A Self-Consistent NLTE-Spectra Synthesis Model of FeLoBAL QSOs

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Abstract

We present detailed radiative transfer spectral synthesis models for the Iron Low Ionization Broad Absorption Line (FeLoBAL) active galactic nuclei (AGN) FIRST J121442.3+280329 and ISO J005645.1-273816. Detailed NLTE spectral synthesis with a spherically symmetric outflow reproduces the observed spectra very well across a large wavelength range. While exact spherical symmetry is probably not required, our model fits are compelling and thus very large covering fractions are strongly implied by our results. We constrain the kinetic energy and mass in the ejecta and discuss their implications on the accretion rate. Our results support the idea that FeLoBALs may be an evolutionary stage in the development of more "ordinary" QSOs.

Introduction

Understanding absorption and emission lines in quasars is fundamental for understanding the quasar central engine, as well as how the quasar and galaxy are connected.

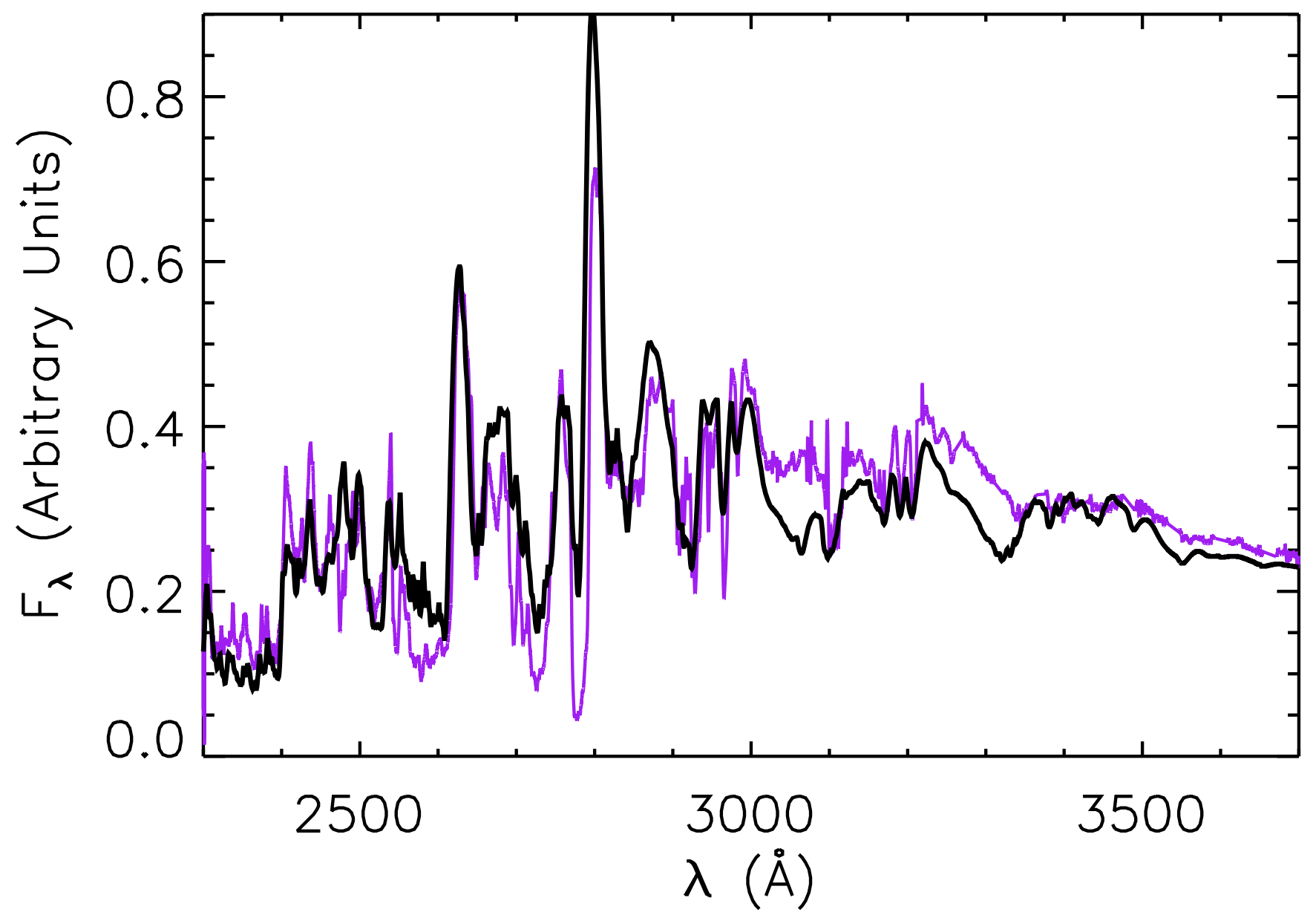
It is very difficult to constrain the Kinetic Luminosity of the winds. While the presence of the blue-shifted absorption lines unequivocally indicates the presence of high-velocity out-flowing gas, the other fundamentally important properties of the gas, including the density, column density, and covering fraction are very difficult to constrain.

The traditional techniques for analysis of troughs (e.g., curve of growth) and modeling (e.g., photoionization modeling to produce absorption line ratios and equivalent widths) are limited. An approach that may be profitable is to construct a physical model for the outflow, and constrain the parameters of the model by the data.

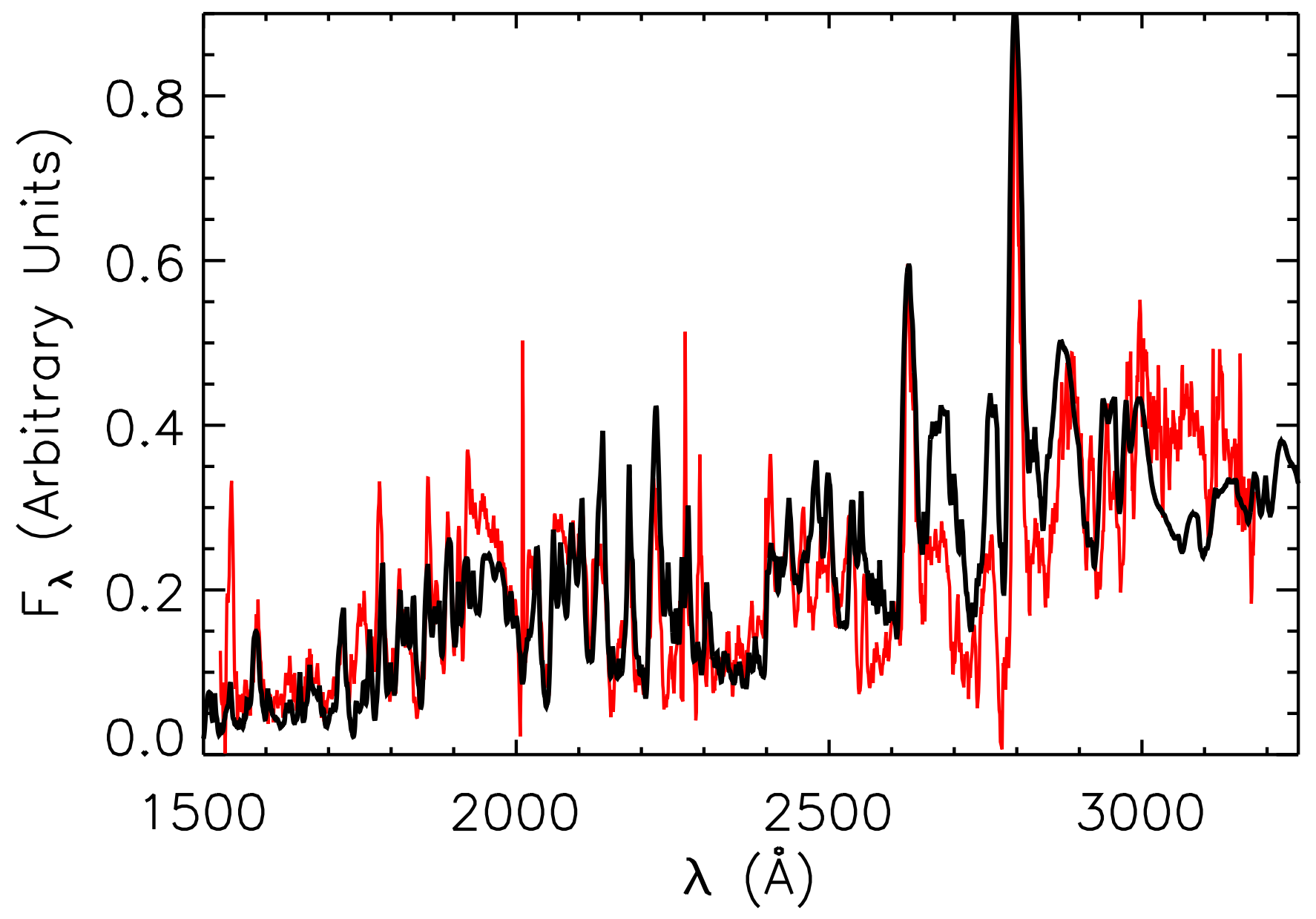
We use a model in which the emission and absorption are produced in the same out-flowing gas. The first foray into constructing physical models for quasar winds was performed by Branch et al. (2002). In that paper, they modeled Iron Low-Ionization Broad Absorption Line (FeLoBAL) spectra FeLoBALs are distinguished by the presence of absorption in low-ionization lines such as Al III and Mg II as well as absorption by excited states of Fe II and Fe III. FIRST J121442.3+280329 was modeled using `SYNOW`, a parameterized, spherically-symmetric, resonant-scattering, synthetic spectrum code.

We test these ideas by using the generalized stellar atmosphere code `PHOENIX` to model the spectra of the two FeLoBALs that were successfully modeled using `SYNOW`, and including spectra that extend to rest-frame optical wavelengths for the FeLoBAL QSO FIRST J121442.3+280329. `PHOENIX` is a much different code than `SYNOW` in that it contains all the relevant physics to determine the spectrum of out-flowing gas. It solves the fully relativistic NLTE radiative transfer problem including the effects of both lines and continua in moving flows. We find that `PHOENIX` is able to model the spectra from these objects surprisingly well, and we are able to derive several important physical parameters from the model.

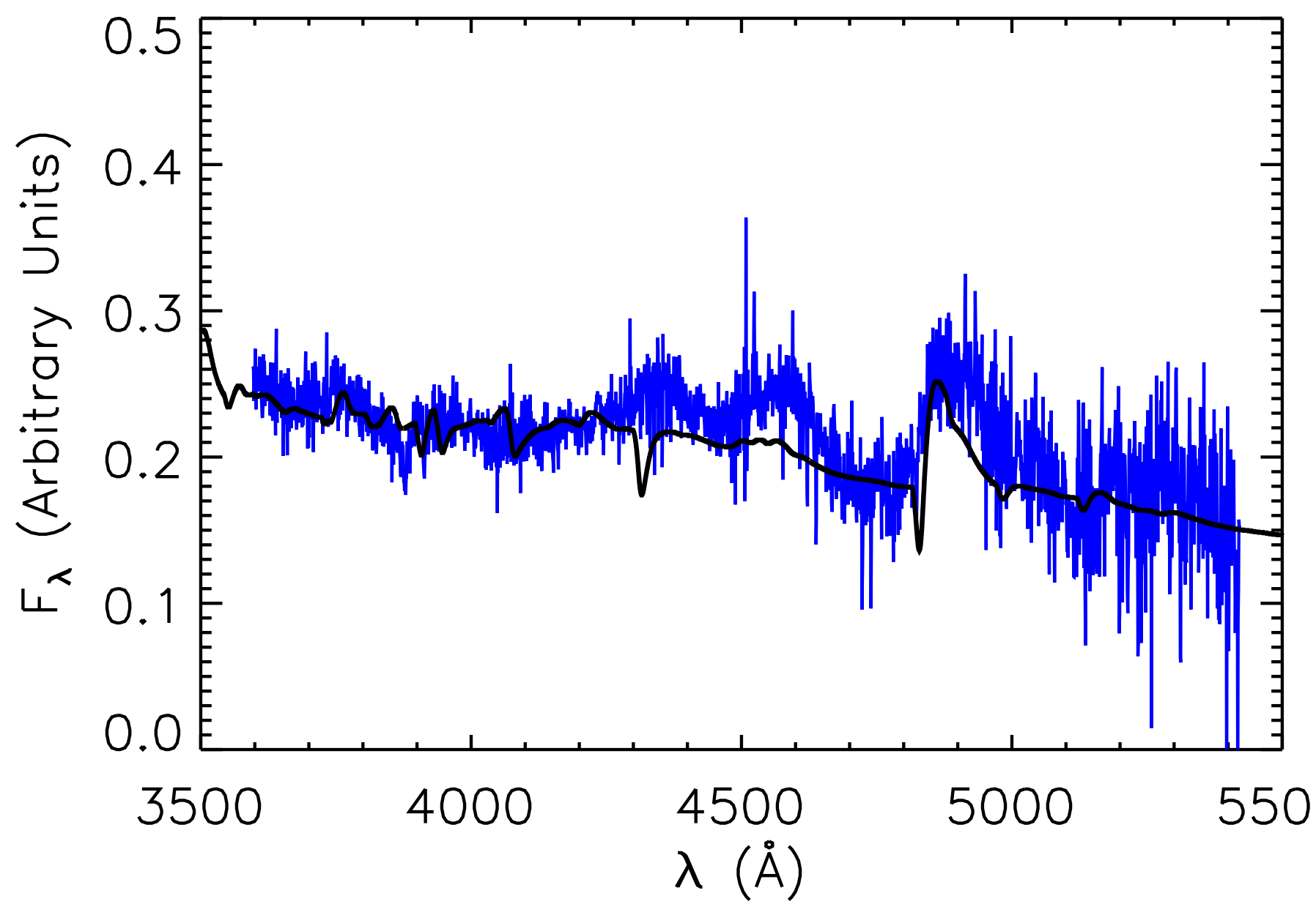
FIRST J121442.3+280329 UV



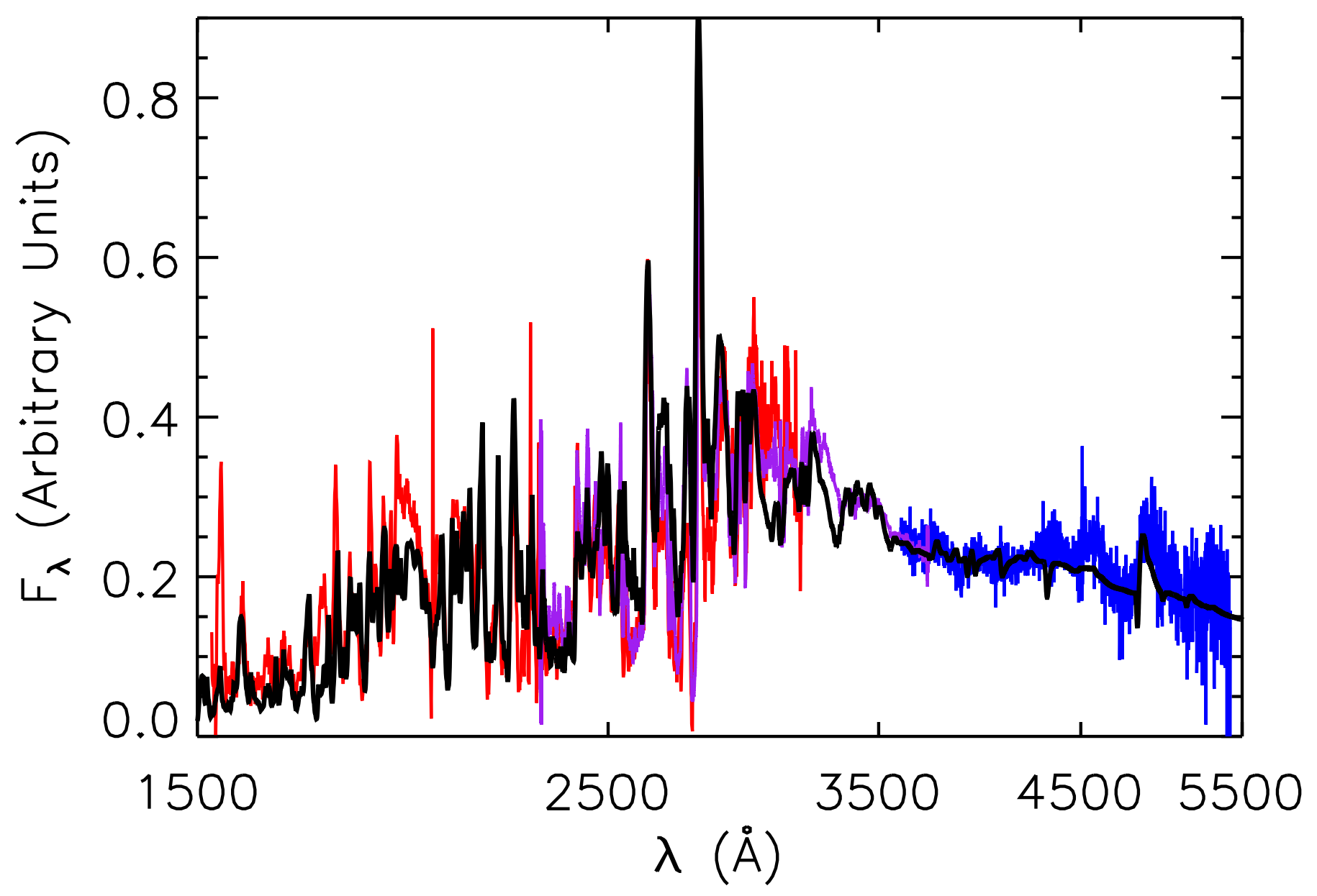
ISO J005645.1-273816 UV



FIRST J121442.3+280329 Opt



Combined Spectra



The `PHOENIX` Model Compared with the Observed Spectra

All figures above show the `PHOENIX` model spectrum in black compared with the observed data in color. Because of the similarity of the spectra of FIRST J121442.3+280329 and ISO J005645.1-273816, we combine the observed spectra while keeping the color scheme displayed in the first three figures for the Combined Spectra figure. The spectra are deredshifted into their rest-frame and dereddened..

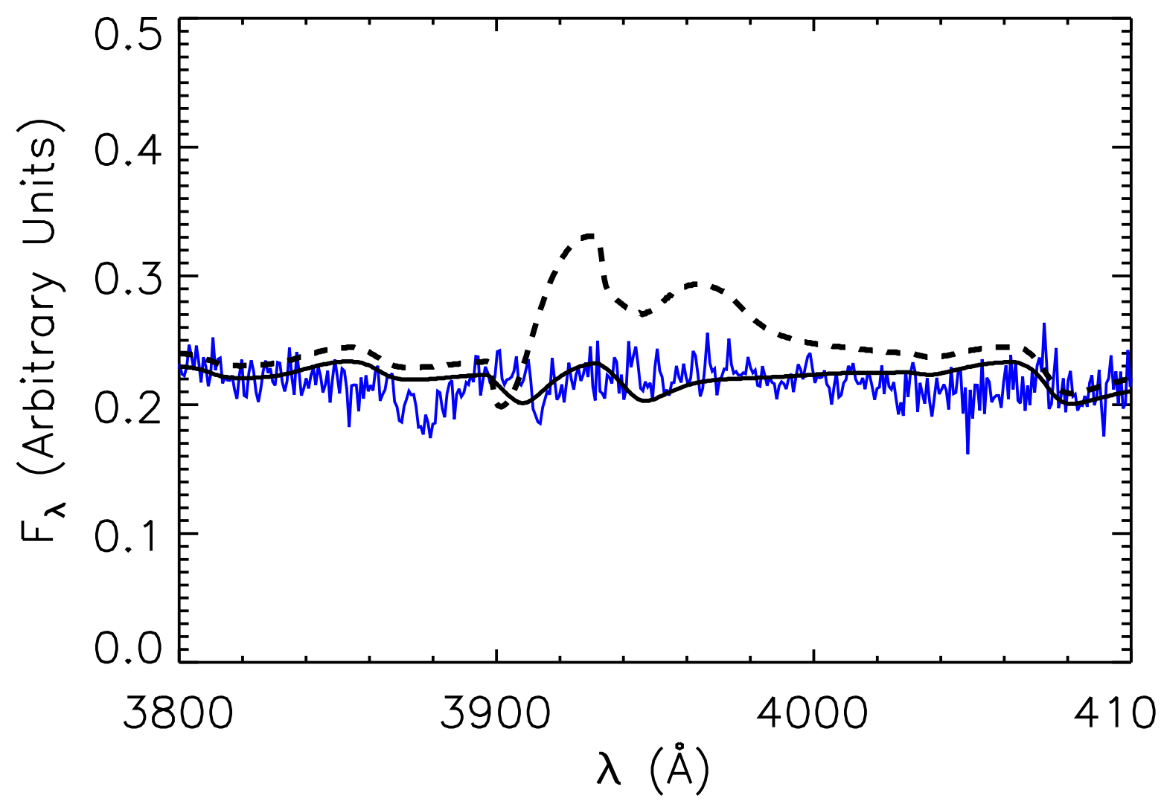
The `PHOENIX` Model Best-Fit Parameters and Physical Constraints

The model atmospheres are characterized by the following parameters : (i) the reference radius R_0, which is the radius where the continuum optical depth in extinction (τ_{std}) at 5000Å is unity; (ii) the model temperature T_{model}, which is defined by means of the luminosity, L and the reference radius, R_0, [$T_{model} = (L/(4\pi R_0^2\sigma))^{1/4}$], where σ is Stefan's constant; (iii) the density structure parameter v_e, [$\rho(v) \propto e^{-v/v_e}$]; (iv) the expansion velocity v_0, at the reference radius; The best-fit parameters for FIRST J121442.3+280329 and ISO J005645.1-273816 are: $T_{model} = 4600$ K, $R_0 = 1.4 \times 10^{17}$ cm, $v_e = 300\ \mathrm{km\ s^{-1}}$, and $v_0 = 2100\ \mathrm{km\ s^{-1}}$.

The synthetic model has $547 M_\odot$ and kinetic energy 30×10^{51} ergs above the "photosphere" ($\tau_{std} = 1$). With $R_0 = 1.4 \times 10^{17}$ cm and maximum velocity $v_{max} = 2860\ \mathrm{km\ s^{-1}}$we estimate a crossing time of $t \simeq\ R_0/v_{max} = 15.5$ yr. We estimate the mass loss rate using $\dot{M} \simeq M/t = 35\ \mathrm{M_\odot\ yr^{-1}}$ which is $1/5$ the mass loss rate in our `PHOENIX` model of $\dot{M} = 159\ \mathrm{M_\odot\ yr^{-1}}$. The kinetic energy luminosity is estimated at $\dot{E}_k \simeq E_k/t = 4.3 \times 10^{43}$ erg s^{-1} which is two orders of magnitude lower than the bolometric luminosity of the model $L_{bol} = 6.3 \times 10^{45}$ erg s^{-1}, thus the flow could be luminosity driven.

Our `PHOENIX` models have a maximum column density of $2 \times 10^{25}\ \mathrm{cm^{-2}}$ for the entire atmosphere and a column density of $2 \times 10^{24}\ \mathrm{cm^{-2}}$ for the region above the "photosphere" $\tau_{std} = 1$.

NLTE vs LTE for Ca II



NLTE vs LTE for Ca II

The figure above shows the importance of NLTE effects in correctly modeling spectra. The solid line has all the species that we included in these calculations in NLTE, whereas the dashed line has everything in NLTE except for Ca I-III. Notice how NLTE is REQUIRED to match the observed spectrum.

Distances

As our models predict the absolute flux we can measure distances to these objects. We use the SEAM method (Baron et al. 1995 and others). Using $m_B = 17.06$ for FIRST J121442.3+280329 we find $\mu = 42.56$ or $d_L = 3.25$ Gpc, which compares favorably with the luminosity distance inferred for our adopted cosmology ($\mathrm{H_0} = 70$, $\Omega_\mathrm{M} = 0.3$, $\Omega_\Lambda = 0.7$) $d_L = 4.2$ Gpc. Using $m_B = 22.74$ for ISO J005645.1-273816 we find $\mu = 46.59$ or $d_L = 20.8$ Gpc, which is a bit high compared with the luminosity distance inferred for our adopted cosmology $d_L = 13.4$ Gpc.

Conclusions

With detailed synthetic modeling using `PHOENIX` we calculate synthetic models which are very good fits to one subtype of FeLoBAL. We are able to determine a luminosity distance estimate which is direct and is accurate to around 50%. Could these objects be used as distance indicators at high z,even if only as a sanity check on the really high-z Hubble diagram from GRBs? While our models are limited to exact spherical symmetry, they provide excellent fits. In order to reconcile our results with the polarization data on these objects we would require a jet, which would only modestly affect the flux spectrum. Our results lend support to the inference that FeLoBALs are an evolutionary stage of the QSO as opposed to a pure orientation effect. Our model with a smaller covering factor may be able to explain other BAL QSO such as overlapping trough QSO's. A constant outflow cannot be disregarded. In addition our model column densities, which are compton thick, match those that are expected from X-ray observations of these objects.