Constraints on Outflow Properties from Mg II in The Broad Absorption Line Quasar FBQS J1151+3822

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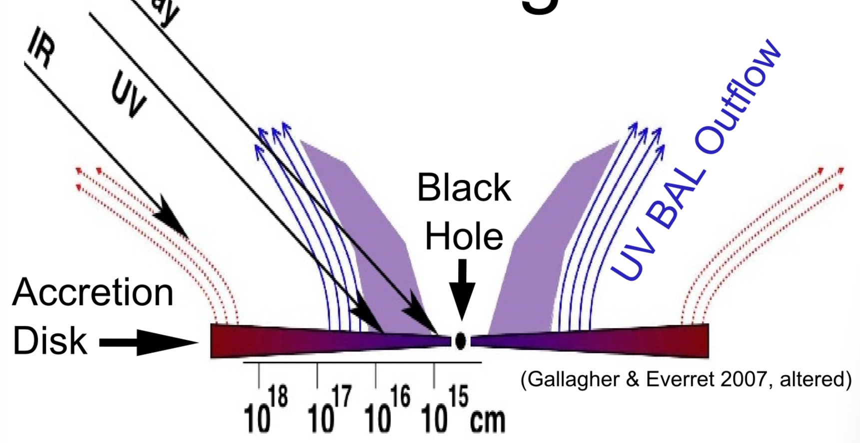
I. Background



Physical conditions in active galactic nucleus outflows remain mysterious. Blueshifted broad absorption lines in the rest frame ultraviolet, present in ~10 to 40% of these nuclei, are manifestations of winds emerging from the central engine at high velocities (Weymann et al. 1991, Gibson et al. 2009, Dai et al. 2008). The strength and structure of these lines elucidate the geometry, velocity, and column density of atomic species in the outflow. Such data help determine outflow acceleration mechanisms (e.g., Leighly et al. 2011) and models of galactic evolution (e.g., Scannapieco & Oh 2004).

FBQS J1151+3822 ($z \approx 0.334$) is the first broad absorption line quasar (BALQSO, $\Delta v \geq 2000$ km/s) known to contain a HeI*λ10830 broad line (Leighly et al.). We use new observations to discover that this quasar is also an Fe low-ionization BALQSO (FeLoBAL), featuring broad FeII and MgII absorption.

Leighly et al. used He I* column density, upper limits on Balmer absorption, dynamical arguments, and the *Cloudy* photoionization code to place loose constraints on the properties of the absorbing gas. We calculate Fe^{+} and Mg^{+} column densities in order to tighten these constraints.

II. Profiles & Templates

Using new spectra obtained with the KPNO 4-meter telescope and RC spectrograph, we observe broad absorption between 2640 and 2800 Å in the quasar's rest frame. At least some of this absorption must be from the MgII doublet at 2800 Å. So in Fig. 1, we plot the apparent optical depth profile such that velocity denotes a blueshift from 2800 Å.

However, MgII is unlikely (e.g., Voit et al. 1993) to be broader than high-ionization lines like HeI*λ10830, observed by Leighly et al. and plotted in red for comparison. Moreover, significant FeII absorption at ~2600 Å and blueward suggests the possibility of iron contamination in regions of our Fig. 1 profile, where the right gas conditions could produce excited state FeII lines. We also note that our profile bears structural similarities to that of HeI*λ10830; similar distributions of optical depth over velocity, particularly from ~1000 to 6000 km/s in Fig. 1, suggest that the MgII and HeI* lines mostly arise in the same gas.

We operate under the assumption that both the MgII and FeII line profiles approximately mimic that of HeI*λ10830. There are no FeII lines between excited states 0.12 and 0.98eV in the observed bandpass, so our FeII lines divide neatly into two groups: Fe+ ions in 0-0.12eV states produce lines only blueward of ~2600 Å, while many in 0.98-1.1eV states contaminate the MgII region. We construct template profiles for each set of atomic species (e.g., Figs. 2 and 3): scaling individual lines by their wavelengths and oscillator strengths, then summing to produce a correctly shaped template.

Fig. 1. Mg IIλ2800 bears structural similarities to the HeI*λ10830 profile.

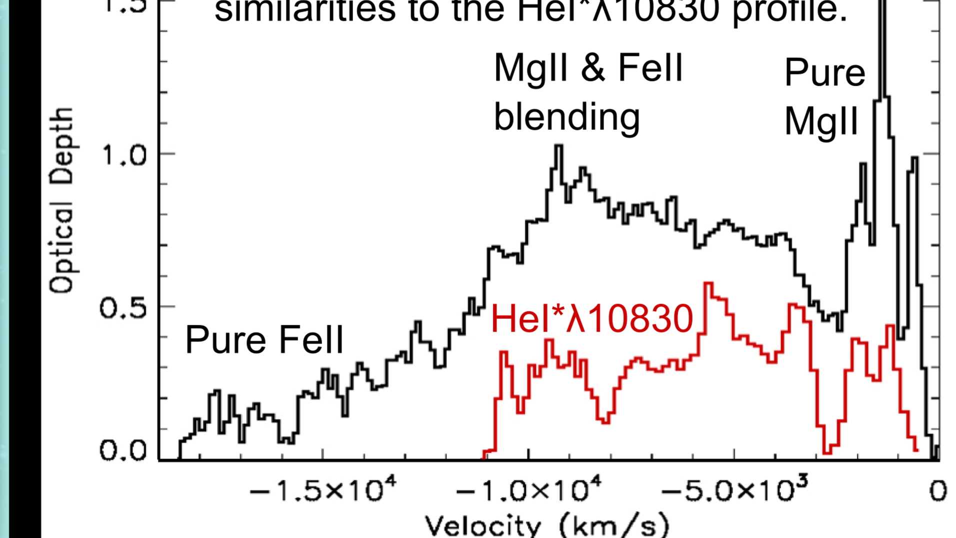


Fig. 2. Template MgIIλ2800 doublet structured to mimic HeI*λ10830.

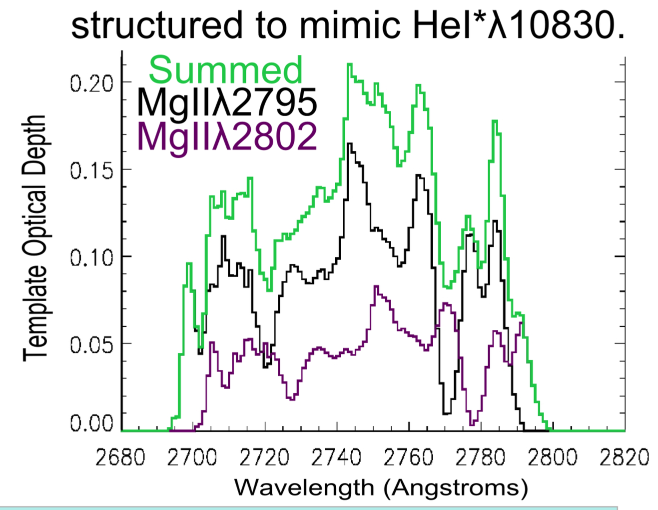


Fig. 3. Similarly constructed FeII 0-.12eV mutliplet template.

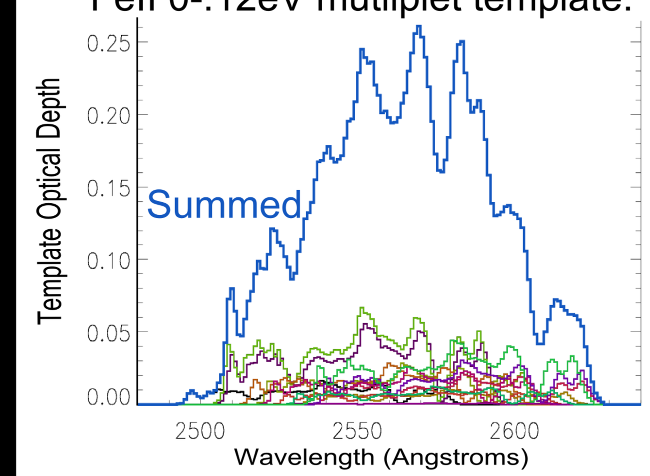
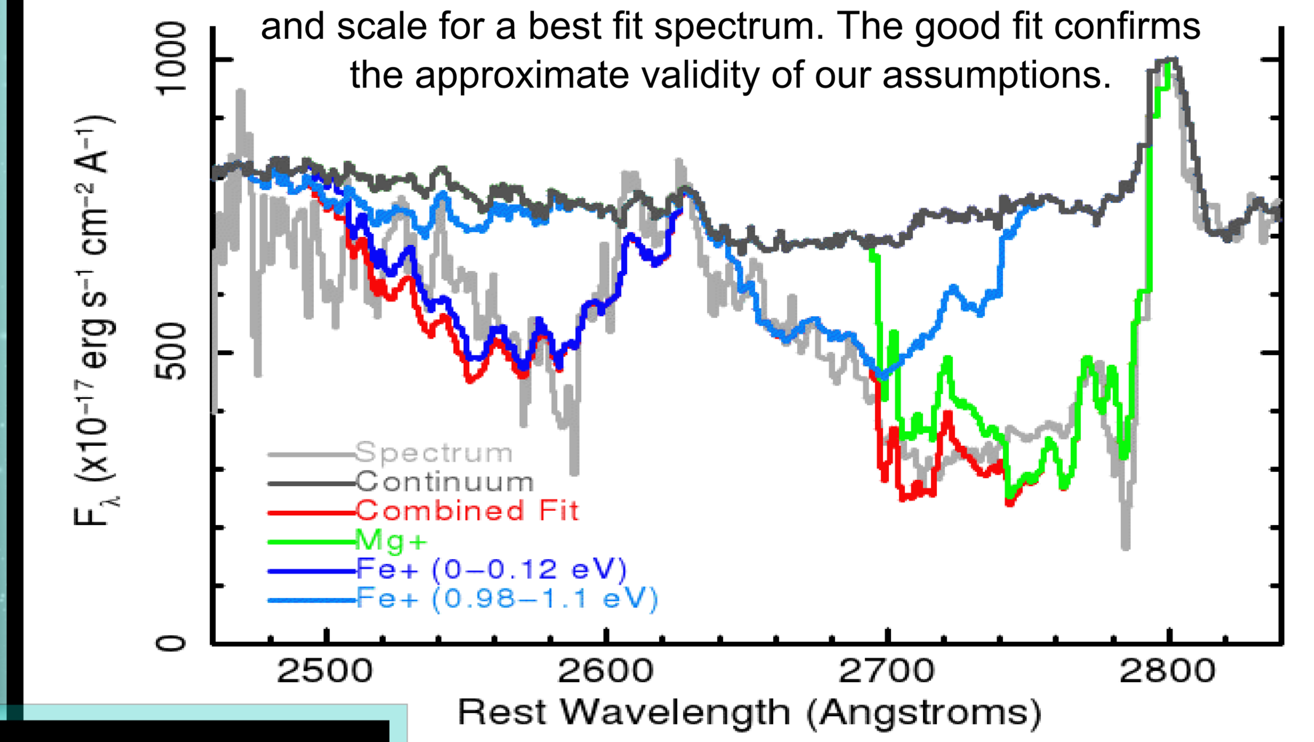


Fig. 4. We make such templates for each set of species and scale for a best fit spectrum. The good fit confirms the approximate validity of our assumptions.



III. Spectrum & Columns

We scale these templates to a χ^2 best fit of our observed spectrum, using PG 1543+489 as a model of the continuum backlight. Integrating, we find apparent log column densities [cm^{-2}] of 15.0 for Mg^{+}, 14.6 for 0-0.12eV Fe^{+}, and 13.7 for 0.98-1.1eV Fe^{+}. For shallow lines like FeII, the conventional average column density is approximately equal to this apparent column density (e.g., Leighly et al.).

In quasar outflows, different ions frequently cover different fractions of the continuum (e.g., Hamann et al. 2001). In this case, the depth of MgII suggests a minimum Mg^{+} mean covering fraction of ~0.45, much higher than the 0.27 mean covering fraction of HeI* established by Leighly et al. However, the FeII lines are sufficiently shallow to be consistent with the HeI* geometry. So we hereafter model a gas that contains the observed Fe^{+} and HeI* average columns together with a high, albeit unspecified, Mg^{+} average column.

IV. Fe^{+} Specifies U

Leighly et al. used partial covering analysis on the 3889 and 10830 components of HeI* to measure a HeI* average log column density of 14.9. HeI* is produced by recombination of He^{+}, and is nearly independent of temperature and density. *Cloudy* modeling could only rule out log ionization parameters of log(U) < -1.4, below which *Cloudy* predicted insufficient HeI*. Higher resolution runs amend that figure to -1.5.

Our measurements of MgII and FeII absorption provide very strong new constraints on the ionization parameter U. As shown in Fig. 5 below, sufficient MgII is produced at log(U) up to at least ~-1.4. But only at the very lowest log(U) of ~-1.5, where HeI* is ionization bounded, is sufficient Fe^{+} found.

This is a consequence of the atomic properties of Mg and Fe. In the HII region, Mg^{+} and Fe^{+} are produced by recombination. The +2→+3 ionization potential for Mg is high, 80.1eV, implying that there is plenty of Mg^{+2} in the HII region. But the similar ionization potential for Fe is 30.7eV, so that iron is distributed among many ionization states in the HII region.

Thus, sufficient Fe^{+} is consistent with the HeI* measured value only at: $\log(U) \approx -1.5$ where the gas is ionization bounded in HeI*.

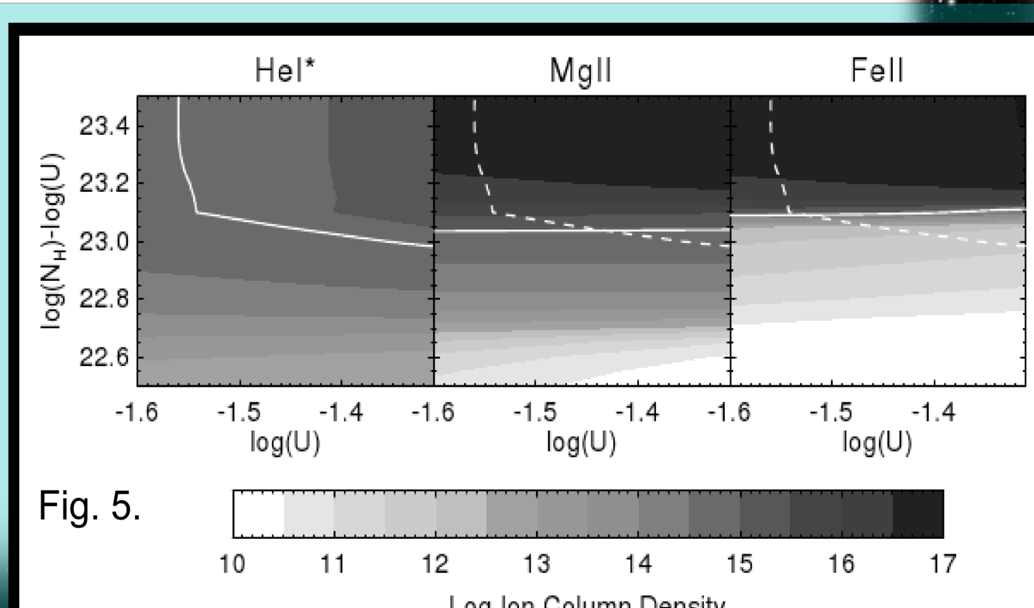
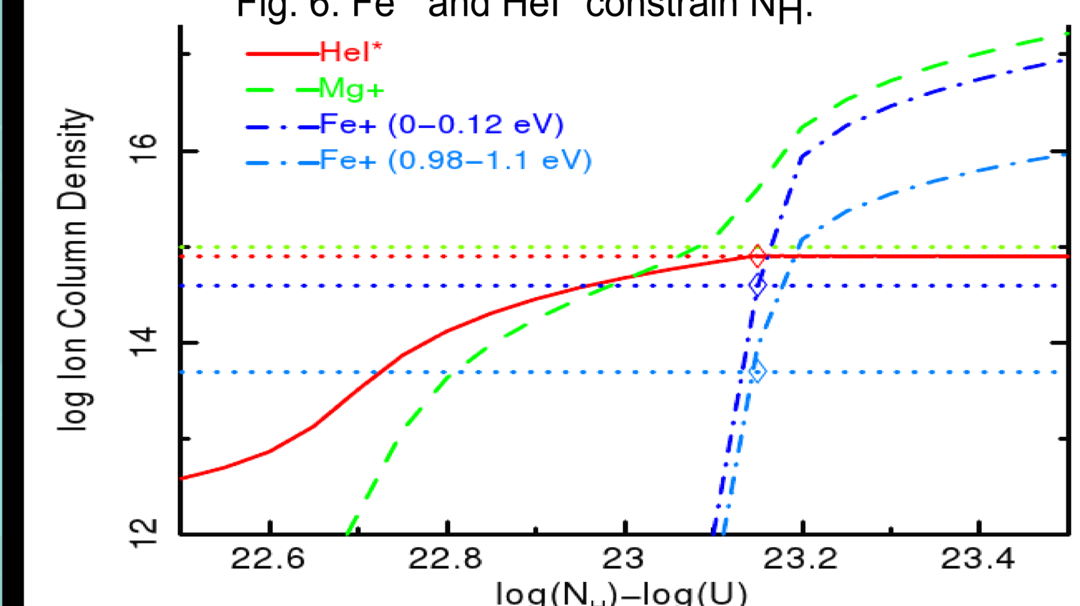


Fig. 5.

Fig. 5. The left panel shows the HeI* column density as a function of log ionization parameter U and the difference of the log hydrogen column density and log U. The solid line marks the location in parameter space where the HeI* column density matches the measured value. The middle and right panels show the Mg^{+} and Fe^{+} column densities. The solid lines show the measured values and the dashed lines show the HeI* curve.

V. More *Cloudy* Constraints

Fig. 6. Fe^{+} and HeI* constrain N_H.



Hydrogen column density N_H is very well constrained by Fe^{+} column density in the regime imposed HeI*. This is because Fe^{+} increases rapidly with N_H, as shown in Fig. 6 (above) for the case where log(U) = -1.5 and the density log(n) = 6.5 [cm^{-3}]. Diamonds denote the position of the best fit for our observed HeI* and Fe^{+} columns; horizontal dotted lines denote observed quantities. Modeled Mg^{+} column density is much greater than the apparent column 15.0 throughout the parameter space permitted by the other ions; we conclude MgIIλ2800 is saturated and exclude it entirely from the fit.

Log(n) is constrained by the excited state Fe^{+} column and upper limits on Balmer absorption to between 5.0 and 7.5. This constrains log(N_H) to between 21.6 and 21.7, absorption-line radius to between 12 and 207 pc, mass flux to between 18 and 257 solar masses / yr, log kinetic luminosity [ergs/s] to between 44.2 and 45.4, and the ratio of kinetic to bolometric luminosity to between 0.3 and 4.5 %.

If we assume that the outflow is accelerated by radiative line driving, Leighly et al. demonstrated that log(n) ≥ 7.0. This constrains log(N_H) to be 21.7, absorption-line radius to between 12 and 21 pc, mass flux to between 18 and 31 solar masses / yr, log kinetic luminosity to between 44.2 and 44.45, and the ratio of kinetic to bolometric luminosity to between 0.3 and 0.5 %.

VI. Broad Implications

Outflow mechanics: Our finding that log(U) is ~-1.5 constitutes new evidence consistent with acceleration by radiative line driving, as Leighly et al. determined that log(U) must be below ~0.2 for radiative line driving to be the acceleration mechanism in FBQS J1151+3822.

Quasar↔host feedback: Typical models have predicted that outflow kinetic to bolometric luminosity ratios of at least ~5% are necessary to truncate star formation in AGN host galaxies; Hopkins & Elvis (2010) suggest that this number should rather be ~0.5% in some circumstances. If we assume acceleration by radiative line driving, our results are sufficient only for the Hopkins & Elvis minimum.

FeLoBALs and evolution: LoBALs appear to be coeval with host mergers and consequent bursts of star formation (Canalizo & Stockton 2001). Farrah et al. suggest that *Fe*LoBALs specifically may be an evanescent transition as starburst nears its end (2007), and find that FeLoBAL outflow strength is anti-correlated with host starburst luminosity (2012). FeLoBAL outflow strengths are therefore of great importance to models of galactic evolution and feedback. FBQS J1151+3822 is a notably low-redshift FeLoBAL and conducive to further study.

VII. References and Acknowledgments

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VIII. Summary

FBQS J1151+3822, which last year became the first HeI*λ10830 BALQSO to be discovered, is also one of the nearest FeLoBALs. Fe^{+} log average column density in the outflow is ~14.65 (preliminary). Log ionization parameter in the outflow is then constrained by FeII, MgII, and HeI* columns to be -1.5, which is consistent with acceleration by radiative line driving. Assuming that the outflow is accelerated by this mechanism, the aforementioned columns necessitate that log(N_H) is 21.7, absorption-line radius is between 12 and 21 pc, mass flux is between 18 and 31 solar masses / yr, log kinetic luminosity is between 44.2 and 44.45, and the ratio of kinetic to bolometric luminosity is between 0.3 and 0.5 %.