



***HST*/COS Observations of Quasar Outflows in the 500–1050 Å Rest Frame. VI. Wide, Energetic Outflows in SDSS J0755+2306**

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Abstract

We present the analysis of two outflows (S1 at -5500 km s^{-1} and S2 at -9700 km s^{-1}) seen in recent *Hubble Space Telescope*/Cosmic Origins Spectrograph observations of quasar SDSS J0755+2306 ($z = 0.854$). The outflows are detected as absorption troughs from both high-ionization species, including N III, O III, and S IV, and very high-ionization species, including Ar VIII, Ne VIII, and Na IX. The derived photoionization solutions show that each outflow requires a two ionization-phase solution. For S1, troughs from S IV* and S IV allow us to derive an electron number density, $n_e = 1.8 \times 10^4 \text{ cm}^{-3}$, and its distance from the central source of $R = 270 \text{ pc}$. For S2, troughs from O III* and O III yield $n_e = 1.2 \times 10^3 \text{ cm}^{-3}$ and $R = 1600 \text{ pc}$. The kinetic luminosity of S2 is $>12\%$ of the Eddington luminosity for the quasar and, therefore, can provide strong AGN feedback effects. Comparison of absorption troughs from O III and O VI in both outflow systems supports the idea that for a given element, higher-ionization ions have larger covering fractions than lower-ionization ones.

Unified Astronomy Thesaurus concepts: Quasar absorption line spectroscopy (1317); Quasars (1319); Active galactic nuclei (16); Broad-absorption line quasar (183)

1. Introduction

Broad absorption line (BAL) outflows are detected as blueshifted absorption troughs in 15%–25% of quasar spectra (Tolea et al. 2002; Hewett & Foltz 2003; Reichard et al. 2003; Trump et al. 2006; Ganguly & Brotherton 2008; Gibson et al. 2009, and references therein). These outflows provide an important mechanism to carry energy, mass, and momentum out of the quasar’s central regions (e.g., Scannapieco & Oh 2004; Ciotti et al. 2009; Ostriker et al. 2010; Hopkins & Elvis 2010; Choi et al. 2014; Hopkins et al. 2016). Theoretical studies and simulations show that these outflows are related to a variety of active galactic nuclei (AGN) feedback processes (see elaboration in Section 1 of Arav et al. 2020, hereafter Paper I). To quantify the extent to which outflows can contribute to AGN feedback, we need to determine their kinetic luminosity (\dot{E}_k). Theoretical models predict that \dot{E}_k needs to be at least 0.5% (Hopkins & Elvis 2010) or 5% (Scannapieco & Oh 2004) of the Eddington luminosity (L_{edd}) in order to provide strong AGN feedback.

In this paper, we analyze two outflows emanating from quasar SDSS J0755+2306. The data is from a spectroscopic survey of 10 quasars in the 500–1050 Å extreme-ultraviolet (EUV500) band (see Paper I). These two outflows present features different from other quasar outflows observed in the EUV500: (1) deep absorption troughs from doubly ionized species, e.g., C III $\lambda 977.02 \text{ Å}$; the N III multiplets near 686 Å, 764 Å, and 990 Å; and the O III multiplets near 703 Å and 834 Å; (2) continuous blended absorption that depress the flux in the $1227 \text{ Å} < \lambda < 1290 \text{ Å}$ and $1340 \text{ Å} < \lambda < 1440 \text{ Å}$ observed-frame regions.

This paper is part of a series of publications describing the results of *Hubble Space Telescope* (HST) program GO-14777, which observed quasar outflows in the EUV500 using the Cosmic Origins Spectrograph (COS).

Paper I summarizes the results for the individual objects and discusses their importance to various aspects of quasar outflow research.

Paper II (Xu et al. 2020a) gives the full analysis for four outflows detected in SDSS J1042+1646, including the largest kinetic luminosity ($\dot{E}_k = 10^{47} \text{ erg s}^{-1}$) outflow measured to date at $R = 800 \text{ pc}$ and an outflow at $R = 15 \text{ pc}$.

Paper III (Miller et al. 2020a) analyzes four outflows detected in 2MASS J1051+1247, which show remarkable similarities, are situated at $R \sim 200 \text{ pc}$, and have a combined $\dot{E}_k = 10^{46} \text{ erg s}^{-1}$.

Paper IV (Xu et al. 2020b) presents the largest velocity shift and acceleration measured to date in a BAL outflow.

Paper V (Miller et al. 2020b) analyzes two outflows detected in PKS 0352-0711, including one outflow at $R = 500 \text{ pc}$ and a second outflow at $R = 10 \text{ pc}$ that shows an ionization-potential-dependent velocity shift for troughs from different ions.

Paper VI is this work.

Paper VII (T. R. Miller et al. 2020, in preparation) discusses the other objects observed by program GO-14777, whose outflow characteristics make the analysis results less certain.

The structure of this paper is as follows. We present the observations and data reduction in Section 2. In Section 3, we present the analysis of the spectrum for the two outflow systems. We determine each outflow’s electron number density (n_e) and distance in Section 4 and constrain their energetics in Section 5. We discuss the results and compare with other EUV500 outflows in Section 6 and summarize the paper in Section 7. We adopt a cosmology with $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.286$, and $\Omega_\Lambda = 0.714$; and we use Ned Wright’s Javascript Cosmology Calculator website (Wright 2006).

2. Observations and Data Reduction

SDSS J0755+2306 (J2000: R.A. = 07:55:14.58, decl. = +23:06:07.13, $z = 0.854$) was observed by *HST*/COS (Green et al. 2012) using gratings G130M and G160M in 2017 September as part of our *HST*/COS program GO-14777 (PI: N. Arav). This object was observed previously in 2010 December using the *HST*/COS G140L grating in the program GO-12289

Table 1
HST/COS Observations for SDSS J0755+2306

Epoch	Date	Exp. ^a	Grating	λ_c ^b
1	2017 Sep 18	1220	G130M	1291
2	2017 Sep 18	2330	G130M	1327
3	2017 Sep 19	2330	G160M	1577
4	2017 Sep 19	2330	G160M	1600
5	2010 Dec 20	900	G140L	1280

Notes.

^a The exposure time of each observation in seconds.

^b The central wavelength of each grating in Å.

(PI: J. Howk). The details of these observations are shown in Table 1. We reduce and process the data and errors in the same way as described in Miller et al. (2018). We corrected for Galactic extinction with $E(B - V) = 0.045$ (Schlafly & Finkbeiner 2011). For the 2017 observations, we combined the two observations for each grating to increase the signal to noise. We show the full, dereddened spectrum in Figure 1. For regions outside the wavelength range of the 2017 epoch data, we show the 2010 epoch data.

Two outflow systems are identified: S1 has a velocity centroid (v_c) at -5520 km s^{-1} (based on its S IV $\lambda 809.66$ trough) and S2 at -9660 km s^{-1} (based on its S VI $\lambda 933.38$ trough). In Figure 1, absorption troughs associated with S1 and S2 are shaded in red and blue, respectively. Blended regions of the two outflow systems are shaded green. The unabsorbed emission model is comprised of a power-law continuum and strong emission lines fitted with Gaussian profiles (Chamberlain et al. 2015; Miller et al. 2018; Xu et al. 2018). The Galactic damped Ly α absorption is modeled with a Voigt profile ($\log(N_H) = 20.4^{+0.15}_{-0.15} \text{ cm}^{-2}$; e.g., Prochaska et al. 2005). The final, adopted emission model is shown as the solid red line in Figure 1.

3. Spectral Analysis

3.1. Column Density Determinations

The ionic column densities (N_{ion}) measured from the spectra represent the ionization structure of the observed outflow material. Like in all 11 outflows in the other objects (see Table 1 of Paper I), we observe in S1 and S2 strong absorption troughs from very high-ionization species, including Ar VIII, Ne VIII, Na IX, and Mg X. Similar to 10 of the outflows in the other objects (the exception is S4 of SDSS J1042+1646; see Paper IV), we observe in S1 and S2 absorption troughs from triply ionized species, e.g., N IV, O IV, and S IV. We also observe absorption troughs from doubly ionized species in S1 and S2, including C III, N III, and O III. The only other outflow analyzed in our EUV500 program that shows such troughs are the -3150 km s^{-1} outflow system in Paper V. Overall, we observe troughs in quasar SDSS J0755+2306 from ions with a larger spread of ionization potentials (IP, 48 eV \sim 367 eV) than in most of the other analyzed outflows in our EUV500 program. The atomic data for these transitions are shown in Table 3 of Paper II.

Following the methodology in Section 3 of Paper II, we analyze the data and measure N_{ion} as follows. Most measured N_{ion} use the apparent optical depth (AOD) method. Visual inspection of the troughs between epochs show no significant variability. Therefore, when possible, we use the N_{ion} measurements from the 2017 epoch data since it has higher signal to

noise and spectral resolution. Most of the measured troughs are treated as lower limits since their levels of non-black saturation are unknown without available partial covering (PC) solutions (Borguet et al. 2012a). For absorption trough regions with a maximum optical depth, $\tau_{\text{max}} < 0.05$, we consider their AOD N_{ion} as upper limits. In Section 4, we show that we can obtain N_{ion} measurements for S IV and S IV* for S1. We show the measured N_{ion} in the third column of Table 2 and the corresponding ion and wavelength in the first two columns. All troughs in Figure 1 that are not listed in Table 2 are severely blended, yielding unreliable N_{ion} measurements or limits.

For the transitions of Mg X $\lambda 624.94$ and Ca VII $\lambda 624.38$, their absorption troughs are too close to be disentangled (S1 around 1135 Å and S2 around 1120 Å, observed frame). In Table 2, we report the N_{ion} values for Mg X or Ca VII, assuming that the whole blended trough is from Mg X or Ca VII, respectively. When determining the photoionization solutions, we investigate several possible scenarios for the blending between Mg X and Ca VII (see Section 3.2).

For the N_{ion} of H I in S2, the ionic transition of H I $\lambda 972.54$ does not show consistently deep absorption trough features near the 1745 Å observed frame. Therefore, we measure the AOD N_{ion} from the trough of H I $\lambda 972.54$ and treat it as an upper limit for H I. The ionic transition of H I $\lambda 1025.72$ exhibits deep absorption near the 1840–1845 Å observed frame, while the right wing is blended with O VI $\lambda 1031.91$. We assume the trough from H I $\lambda 1025.72$ is symmetric and double its blue half AOD value for the lower limit N_{ion} of H I. Therefore, the N_{ion} of H I for outflow S1 is constrained to the range of 15.68 to 16.15 (in units of $\log(\text{cm}^{-2})$).

3.2. Photoionization Analysis

We assume the spectral energy distribution HE 0238 spectral energy distribution (SED; Arav et al. 2013). This SED is physically plausible since it is based on observations of quasar HE 0238–1904 in the EUV500 band (Arav et al. 2013). Two main parameters govern the photoionization structure of each outflow: the total hydrogen column density (N_H) and the ionization parameter (U_H):

$$U_H \equiv \frac{Q_H}{4\pi R^2 n_H c}, \quad (1)$$

where R is the distance from the central source to the absorber, n_H is the hydrogen number density, c is the speed of light, and $Q_H = 3.1 \times 10^{56} \text{ s}^{-1}$ is the emission rate of hydrogen-ionizing photons (obtained by integrating the HE 0238 SED for energies above 1 Ryd). The corresponding bolometric luminosity is $\sim 4.4 \times 10^{46} \text{ erg s}^{-1}$.

We start by assuming the solar metallicity and compare the measured N_{ion} (Table 2) to the model predicted N_{ion} from the spectra synthesis code Cloudy (version c17.00; Ferland et al. 2017; top panel of Figure 2). The colored contours for individual ions show where the measured N_{ion} are consistent ($\leq 1\sigma$) with the modeled N_{ion} from Cloudy (Borguet et al. 2012b). The colored contours with solid lines are N_{ion} measurements, and dotted or dashed lines are N_{ion} upper or lower limits, respectively. It is evident that there is no viable solution for the solar metallicity. Any solution that matches the upper limit N_{ion} of H I will simultaneously underpredict N_{ion} of N III, S IV, and S VI by up to a factor of 5.

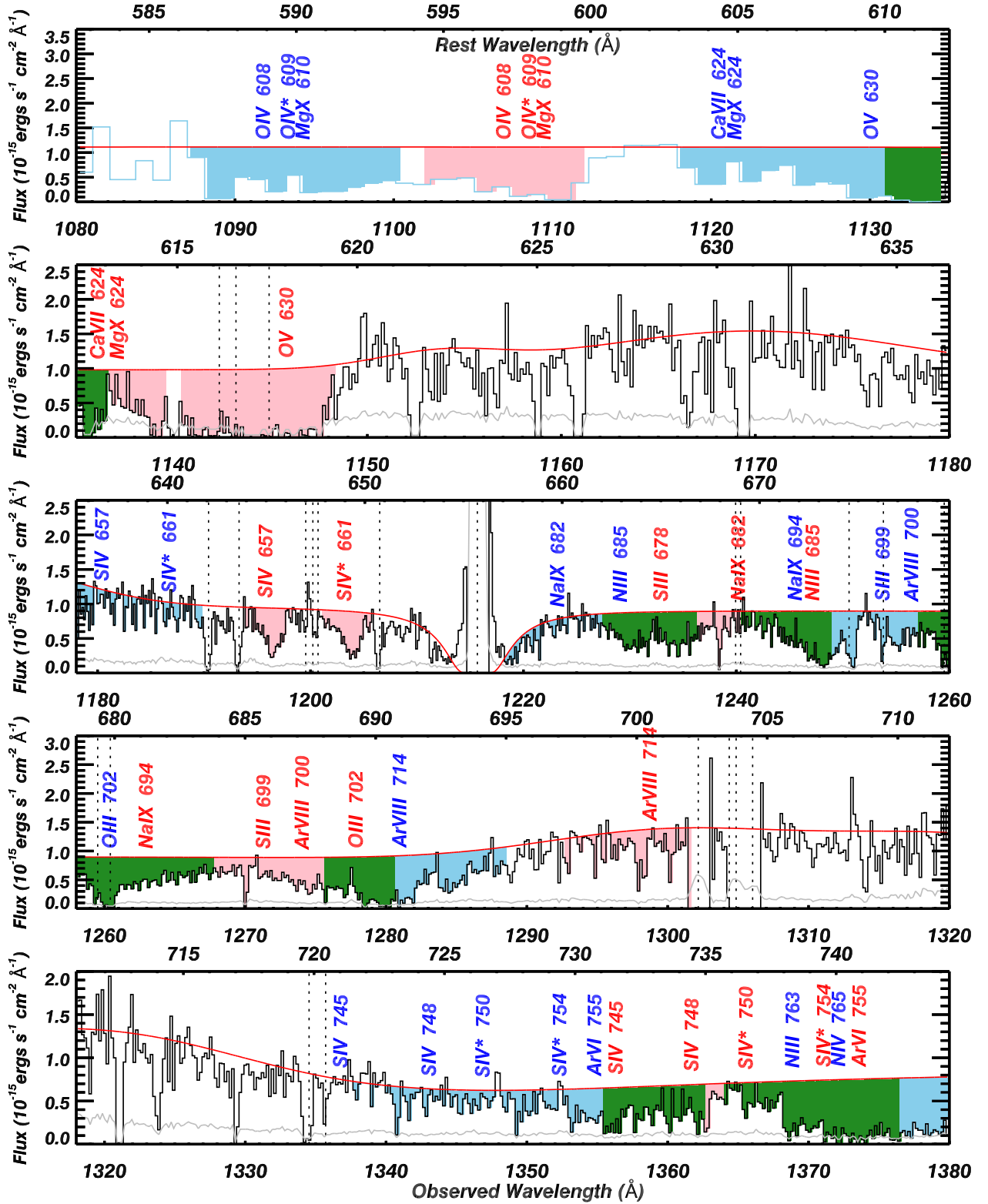


Figure 1. (a) *HST*/COS dereddened spectrum of SDSS J0755+2306 ($z = 0.854$). The black histogram shows the data from the 2017 epoch. The unabsorbed emission model and the flux error are shown as the red and gray solid lines, respectively. We shade the significant ionic absorption troughs for the two outflow systems, S1 and S2, of the 2017 epoch in red and blue, respectively. Blended regions of the two outflow systems are shaded green. Strong Galactic interstellar medium lines (e.g., C II $\lambda 1334.53$ and C II* $\lambda 1335.71$) and geocoronal lines (e.g., H I at 1215.67, O I at 1302.17 Å, and O I* at 1304.86 Å and 1306.03 Å) are marked with black dotted lines. The Galactic damped Ly α (at 1215.67 Å rest frame) is modeled by a Voigt profile with $\log(N_{\text{H}}) = 20.4 \text{ cm}^{-2}$. The 2010 data are the blue histograms in the first panel. This covers an extra wavelength range from 1080 to 1135 Å. The 2010 data are consistent with the 2017 data in the overlapping regions. (b) The 2010 data are the blue histograms in the last panel. This covers an extra wavelength range from 1778 to 1900 Å. The 2010 data are consistent with the 2017 data in the overlapping regions.

Table 2
Ionic Column Densities for Outflows in SDSS J0755+2306

Ion	λ^a (Å)	$N_{\text{ion, mea}}^b$ $\log(\text{cm}^{-2})$	$N_{\text{ion, mea}}/N_{\text{ion, model}}^c$
Outflow S1, $v = [-7000, -5200]^d$			
H I	949.74	<15.96	<0.85
N III	685.52	>15.55	>1.12
O III	832.93	>16.02	>1.20
O V	630.80	>15.83	>0.12
O VI	1037.62	>16.30	>0.24
Ne VIII	780.32	>16.49	>1.00
Na IX	682.72	<15.71	<31.6
Mg X	624.94	>16.69	\dots^e
S IV+S IV*	809.66, 815.94	$15.32^{+0.12}_{-0.16}$	0.85
S VI	944.52	>15.56	>1.12
Ar IV	850.60	<14.78	<1.51
Ar VIII	713.80	<15.14	<3.80
Ca VII	624.38	>15.40	\dots^e
Outflow S2, $v = [-11200, 8000]^d$			
H I	972.54	<16.15	<1.02
H I	1025.72	>15.68	>0.35
N III	685.52	>15.63	>1.23
O III	832.93	>15.76	>1.12
O V	630.80	>15.98	>0.06
O VI	1037.62	>16.49	>0.05
Ne VIII	770.41	>16.47	>0.31
Na IX	682.72	<15.40	<7.24
Mg X	624.94	>16.40	\dots^e
S IV+S IV*	809.66, 815.94	<15.37	<1.35
S VI	933.38	>15.59	>1.12
Ar IV	850.60	<14.68	<1.78
Ar VIII	700.24	>15.39	>0.41
Ca VII	624.38	>15.70	\dots^e

Notes.

^a The rest wavelength of the measured transitions for each ion. For ions which are a doublet or multiplet, we show all the uncontaminated transitions.

^b The measured N_{ion} . Lower limits are shown in bold while upper limits are shown in italic. S IV+S IV* is for the sum of the resonance and excited transitions for S IV.

^c The ratio of the measured N_{ion} to the model predicted N_{ion} .

^d The N_{ion} integration range in km s^{-1} .

^e For the transitions of Mg X $\lambda 624.94$ and Ca VII $\lambda 624.38$, their absorption troughs are too close to be disentangled. We report the N_{ion} values for Mg X or Ca VII, assuming that the whole blended trough is from Mg X or Ca VII, respectively (see Section 3.1). In the photoionization models, we investigated several possible scenarios (Section 3.2).

One possible solution is to invoke a super-solar metallicity. There were outflow systems that have been found to have super-solar metallicity (e.g., Gabel et al. 2006; Arav et al. 2007, 2020). In the middle and bottom panel of Figure 2, we present the photoionization solutions assuming the HE 0238 SED and the super-solar metallicity described in Paper V ($Z = 4.68 Z_{\odot}$). As in most of the other EUV500 outflows in our *HST* program GO-14777 (see Table 1 of Paper I, except S4 in SDSS J1042+1646), we invoke a two-phase photoionization solution for both S1 and S2 (Arav et al. 2013). The very high- and high-ionization-phase solutions are the blue and red “x” along with their 1σ error contours (the black ellipses), respectively. The ratios of the measured N_{ion} to the model predicted N_{ion} are given in the fourth column of

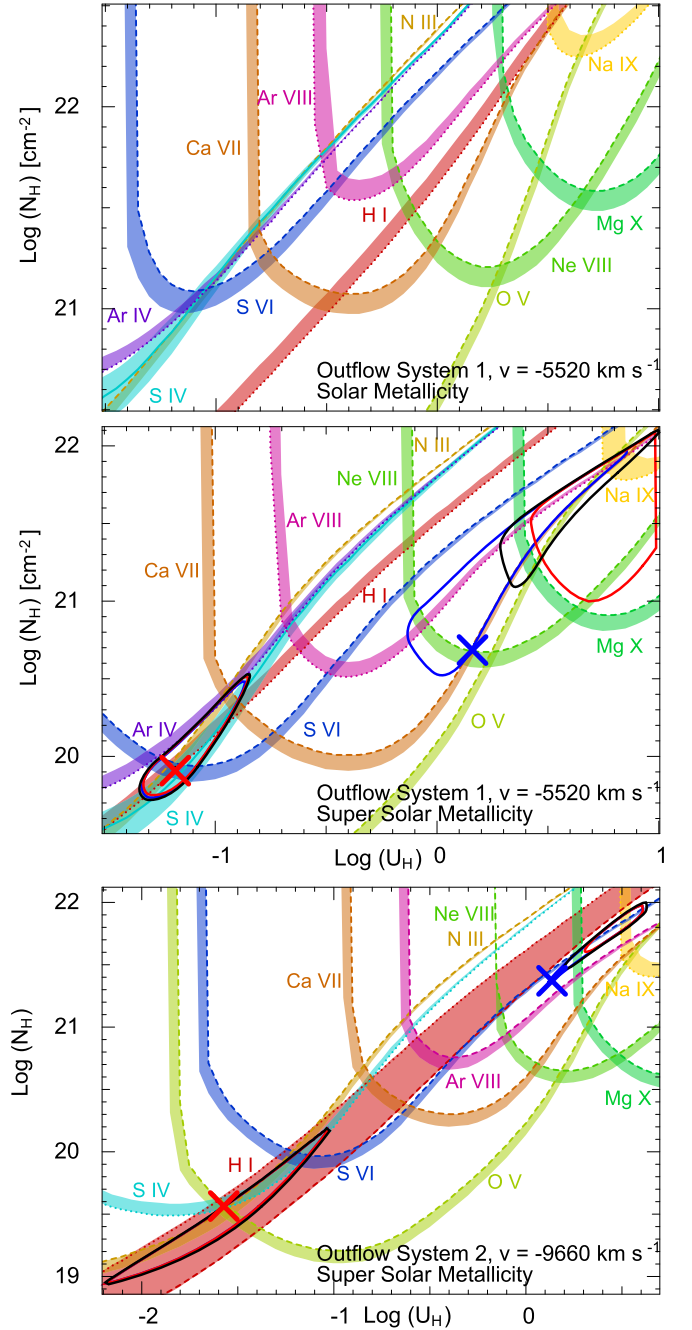


Figure 2. Best-fitting photoionization solutions for outflows S1 and S2. Top: comparison of the Cloudy modeled N_{ion} to the measured N_{ion} in S1 assuming the solar metallicity. Each colored contour represents the region where the $(N_{\text{H}}$ and $U_{\text{H}})$ model produces consistent N_{ion} within the errors with the observed values. Solid lines represent N_{ion} measurements, while dotted and dashed lines represent upper and lower N_{ion} limits, respectively. Any solution that matches the upper limit N_{ion} of H I underpredicts N_{ion} of N III, S IV, and S VI by up to a factor of 5. Middle and bottom: the under super-solar metallicity; the N_{ion} from S1 and S2 match with two-phase photoionization solutions (see Section 3.2). The very high- and high-ionization-phase solutions are the blue and red “x” along with their 1σ error contours (the black ellipses), respectively. The black, blue, and red ellipses are accounting for the blending of troughs from Mg X $\lambda 624.94$ and Ca VII $\lambda 624.38$ (see Section 3.2). The other N_{ion} lower and upper limits that are not shown here are consistent with the solutions and omitted for clarity’s sake.

Table 2. When $N_{\text{ion, mea}}$ is a lower limit, we expect to have $N_{\text{ion, mea}}/N_{\text{ion, model}} < 1$ and vice versa.

Due to the blending absorption troughs from Mg X $\lambda 624.94$ and Ca VII $\lambda 624.38$ (S1 around 1135 Å and S2 around the

Table 3
Atomic Data for S IV and S IV* Transitions

Ion	λ^a (Å)	E_{low}^b (cm ⁻¹)	f^c
S IV	657.319	0.00	1.130
S IV*	661.396	951.4	1.130
S IV	744.904	0.00	0.249
S IV	748.393	0.00	0.459
S IV*	750.221	951.4	0.597
S IV*	753.760	951.4	0.131
S IV	809.656	0.00	0.118
S IV*	815.941	951.4	0.085

Notes.

^a Rest wavelength of S IV and S IV* transitions.

^b Lower-level energy of these transitions from the National Institute of Standards and Technology (NIST) database (Kramida et al. 2018).

^c Oscillator strengths from the NIST database.

1120 Å observed frame, see Figure 1), we present the photoionization solutions considering three different blending scenarios (Figure 2): (1) half of the trough's optical depth is from the Ca VIII ionic transition and the other half is from the Mg X ionic transition black ellipses), (2) the trough is comprised of only the ionic transition of Ca VII λ624.38 (blue ellipses), and (3) the trough is only contributed by the ionic transition of Mg X λ624.94 (red ellipses). For both S1 and S2, the blue “×” denotes the photoionization solution with the least N_{H} for the very high-ionization phase.

4. Electron Number Density and Distances

By assuming the outflow is governed by photoionization, we can solve for R from Equation (1). The only other unknown parameter is n_{H} , and in a highly ionized plasma, $n_{\text{H}} \approx 0.8 n_{\text{e}}$. Here, we use the density sensitive N_{ion} ratio from S IV*/S IV (for S1) and O III*/O III (for S2) to constrain n_{e} .

4.1. Determination of n_{e} for S1 from S IV*/S IV

For S1, we observe absorption at the expected wavelength locations of the S IV lines listed in Table 3. However, the 744.90, 748.39, 750.22, and 753.76 Å troughs are severely blended with absorption troughs from S2 (see Figure 1). Therefore, the N_{ion} from these S IV transitions cannot be reliably determined. The 657.32, 661.40, 809.66, and 815.94 Å troughs are not blended with other troughs from S2 or strong intervening systems (see Figure 3). We show the comparison of these troughs in velocity space in Figure 3.

The velocity centroids match well for these troughs as indicated by the green solid lines, while the N_{ion} integration ranges are the green dotted lines. The 815.94 Å trough clearly has less N_{ion} than the 809.66 Å trough, which is consistent with our derived $N(\text{S IV}^*)/N(\text{S IV})$ ratio. For the AOD method, the expected optical depth (τ) ratio of the 657.32 Å trough to the 809.66 Å trough is

$$\frac{\int \tau(v)_{657.32} dv}{\int \tau(v)_{809.66} dv} = \frac{N_{\text{S IV}} \times f_{657.32} \times 657.32}{N_{\text{S IV}} \times f_{809.66} \times 809.66} = 7.8, \quad (2)$$

where $N(\text{S IV})$ is the column density of S IV and $f_{657.32}/f_{809.66} \approx 9.6$ is the oscillator strength ratio between the two transitions. By

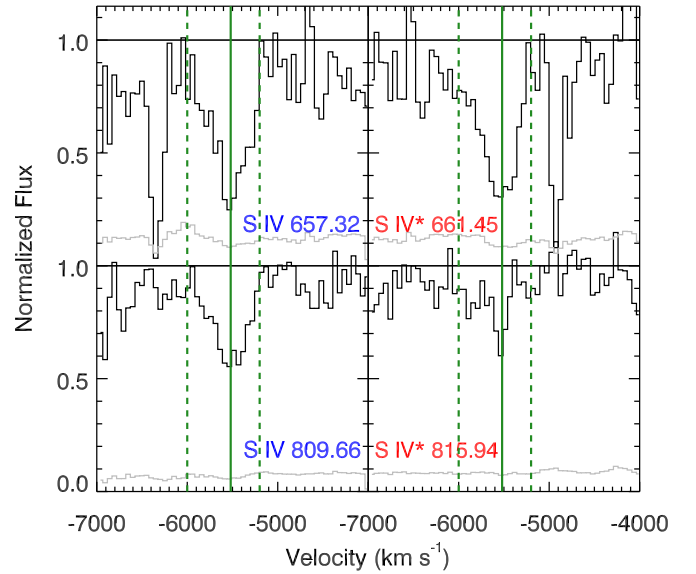


Figure 3. Comparison between two pairs of S IV and S IV* troughs for S1. The data are shown as the black histogram. The vertical green solid line shows the velocity centroid of S1, while the N_{ion} integration range are shown as the dashed green lines (see Section 4).

assuming that $\tau(v)_{657.32}/\tau(v)_{809.66}$ equals a constant, the expected ratio in the AOD case, i.e., $[\tau(v)_{657.32}/\tau(v)_{809.66}]_{\text{AOD}}$, is 7.8. However, the observed ratio, i.e., $[\tau(v)_{657.32}/\tau(v)_{809.66}]_{\text{obs}}$, is around 3, which indicates that the 657.3 Å trough is non-black saturated. Similarly, for the excited states of S IV, we derived $[\tau(v)_{661.40}/\tau(v)_{815.94}]_{\text{AOD}} = 9.7$ and $[\tau(v)_{661.40}/\tau(v)_{815.94}]_{\text{obs}} \approx 3$. Therefore, the 661.40 Å trough is also non-black saturated. Thus, we use the PC method to obtain the N_{ion} for the S IV resonance state ($E_{\text{low}} = 0 \text{ cm}^{-1}$) from the 657.32 Å and 809.66 Å troughs and the excited state from the 661.40 Å and 815.94 Å troughs. The resulting ratio of the S IV* column density to the S IV column density, i.e., $N(\text{S IV}^*)/N(\text{S IV})$, is $0.54^{+0.20}_{-0.17}$.

In Figure 4, we compare this S IV column density ratio to those predicted by the CHIANTI database (version 7.1.3; Landi et al. 2013). The mean temperature for S IV is 8700 K, which is based on the photoionization solution for the high-ionization phase (HP) of S1 (Section 3.2). The red curve is the model predictions from CHIANTI, while the red cross is the derived $N(\text{S IV}^*)/N(\text{S IV})$ ratio with its uncertainties. We find $\log(n_{\text{e}}) = 4.26^{+0.21}_{-0.20}$ (hereafter, n_{e} is in units of $\log(\text{cm}^{-3})$).

For outflow S1, we also observe absorption troughs from other density sensitive transitions, e.g., O IV λ787.71, O IV* λ790.20, and O III+O III* near 833 Å in the observed frame (see Figure 1). Unfortunately, their absorption troughs are either saturated or too blended to provide useful n_{e} constraints. However, their absorption troughs are consistent with our best-fitting photoionization model. Therefore, by adopting the best-fit U_{H} and S IV-determined n_{e} into Equation (1), we obtain $R = 270^{+100}_{-90} \text{ pc}$.

4.2. Determination of n_{e} for S2 from O III*/O III

For outflow S2, the stronger S IV and S IV* transitions at 657.32 Å and 661.40 Å do not show distinctive troughs. However, we detect deep absorption features at the expected wavelength location of the O III+O III* multiplet (O III λ832.93

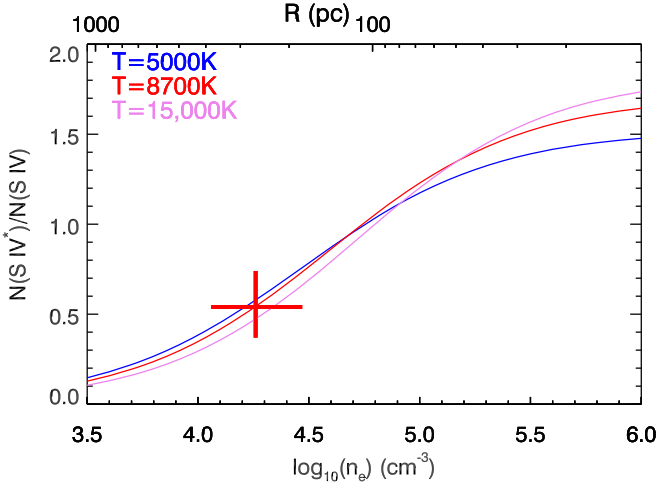


Figure 4. Column density ratio of S IV* to S IV vs. the electron number density, n_e , for outflow S1. The red cross marks the ratio with the uncertainties derived in Section 4. The colored curves are the predictions from the CHIANTI database (version 7.1.3; Landi et al. 2013), assuming different temperature. The mean temperature of the S IV gas based on the photoionization solution for the HP of S1 is 8700 K (Section 3.2).

and O III* $\lambda\lambda 833.75$ and 835.29). To determine n_e , we adopt the same analysis method from Paper II.

To fit the observed absorption features, we start with the photoionization solution inside the 1σ contour of the HP for S2 (the contour surrounding the red \times in the bottom panel of Figure 2). We vary $\log(n_e)$ from 2 to 8 and overlay the model predicted O III+O III* troughs to the 1490–1510 Å observed-frame region (see Figure 5). We then do a χ^2 minimization of the data and model for the O III+O III* region. The red dashed lines represent the modeled troughs of the O III+O III* multiplet for a particular n_e , while the solid black lines are the summation of all models in the region.

Since a single-Gaussian optical depth profile (e.g., Equation (2) of Paper II) does not fit the O III+O III* region well, we adopt a two-Gaussian optical depth profile following Borguet et al. (2012a). The two Gaussians have the same velocity width (σ) of 350 km s^{-1} . The main Gaussian contains 65% of the total N_{ion} and has a velocity centroid (v_c) of -9660 km s^{-1} , while the secondary Gaussian contains 35% of the total N_{ion} with $v_c = -8860 \text{ km s}^{-1}$. The same two-Gaussian profile also fits the lower-velocity wing of other outflow troughs in S2 well, e.g., from Ar VIII $\lambda 713.80$.

By adopting the two-Gaussian profile, the best-fitting $\log(n_e) = 3.1$, where the corresponding models are shown in the panel 2 of Figure 5. The models with $\log(n_e) = 2.6$ and $\log(n_e) = 3.9$ deviate from the best-fitting model by 1σ (see panel 1 and 3 of Figure 5), where they clearly underestimate the absorption troughs from the 1500–1510 Å and 1493–1498 Å observed frames, respectively. Overall, we get $\log(n_e) = 3.1^{+0.8}_{-0.5}$.

By adopting the best-fitting n_e value and errors into Equation (1), we obtain $R = 1600^{+2000}_{-1100} \text{ pc}$.

5. Outflow Energetics

By assuming each outflow is in the form of a thin shell, covering a solid angle of $4\pi\Omega$ around the source, moving with a radial velocity, v , at a distance, R , from the central source (see Paper I and Borguet et al. 2012b), the mass flow rate (\dot{M}) and

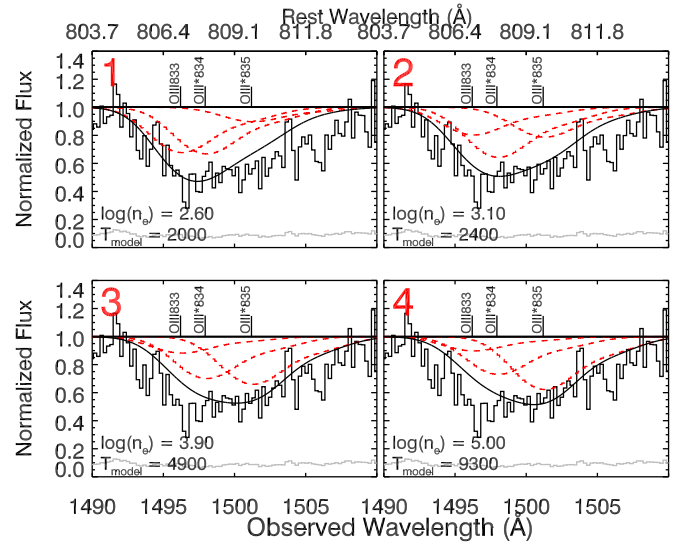


Figure 5. Fits to the O III+O III* multiplet region for outflow S2. To get the best fit, we vary n_e (in units of cm^{-3}) and probe the photoionization solution inside the 1σ error contour of the HP in S2. The n_e and the corresponding temperature predicted from Cloudy are shown at the bottom left corner of each panel. The black and gray solid histograms are the normalized flux and errors from the *HST*/COS observations in 2017. For each subplot, the red dashed lines represent the models of the O III+O III* multiplet for a particular $\log(n_e)$, while the solid black lines are the summation of all models in this region. See Section 4.2 for a detailed discussion.

kinetic luminosity (\dot{E}_k) of the outflow are given by

$$\dot{M} \simeq 4\pi\Omega R N_{\text{H}} \mu m_p v, \quad \dot{E}_k \simeq \frac{1}{2} \dot{M} v^2, \quad (3)$$

where N_{H} is the total hydrogen column density, m_p is the proton mass, and $\mu = 1.4$ is the mean atomic mass per proton.

Using R with the U_{H} and N_{H} from the best-fitting photoionization solutions, we present the derived \dot{M} and \dot{E}_k values in Table 4, where we assume $\Omega = 0.2$ (see Section 6.4 of Paper II).

Using Sloan Digital Sky Survey (SDSS) data, we measure the FWHM of the Mg II broad emission line and estimate the Eddington luminosity (L_{edd}) with the Mg II-based black hole mass equation in Bahk et al. (2019). This leads to $L_{\text{edd}} = 1.0 \times 10^{47} \text{ erg s}^{-1}$. Therefore, outflows S1 and S2 yield the ratio of kinetic luminosity to L_{edd} of $>0.2\%$ and 12% – 250% , respectively. The large range for S2 is due to the uncertainties of its N_{H} and n_e , while the conservative lower limit of 12% is assured. Outflow S2, with \dot{E}_k greater than 5% of L_{edd} , is a good candidate for producing strong AGN feedback (Scannapieco & Oh 2004).

6. Discussion

6.1. Partial Covering and Ionization State Relationship

Outflows are found to only partially cover the emission source (e.g., Korista et al. 1992; Arav et al. 1999, 2001, 2012; Hamann et al. 2001), and evidence exists to support the idea that the covering factor (f_{cov}) becomes larger when the level of ionization within the outflow increases. For example, Korista et al. (1992) reported that the quasar 0226–1024 has an outflow with troughs from multiple doublet transitions arising from ions with different IP. From the atomic data in Allen (1977),

Table 4

Physical Properties of the Outflow Systems Seen in Quasar SDSS J0755+2306

Outflow System	−5520 km s ^{−1} (S1)	−9660 km s ^{−1} (S2)
Ionization phase	Very high	High
log(N_{H}) (cm ^{−2})	>20.7	19.9 ^{+0.6} _{−0.2}
log(U_{H}) (dex)	>0.1	−1.2 ^{+0.3} _{−0.2}
log(n_{e}) (cm ^{−3})	^a <3.0	4.3 ^{+0.2} _{−0.2}
Distance (pc)	270 ⁺¹⁰⁰ _{−90}	1600 ⁺²⁰⁰⁰ _{−1100}
\dot{M} [M_{\odot} yr ^{−1}]	>20	450–8000
log(\dot{E}_{k}) ^b (erg s ^{−1})	>44.3	46.1–47.4
$\dot{E}_{\text{k}}/L_{\text{edd}}$	>0.002	0.125–2.5
log(f_{V}) ^c	<−2.1	<−3.3

Notes. The bolometric luminosity is $L_{\text{bol}} = 4.4 \times 10^{46}$ erg s^{−1}, assuming the HE 0238 SED.

^a Assuming that both ionization components are at the same distance.

^b Assuming $\Omega = 0.2$ and where N_{H} is the sum of the two ionization phases.

^c The volume filling factor of the outflow's high-ionization phase to the very high-ionization phase (see Table 1 in Paper I and Arav et al. 2013).

IP(O VI) = 77.41 eV > IP(C IV) = 64.49 eV > IP(Si IV) = 45.14 eV, and Korista et al. (1992) found that the depths of the saturated absorption troughs from these doublets follow the same trend. Possible explanations include that the outflows have small dense cores covered by loose envelopes. Therefore, the low-density envelopes with larger f_{cov} would tend to have higher-ionization levels than the high-density cores. However, elemental abundances are also found to affect the f_{cov} (Telfer et al. 1998; Arav et al. 1999). Studying different ionization states from the same element eliminates the abundance effects and provide us with a direct test of the relationship between f_{cov} and ionization states.

Outflow S2 shows absorption troughs from two different ions of oxygen: the O III (IP = 55.9 eV) multiplet around 834 Å and the O VI (IP = 138.1 eV) doublet at 1031.93 Å and 1037.62 Å (see Figure 1). From our photoionization solutions, the very high-ionization phase (VHP) produces a negligible amount of the N_{ion} for O III (<0.1%) and almost 10 times more N_{ion} for O VI than the HP. Therefore, O III and O VI are good candidates for testing the difference in f_{cov} between the phases. Our best-fitting photoionization models predict that the absorption troughs from both of them are saturated, with $N_{\text{model}}/N_{\text{mea}} \sim 5$ and 30 for O III and O VI, respectively (see Table 2). However, the O III doublet shows non-black saturation with a residual flux of ~30%–50%, while the O VI doublet has nearly zero residual flux (see Figure 1). This directly supports the idea that for the same element, higher-ionization ions indeed cover a larger area of the emission source.

The O III and O VI troughs in S1 show a similar behavior and support the same idea, while the saturated O III multiplet in S1 shows a residual flux of ~10% and the saturated O VI doublet has nearly zero residual flux.

6.2. The $\lambda > 1050$ Å Portion of the Outflow Spectra

Ground-based BAL quasar outflow (BALQSO) studies mainly cover the rest-frame wavelength range of $\lambda > 1050$ Å, which usually shows absorption troughs from only H I, N V, Si IV, and C IV. The widest trough with a measurable width for S1 is the O III multiplet near 820 Å (rest frame) with $\Delta v = 2500$ km s^{−1} (measured for continuous absorption below the normalized flux of $I = 0.9$). For S2, we measure a width of 3100 km s^{−1} from the S VI 933.38 Å trough. Therefore, both of these outflows are identified as broad absorption line outflows (see Section 6.3 of Paper II for elaboration).

From the best-fitting photoionization solution derived in Section 3.2, we can predict the absorption features for the $\lambda > 1050$ Å rest-frame region for each outflow by assuming this region has the same absorption trough shape as in the EUV500 region. In Figure 6, we show the predicted troughs. For outflows S1 and S2, the predicted C IV $\lambda\lambda 1548.19$ and 1550.77 absorption troughs are saturated, blended, and have widths of 2400 km s^{−1} and 2600 km s^{−1}, respectively. Therefore, they are predicted to be BALs following the criteria of Weymann et al. (1991).

The models also predict weak absorption troughs for both S IV $\lambda 1062.66$ and S IV* $\lambda 1072.97$ with oscillator strengths (f) for both about 0.05, which are the main density sensitive transitions for the $\lambda > 1050$ Å rest-frame region (Arav et al. 2018). However, the predicted troughs have maximum optical depths around 0.05, which make their detection unlikely with ground-based telescopes for a couple of reasons. First, $\tau = 0.05$ troughs are difficult to detect in principle due to their shallowness and systematic issues regarding the unabsorbed emission model. Second, and more importantly, from the ground, we can detect the 1062 Å rest-frame wavelength region only for quasars with redshifts $z \gtrsim 2.5$. At these redshifts, the Ly α forest severely contaminates the S IV troughs, which makes the task of identifying such a shallow trough hopeless in SDSS data and very difficult in Very Large Telescope/X-shooter observations (the latter observations have both a higher signal-to-noise ratio and spectral resolution than the SDSS data; see Arav et al. 2018; Xu et al. 2018, 2019).

In contrast, for the same outflow, we have four detected pairs of S IV and S IV* troughs in the EUV500 with associated f values up to 20 times larger (resulting in deeper troughs for the same amount of S IV N_{ion}). Also the availability of two uncontaminated pairs of S IV and S IV* troughs in S1, with large f value differences, makes the n_{e} determination more robust and less affected by possible systematic issues. Based on these S IV and S IV* EUV500 troughs, we were able to determine the n_{e} , R , and energetics for outflow S1 (see Section 4).

We also note that the predicted P V troughs are even shallower than the S IV $\lambda 1062.66$ and S IV* $\lambda 1072.97$ ones, which explains the low detection rate of P V troughs among BAL quasars (3.0%–6.2%; see Capellupo et al. 2017).

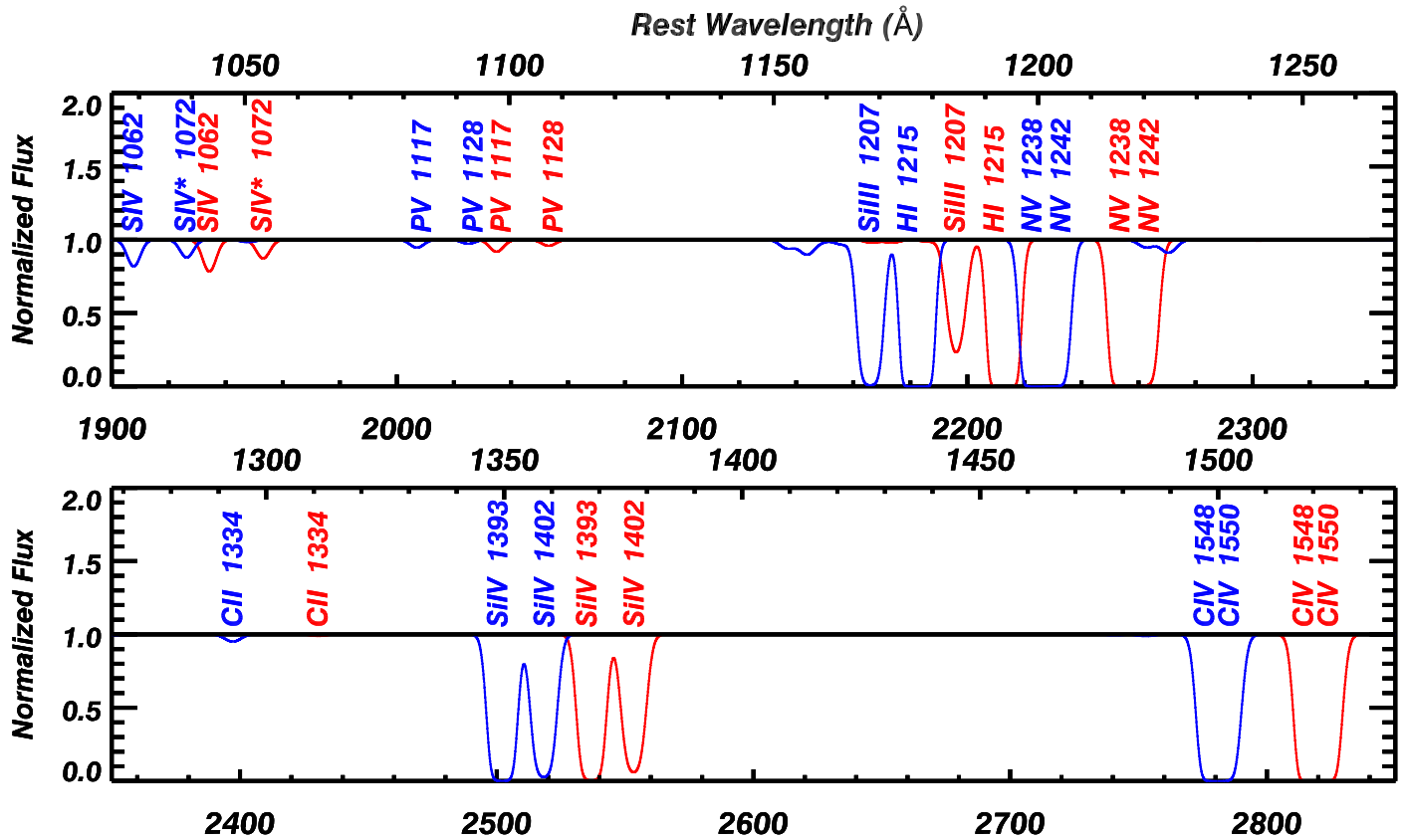


Figure 6. Predictions of the strong absorption troughs for outflows S1 and S2 in the $\lambda > 1050$ Å rest frame from the best-fitting photoionization models (see Section 3). The models for outflow S1 and S2 are shown in blue and red, respectively.

7. Summary

In this paper, we analyzed outflows seen in the recent *HST*/COS spectra of quasar SDSS J0755+2306. The main results are summarized as follows:

1. Two outflow systems are identified. They present clear absorption troughs from both high-ionization species, e.g., N III, O III, O IV and S IV and very high-ionization species, e.g., Ar VIII, Ne VIII, and Na IX (see Section 2). Both outflows are classified as BALs from their widest EUV500 absorption trough widths.
2. Similar to the outflow analysis in Papers II, III, and V, each outflow system requires a two ionization-phase solution (see Section 3.2).
3. For outflow system 2, we derive $\log(n_e) = 3.1$ based on the density sensitive transitions of O III and O III* in the EUV500 band. The determined distance of this outflow is 1600 pc and the kinetic luminosity is $>12\%$ of L_{edd} (see Sections 4 and 5). Therefore, this outflow is a good candidate for producing strong AGN feedback.
4. The absorption troughs from O III and O VI support the idea that high-ionization ions have a larger covering fraction compared to lower-ionization ions (see Section 6.1).

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