Massive Outflows in CII Low-Ionization Broad Absorption Line Quasars

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Abstract

About 20% of quasars have Broad Absorption Lines (BALs) in their spectra, indicating massive outflows emerging from the central engine. These outflows potentially remove accretion angular momentum, distribute metals into the intergalactic medium, and contribute to the evolution of galaxies through feedback.

BAL quasars, identified by C IV absorption, exhibit a diverse phenomenology that suggests a wide distribution of physical properties. A subset of BAL quasars shows P V absorption, and because phosphorus has a relatively low abundance these P V systems are inferred to have thick outflows and high ionization parameters. In a smaller subset, Mg II and Al III identify low-ionization broad absorption line quasars (LoBALs) with thick outflows approaching the hydrogen ionization front. Crossing the hydrogen ionization front results in a complex of Fe II absorption lines, creating FeLoBALs that can be difficult to analyze due to line blending.

Between LoBALs and FeLoBALs lie C II LoBALs, identified by C II absorption at 1335 Å that is present in the H II region through recombination onto C+2. We propose that these objects represent some of the thickest outflows that are accessible to detailed spectral analysis. Here we present new measurements of C II absorption-line equivalent widths in a set of P V broad absorption line quasars identified by Capellupo et al. (2017). We present analysis of a subset of these using *SimBAL*, a novel spectral-synthesis method that uses Bayesian model calibration to extract the physical conditions of the outflows.

1. Analysis of Carbon II in the Phosphorous V Sample

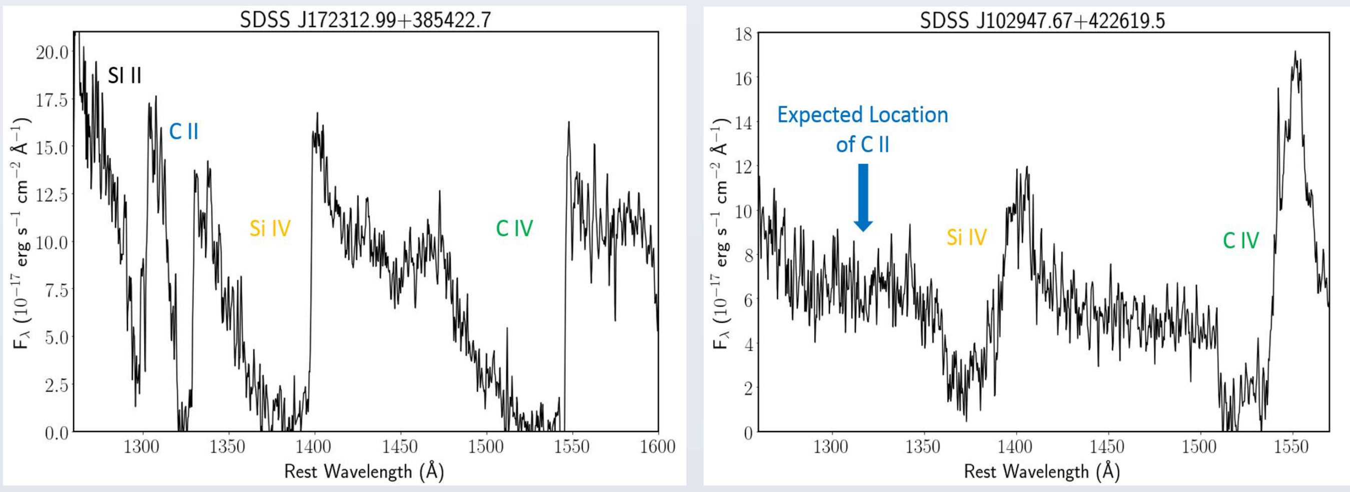

Fig. 1. The spectra of two objects from the Capellupo et al. 2017 sample contain P V absorption indicating a thick outflow, but low ionization C II differs dramatically.

Studies of P V absorption at 1118 Å and 1128 Å by Hamann (1998) and further investigated in Leighly et al. (2009) and Borguet et al. (2013) found that P V is a strong indicator of a highly saturated C IV absorption. The low abundance of phosphorous combined with the relation to C IV led to the conclusion that P V identifies a thick outflow with a high column density.

Capellupo et al. (2017) compiled a sample of 81 objects with P V absorption from Sloan Digital Sky Survey III for future studies of BAL outflows. The selection of objects displayed an above average incidence of low-ionization lines Mg II and Al III compared to other BALQSOs.

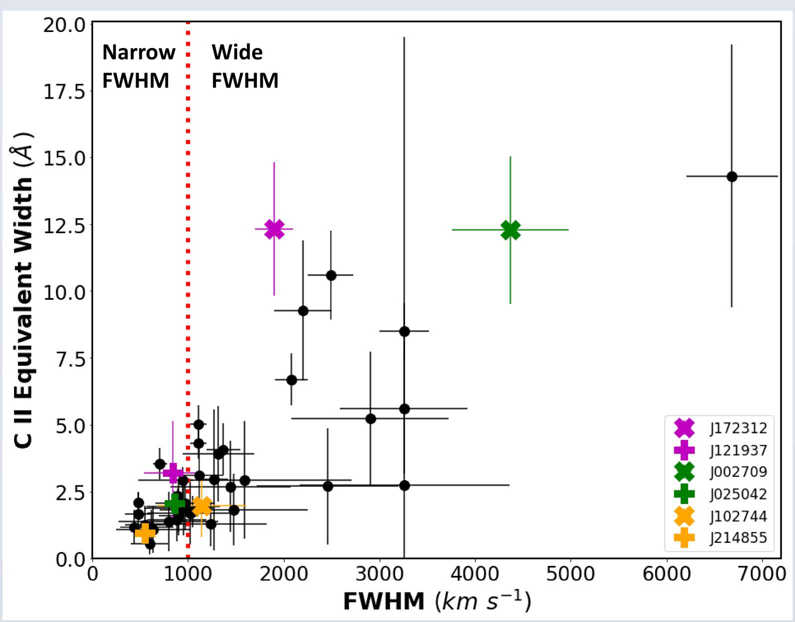

Fig. 2. *Sherpa* results for 44 objects with C II absorption. Crosses (plusses) denote objects with broad (narrow) CII lines, and magenta, green and gold denote objects with decreasing CII optical depth.

The low-ionization lines present in the P V sample have been observed in other BALQSOs. Voit et al. (1993) concluded that Mg II and Al III normally are narrower and lie at the lower velocities of C IV. Additionally, physical parameters derived using the lines describe gas between the He II and H I ionization fronts, and possibly identifies thick outflows.

After inspection of the P V sample we discovered tremendous variation in C II absorption, shown in **Fig. 1**. C II is a low ionization line like Mg II and Al III that can describe even thicker outflows. We hypothesized that objects with significant C II absorption lines may have the highest outflow column densities among the P V quasars. It then follows that the narrow region of the outflow described by C II identifies the concentration of the outflow.

Before quantifying C II absorption in the P V sample, 37 spectra with no apparent C II are removed. The remaining objects are then sorted into 6 groups based on C II apparent optical depth and full width at half maximum (FWHM) of the absorption. Using the modeling application *Sherpa* (Freeman et al. 2001), estimates of optical depth and FWHM are obtained by fitting a gaussian to the C II absorption.

Equivalent width is calculated for C II because FWHM and equivalent width together are good metrics to describe line size and strength. A majority of the objects are found to contain narrow C II with lower equivalent widths, shown in **Fig. 2**. Six groups are created by comparing the morphologies of spectra with either narrow or wide FWHM and similar C II apparent optical depth through visual inspection. Six objects representative of their group are then selected for modeling, marked in **Fig. 2**.

2. Modeling BALQSOs using *SimBAL* Spectral Synthesis

Constraining physical parameters for each object using the traditional method of individual absorption modeling can be difficult due to complex line structure. The spectral synthesis method *SimBAL* uses *Cloudy* grids of ionic column densities (Ferland et al. 2013) to model all absorption. The synthetic spectra created by *SimBAL* allow the physical properties of BALQSO outflows and their relation to feedback to be extensively examined for the first time (Leighly et al. 2018; Leighly et al. poster 242.39).

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3. Model Fits

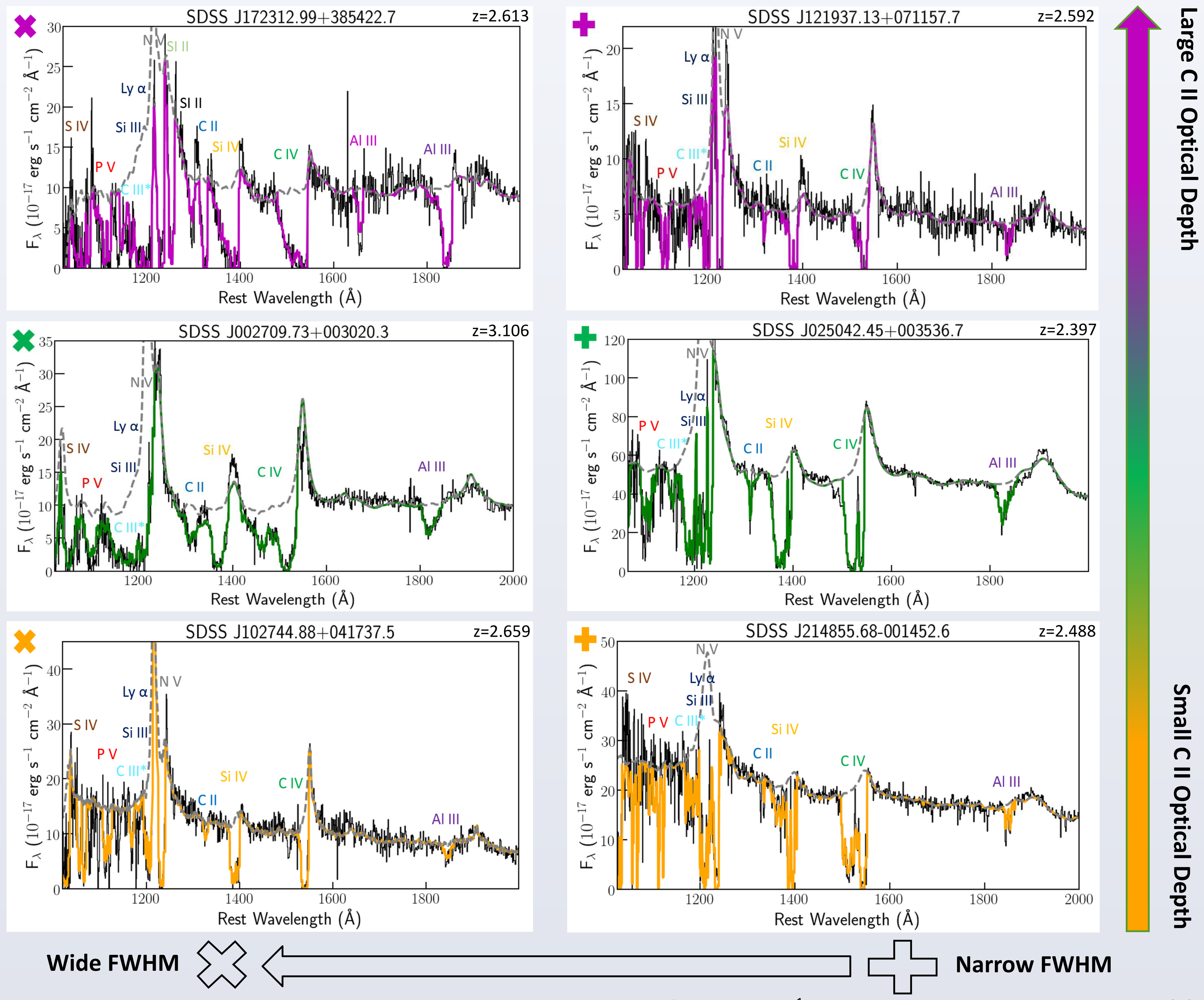

Fig. 3. Continuum model is represented by a dotted grey line. Wide FWHM is greater than 1000 km s^{-1}. Apparent optical depth is between $0.4 < \tau < 3.2$.

The *SimBAL* continuum model consists of a power law plus SMC reddening (Pei 1992), and emission lines modeled using principal component eigenvectors constructed by us from SDSS spectra.. Then, absorption troughs were modeled using equal velocity bins between 480 – 960 km s^{-1} with parameters ionization log U, gas density log n, log N_H - log U, and covering fraction assigned to ranges of bins depending on application. The observed and synthetic spectra are compared using the Markov Chain Monte Carlo method *emcee* (Foreman-Mackey et al. 2013) producing posterior probability distributions for each parameter.

4. Physical Properties

The contours for various lines at τ=1, assuming a typical velocity width of 1000 km s^{-1}, are shown in **Fig. 4**. as a function of log U and a combination parameter log N_H - log U which measures the column density relative to the hydrogen ionization front. The best-fitting parameters for the six objects modeled using *SimBAL* are marked.

As expected, objects with the deepest and widest CII lines have the thickest outflows with respect to the hydrogen ionization front. These objects also show other low ionization lines including Si II, and in one case Al III and Fe II (**top left, Fig. 3**)

Covering fraction weighted column densities were calculated for outflow concentrations in each object. **The results presented in Fig. 5 suggest that strong C II absorption indicates a thick outflow.**

We note that there is a significant selection bias in this P V-selected sample. The presence of P V signals a high ionization parameter (e.g., **Fig. 4**, and Leighly et al. 2009). As shown in **Fig. 4**, significant C II is predicted in outflows with log U < -0.5, where the column density would be much lower. Therefore C II can be used as a column density indicator when coupled with the presence of other high-ionization lines such as N V and P V.

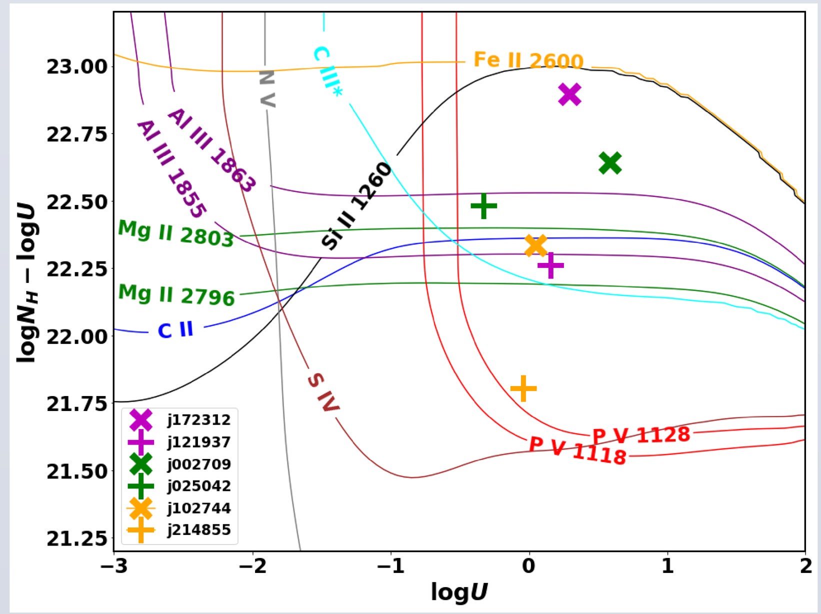

Fig. 4. Contours of τ =1 for the case of log n =6.6 [cm^{-3}] assuming a velocity width of 1000 km s^{-1}.

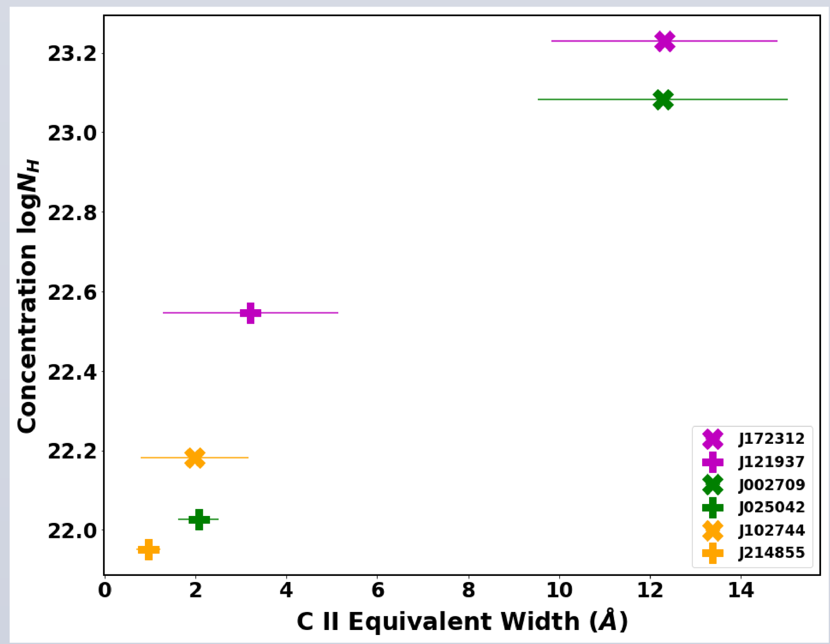

Fig. 5. Column densities for the portion of the outflow exhibiting C II (the concentration). We observe a strong correlation between C II optical depth and column density as expected.

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