression since this sample was the largest of the three UV-based redshift estimates. Prior to correction, the sample of 10 UKIRT sources had a mean, median, and $\sigma$ of $-641 \, \text{km} \, \text{s}^{-1}$, $-690 \, \text{km} \, \text{s}^{-1}$, and $952 \, \text{km} \, \text{s}^{-1}$.
the C IV redshift determination methods involve a correction based on the uncertainty on the redshift determination. The most robust and, when included in the regression analysis, it nearly tripled the mean systematic offset for this redshift estimate.

The mean systematic offset for this redshift estimate is 1, and +1, respectively. After running the regression on the M17 sample and applying the new correction to the UKIRT sources, the mean, median, and σ improved to 474 km s$^{-1}$, 376 km s$^{-1}$, and 772 km s$^{-1}$ respectively, demonstrating the validity of our method.

The SDSS pipeline redshift estimate, as noted in P18, is subject to highly uncertain redshift determinations due to lower S/N or unusual objects. As seen in our relatively small sample, large redshift discrepancies are apparent particularly in two of the 39 objects that we have with available SDSS pipeline-based redshifts. In each case, the velocity offsets are $>10^4$ km s$^{-1}$ and, when included in the regression analysis, it nearly tripled the uncertainty on the redshift determination. The most robust redshift determination methods involve a correction based on the C IV spectral properties and UV continuum luminosity to either C IV- or HW10-based redshifts. P18 also provides a redshift based off of visual inspection, $z_{VI}$. We find that this estimate, where available, provides a much more reliable redshift estimate than the one provided by the SDSS pipeline. The mean systematic offset for this redshift estimate is $-290$ km s$^{-1}$ with a standard deviation of 762 km s$^{-1}$.

Regarding the two sources with extremely large velocity offsets, SDSS J142243.02+441721.2 and SDSS J115954.33+201921.1, we note that our best corrections for their UV-based redshifts provide only modest improvements to the redshift determinations, and that their negative velocity offsets (i.e., blueshifts) take on positive velocity offsets (i.e., redshifts), after the correction is applied. The velocity offsets for SDSS J142243.02+441721.2 improve from $-5097$ km s$^{-1}$ to 2300 km s$^{-1}$, $-7740$ km s$^{-1}$ to 6016 km s$^{-1}$, and $-16,384$ km s$^{-1}$ to 11,848 km s$^{-1}$ for C IV-, HW10-, and SDSS pipeline-based redshift estimates, respectively. Similarly, the velocity offsets for SDSS J115954.33+201921.1 changed from $-1264$ km s$^{-1}$ to $-58$ km s$^{-1}$, 407 km s$^{-1}$ to $-656$ km s$^{-1}$, and $-10,642$ km s$^{-1}$ to 8720 km s$^{-1}$, respectively. While most of the corrected velocity offsets are closer to zero, they do not improve appreciably and still affect the statistics significantly.

The origin for the abnormally large velocity offset of the SDSS pipeline redshift of SDSS J115954.33+201921.1 most likely stems from the misidentification of the emission lines in the SDSS spectra by the SDSS pipeline, as discussed in Section 3.1. As for SDSS J142243.02+441721.2, the origin of the large velocity offset of the C IV-based redshift is intrinsic to the quasar and this should not be confused with the coincidental abnormally large velocity offset stemming from the failure of the SDSS pipeline to correctly identify the UV

**Table 6**

| Correction Coefficients | Equation | Coefficients | Value | Error | r-value |
|-------------------------|----------|--------------|-------|-------|---------|
| C IV                    | $\alpha \log_{10}(FWHM_{CIV}) + \beta \log_{10}(EW_{CIV})$ | $\alpha$ | $-1301$ | $195$ | $-6.68$ |
|                         |          | $\beta$      | $2501$ | $472$ | $5.29$  |
|                         | $\alpha \log_{10}(FWHM_{CIV}) + \gamma \log_{10}(L_{3350})$ | $\alpha$ | $-3966$ | $600$ | $-6.61$ |
|                         |          | $\gamma$     | $293$  | $48$  | $6.14$  |
|                         | $\beta \log_{10}(EW_{CIV}) + \gamma \log_{10}(L_{4350})$ | $\beta$ | $2058$ | $601$ | $3.43$  |
|                         |          | $\gamma$     | $-88$  | $20$  | $-4.50$ |
|                         | $\alpha \log_{10}(FWHM_{CIV}) + \beta \log_{10}(EW_{CIV}) + \gamma \log_{10}(L_{4350})$ | $\alpha$ | $-3670$ | $549$ | $-6.68$ |
|                         |          | $\beta$      | $1604$ | $450$ | $3.57$  |
|                         |          | $\gamma$     | $217$  | $48$  | $4.53$  |
| HW10                    | $\alpha \log_{10}(FWHM_{CIV}) + \beta \log_{10}(EW_{CIV})$ | $\alpha$ | $-1069$ | $254$ | $-4.22$ |
|                         |          | $\beta$      | $2517$ | $612$ | $4.11$  |
|                         | $\alpha \log_{10}(FWHM_{CIV}) + \gamma \log_{10}(L_{3350})$ | $\alpha$ | $-3191$ | $869$ | $-3.67$ |
|                         |          | $\gamma$     | $251$  | $69$  | $3.63$  |
|                         | $\beta \log_{10}(EW_{CIV}) + \gamma \log_{10}(L_{4350})$ | $\beta$ | $2219$ | $715$ | $3.10$  |
|                         |          | $\gamma$     | $-75$  | $24$  | $-3.18$ |
|                         | $\alpha \log_{10}(FWHM_{CIV}) + \beta \log_{10}(EW_{CIV}) + \gamma \log_{10}(L_{4350})$ | $\alpha$ | $-2834$ | $819$ | $-3.46$ |
|                         |          | $\beta$      | $1877$ | $652$ | $2.88$  |
|                         |          | $\gamma$     | $161$  | $71$  | $2.26$  |
| SDSS pipe               | $\alpha \log_{10}(FWHM_{CIV}) + \beta \log_{10}(EW_{CIV})$ | $\alpha$ | $-2380$ | $785$ | $-3.03$ |
|                         |          | $\beta$      | $5087$ | $1891$ | $2.69$  |
|                         | $\alpha \log_{10}(FWHM_{CIV}) + \gamma \log_{10}(L_{3350})$ | $\alpha$ | $-8024$ | $2732$ | $-2.94$ |
|                         |          | $\gamma$     | $613$  | $216$ | $2.83$  |
|                         | $\beta \log_{10}(EW_{CIV}) + \gamma \log_{10}(L_{4350})$ | $\beta$ | $4732$ | $2240$ | $2.11$  |
|                         |          | $\gamma$     | $-176$ | $74$  | $-2.39$ |
spectral features (see Section 3.1). Our measured velocity offset of the C IV line ($-5097$ km s$^{-1}$) is consistent, within the errors, with the value reported in Table 6 of Vietri et al. (2018) for the source ($-4670$ km s$^{-1}$). Such sources may point to additional spectral parameters that should be taken into account in future prescriptions for UV-based redshift corrections. While such objects may be rare ($\lesssim5\%$ in our combined sample), their potential effects on future redshift estimates should be scrutinized to ensure that redshift corrections for the general quasar population are not skewed. The difficulty in correcting the UV-based redshift of SDSS J142243.02+441721.2 is also manifested by the HW10-based redshift which is unable to improve the estimate but rather provides a larger velocity offset ($-7740$ km s$^{-1}$) with respect to the C IV-based value ($-5097$ km s$^{-1}$).

With our combined sample of 55 high-redshift quasars, we verify large velocity offsets between UV-based redshift estimates and $z_{\text{sys}}$. Our calibrations to the UV-based redshift estimates can be used to establish more reliable estimates for $z_{\text{sys}}$ when working with high-redshift quasars in the optical band. This effort will lead to more reliable constraints on a range of measurements that require precise distances for quasars.
5. Conclusions

In the coming decade, \( \approx 10^6 \) high-redshift (\( z \gtrsim 0.8 \)) quasars will have their redshifts determined through large spectroscopic surveys conducted in the visible band (i.e., rest-frame UV band), e.g., the Dark Energy Spectroscopic Instrument survey (e.g., Levi et al. 2013; DESI Collaboration et al. 2016). Many of these quasars, at \( 1.5 \lesssim z \lesssim 6.0 \), will have the prominent C IV emission line covered in their spectra. The spectral properties of this line can provide a valuable means for correcting UV-based redshifts as we have shown in this work.

Using a sample of 55 quasars, our prescription for correcting UV-based redshifts yields a mean systematic velocity offset which is consistent with zero and further improves the uncertainty on the redshift determination by \( \sim 25\% - 35\% \) with respect to the method of HW10. We also find that UV-based redshifts derived from the SDSS pipeline provide the least reliable results, and the associated uncertainties with respect to \( z_{\text{sys}} \) cannot be reduced appreciably. With a larger, uniform sample of high-redshift quasars with NIR spectroscopy (e.g., B. Matthews et al. 2020, in preparation), we plan to improve the reliability of our redshift estimates further and search for additional spectral properties that may further improve these estimates.

We show that the uncertainties on UV-based redshifts for the majority of high-redshift quasars can be reduced considerably by obtaining NIR spectroscopy of a larger sample of sources and using the [O III]-based systemic redshift to inform a C IV-based regression analysis. The reduction in redshift uncertainties is particularly useful for a range of applications involving accurate cosmological distances.

We gratefully acknowledge the financial support by National Science Foundation grants AST-1815281 (C.D., O.S.), and AST-1815645 (M.S.B., A.D.M.). A.D.M. was supported by the Director, Office of Science, Office of High Energy Physics of the U.S. Department of Energy under Contract No. DE-AC02-05CH1123 and Award No. DE-SC0019022. We thank the anonymous referee for the constructive report that has improved this manuscript. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, as well as NASA’s Astrophysics Data System Bibliographic Services.

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