Anisotropic Diffuse Continuum Emission in the Broad Line Region - a Case Study for NGC 5548

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1 Introduction

2 Pressure-law Broad-line Region Models

We denote models for which the pressure P depends on the radius r as

$$P(r) \propto r^{-s}.$$

as pressure-law BLR models. In this work we examine the extreme cases, $s = 0$ and $s = 2$. Evidently, $s = 0$ corresponds to a constant pressure as a function of radius; we show below that $s = 2$ corresponds to a constant ionization parameter. A power-law pressure distribution leads to the following relations (e.g., Rees+1989, Goad+1993). Assuming that the clouds have a constant temperature, the cloud hydrogen density $n_{\mathrm{H}}$is proportional to the pressure:

$$n_{\mathrm{H}}(r) \propto r^{-s}$$

The ionization parameter U at ionizing photon-counting flux $Q(\mathrm{H})$ is defined as:

$$U = \frac{Q(H)}{4\pi r^2 c n_{\mathrm{H}}}$$

Thus, $s = 2$ corresponds to a constant ionization parameter.

$$U(r) \propto r^{s-2}$$

The surface area per cloud, A_c, is proportional to R_c^2, where R_c denotes the radius of a cloud. In general, R_c depends on the pressure P, and is therefore constant for $s = 0$. If we demand that the mass of each cloud is conserved as the clouds move radially (i.e., clouds do not break up or coalesce within our region of interest), mass conservation implies that $R_c^3 n_H$ is constant. Thus, we obtain the relation

$$A_c(r) \propto R_c^2(r) \propto r^{2s/3}.$$

The column density of each cloud, $N_{\rm col}$, depends on the gas density and cloud radius:

$$N_{\rm col}(r) \propto R_c n_{\rm H} \propto r^{-2s/3}$$

Evidently, both the column density $N_{\rm col}$ and the cloud density $n_{\rm H}$ are constant for $s = 0$. Therefore, for the constant-pressure case, we work with constant-$n_{\rm H}$ slices through $\log(n_{\rm H})$, $\log(\Phi({\rm H}))$ grids generated at a single value of $N_{\rm col}$. For $s = 2$, the ionization parameter is constant. Such models correspond to diagonal lines through grids of $\log(n_{\rm H})$ and $\log(\Phi({\rm H}))$, with $N_{\rm col}$ decreasing with radius.

3 Method: from *Cloudy* Grids to BLR Models

3.1 Photoionization Modeling Using *Cloudy*

include info on the grids supplied by Otho - cloudy version, assumptions, min/max values and step sizes etc. perhaps include some phi vs nH contour plots for a couple lines, a couple continuum wavelengths. include info + plot of incident continuum, Mehdipour+2014

3.2 Line Luminosities and Effective Radii

Our model assumes that the BLR clouds do not self-shadow, and that there is no reddening between the nuclear continuum and the inwards-facing cloud surface. In that case, the ionizing continuum for a given cloud is inversely proportional to its distance from the continuum source. We parametrize the radial dependence of $\log(\Phi({\rm H}))$as

$$\log(r) = -0.5(\log(\Phi({\rm H})) - 20) + 15.413 + r_{20}. \tag{3.1}$$

Here, r_{20} is the radius (in lightdays) at which $\log(\Phi({\rm H}))$=20. This is a function of the luminosity and continuum SED shape of the nuclear source; for NGC 5548, $r_{20} \approx 14.8$ lightdays for the AGN STORM observing campaign, using the Mehdipour et al. continuum SED (§3.1). We use Equation 3.1 to relate the pressure-law relations of §2 to the $N_{\rm col}$, $n_{\rm H}$, $\Phi({\rm H})$ grids produced by *Cloudy*.

The total luminosity for a BLR line is given by the integral

$$L = 4\pi \int_{r_{\rm in}}^{r_{\rm out}} \epsilon(r) A_c(r) n_c(r) r^2 dr$$

Here, ϵ denotes the line emissivity per cm^2 of cloud surface, and $n_c(r)$ is the number density of clouds. Assuming a power-law distribution $n_c \propto r^{-p}$, and virial motion of the clouds ($v(r) \propto r^{-1/2}$), mass conservation implies the following relation for the differential covering factor:

$$dC(r) \propto A_c(r) n_c(r) dr \propto r^{2s/3-3/2} dr$$

This relation allows us to determine a normalization constant $K(s, r_{\rm in}, r_{\rm out})$ for the total line-emitting surface of the clouds, assuming total coverage of the central source (in this formalism, the solid angle Ω covered 'as seen from the source' follows $d\Omega = dA_c n_c / r^2$). The luminosity integral becomes:

$$L = 4\pi K \int_{r_{\rm in}}^{r_{\rm out}} \epsilon(r) r^{2s/3+1/2} dr. \tag{3.2}$$

The resulting line luminosities depend on the inner and outer BLR radii, and on the total covering fraction of the BLR; the latter dependence corresponds to a linear scaling of K. The dependence of L on $r_{\rm in}$ is strong for $s = 0$, in the sense that smaller inner radii lead to smaller integrated luminosities - this is due to the model distributing most of the clouds close to the inner radius, where they become overionized at small $r_{\rm in}$. To start with we assume total coverage of the continuum source, so as to obtain an upper limit on the line luminosities attainable. We assume an inner BLR radius of 1 lightday (as suggested by RM monitoring), and an outer radius of 140 lightdays (as set by the dust sublimation radius for our adopted source luminosity) details needed on rin rout determination!.

3.2.1 Responsivity-Weighted Radii

The luminosity weighted effective radius of the BLR for a given line is given by the centroid of the differential luminosity as a function of radius:

$$r_\epsilon = \frac{\int_{r_{\rm in}}^{r_{\rm out}} r \, \mathrm{d}L_{\rm line}(r)}{\int_{r_{\rm in}}^{r_{\rm out}} \mathrm{d}L_{\rm line}(r)}.$$

If the emission of each BLR cloud varied in strength on a 1:1 ratio with respect to the nuclear continuum variation, r_ϵ would also represent the observed effective reverberation radius. However, the response of realistic BLR clouds to continuum variation depends on the properties of the line transition, on the thermodynamic properties of the clouds, and on the steady-state value of (and the change in) $\Phi(\mathrm{H})$. Locally, we define the responsivity η for a given BLR cloud as:

$$L_{\rm line}(\mathrm{cloud}) \propto \Phi(\mathrm{H})^\eta$$

Thus, for a spherically symmetric pressure-law BLR with a given steady-state continuum luminosity, each emission line has a responsivity that depends on the distance from the central source. For $\eta = 1$ at all radii, the equivalent width of each line is constant as a function of continuum luminosity, and the effective variability radius of the BLR is equivalent to r_ϵ. Otherwise, we define the effective variability radius as

$$r_\eta = \frac{\int_{r_{\rm in}}^{r_{\rm out}} r \eta(r) \mathrm{d}L_{\rm line}(r)}{\int_{r_{\rm in}}^{r_{\rm out}} \eta(r) \mathrm{d}L_{\rm line}(r)}. \tag{3.3}$$

In the linear regime (i.e., small luminosity fluctuations), the responsivity is simply the logarithmic slope of the $\log(\Phi(\mathrm{H}))$ versus ϵ relationship. In practice, given our assumption that there is no internal extinction or cloud shadowing in the BLR, a change in ionizing flux corresponds to an instantaneous 'shift' of the clouds along the radial axis, allowing us to measure η as

$$\eta = \frac{d\log(\epsilon)}{d\log(\Phi(\mathrm{H}))} = -\frac{d\log(\epsilon)}{0.5 d\log(r)}. \tag{3.4}$$

3.3 Anisotropic Emission

4 Results

4.1 Steady-State Models

4.2 $s = 0$

Figure 4.4 shows the line luminosity ratios produced for the Lyα, CIV, Hβ and He II 4686Å emission lines, as a function of n_{H}, for $22 \leq \log(N_{\mathrm{col}}) \leq 24$. Ideally we want these luminosities to be larger than the observed, dereddened line luminosities, as this will allow us to assume a smaller covering fraction - our model does not take BLR self-shadowing into account, so becomes unreliable at high covering fractions. At $n_{\mathrm{H}} \sim 11$, our $s = 0$ model can exceed the observed broad-line luminosities for Lyα and CIV, but has trouble reproducing the observed Hβ emission.

In Figure 4.3 we compare the luminosity-weighted radii with resposivity-weighted radii. Thus, $\eta = 1$ implies that the equivalent width of a line is constant for a small change in the ionizing flux level. The responsivity-weighted radii are more relevant to RM campaigns, as they give the radius at which we will preferentially see emission line response to continuum variations. For these emission lines, we tend to see larger emissivity-weighted radii compared to luminosity-weighted, i.e, the gas at larger radii responds more strongly to the continuum flux.

Note: at very low densities $\log n_H < 8$, the responsivities are negative for much of the inner region of the BLR - and, as the BLR is sparsely sampled in Φ here, there are likely numerical issues with my code, giving strongly negative responsivity-weighted radii here - need to look into this more!

4.3 $s = 2$

4.4 The Diffuse Continuum

The 'diffuse continuum' is the continuum emission produced by the BLR clouds themselves. The *Cloudy* grids provided include the diffuse continuum emissivity in several wavelength bands, again as a function of n_H, $Phi(H)$, and N_{col}; we integrate the total luminosity of each of these bands in the same way as for the emission lines, providing a spectrum of νL_ν as a function of wavelength for the diffuse continuum (Figure 4.6, top left). We note the strong Balmer continuum feature at wavelengths below the Balmer break ~ 3646 Å. Using the same

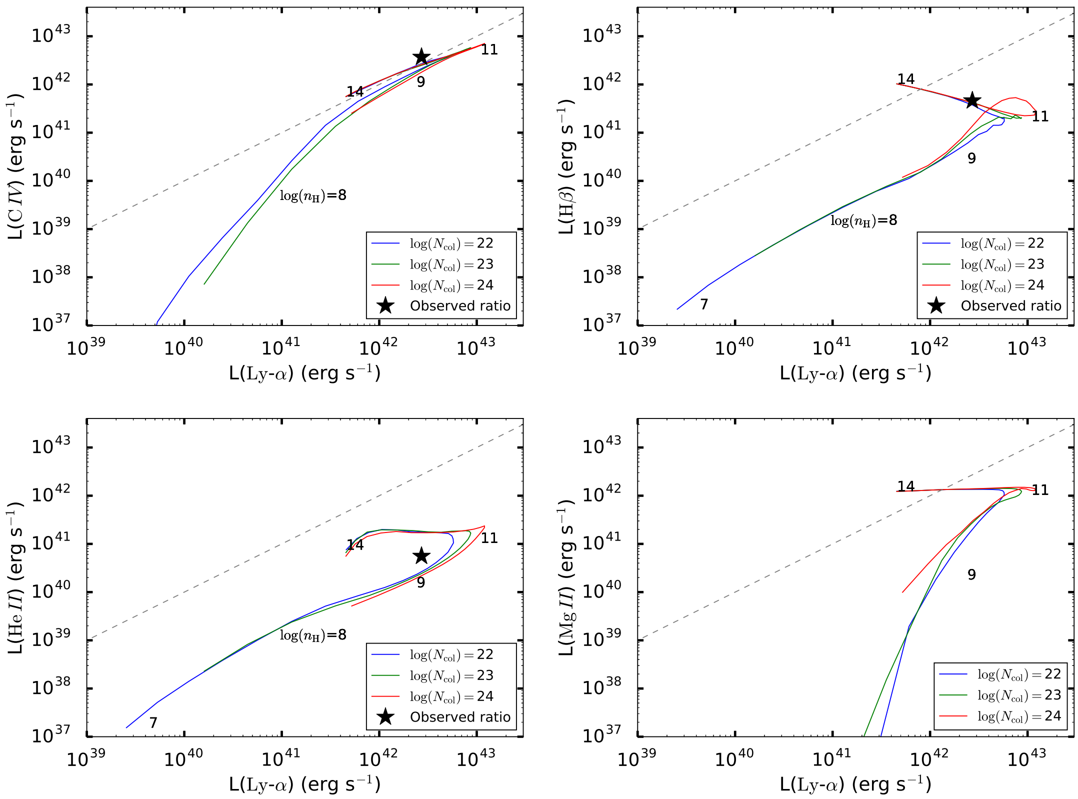

Figure 4.1: Line luminosity ratios for CIV, Hβ, He II 4686Åand Mg *II*, relative to Lyα, for the $s = 0$ (constant pressure) steady-state model. The black stars represent the observed, dereddened line ratios, after subtraction of a narrow-line component (CITE DeRosa+17 for UV, Pei+17 for opt., K+G2000 for UV line decomposition, Peteson+199 for Hbeta decomposition.). These values of $L_{\rm line}$ assume that the BLR covers 4π str of the continuum source (see discussion in 4.1).

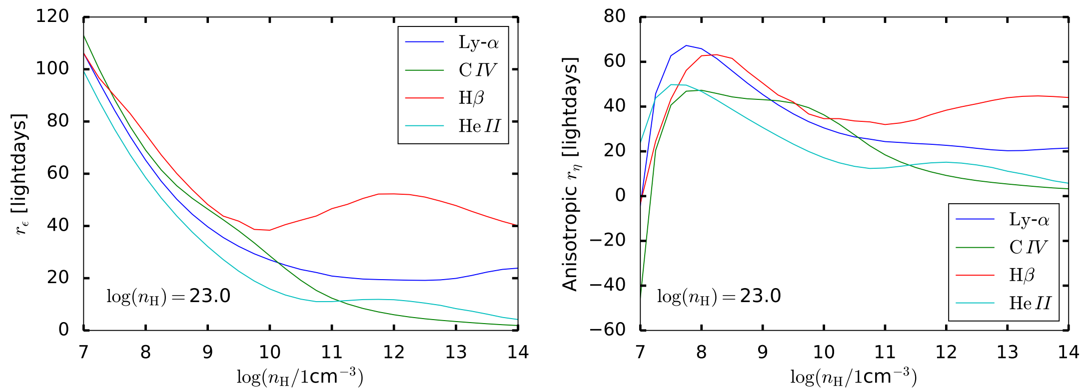

Figure 4.2: Effective BLR radii as a function of n_H for $s = 0$ models with $\log(N_{col})$=23, using isotropic emission with emissivity-weighting (left panel) and anisotropic emission with responsivity-weighting (right panel).

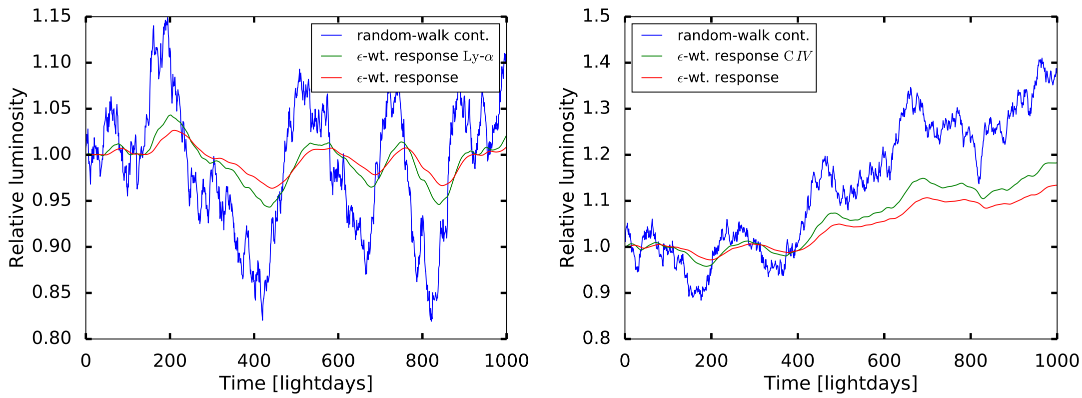

Figure 4.3: Driving the emission lines with a random-walk continuum.

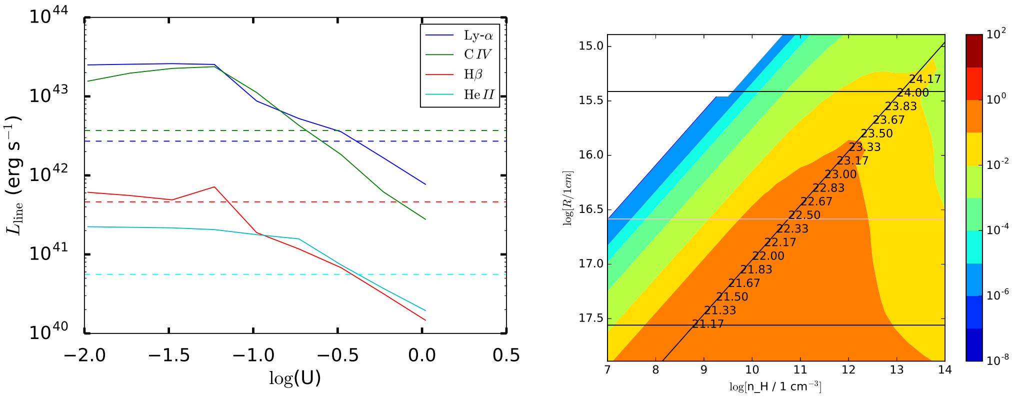

Figure 4.4: *Left:* Line luminosities for Lyα, CIV, Hβ, and He II 4686Å, for the $s = 2$ (constant ionization parameter) steady-state model. These values of $L_{\rm line}$ assume that the BLR covers 4π str of the continuum source (see discussion in 4.1). *Right:* Contours of line emissivity (relative to that of the ionizing continuum) for Lyα, for log($N_{\rm col}$)=23. Horizontal black lines show $r_{\rm in}$=1 lightday and $r_{\rm out}$=140 lightdays. The diagonal line shows the trajectory of our $s = 2$ model with $\log(U) = -1.22$ in r, Φ(H)-space; the appropriate values of $N_{\rm col}$ at each radius are shown along the line, for a model normalized at $\log(\Phi({\rm H}))(r_{20}) = 22.5$.

Mehdipour et al. continuum SED used to generate the *Cloudy* grids, we calculate the ratio of diffuse continuum to total (nuclear + diffuse) as a function of wavelength. As for the emission lines, we calculate the luminosity-weighed and emissivity-weighted radii for the diffuse continuum, and the effect of diluting the diffuse continuum emission with the appropriate fraction of nuclear-continuum light (assuming the latter is a point-source). EXPAND It is interesting that these models predict elevated continuum delays near the Balmer break, relative to the $R \propto \lambda^{-4/3}$ dependence suggested for emission from the surface of an accretion disk.

5 Discussion

Comparison with anomalous lag feature seen in UVOT monitoring, Fausnaugh+ paper. Need to drive continuum at relevant UVOT pivot wavelength and measure lag, for various continuum variability amplitudes!

6 Conclusion

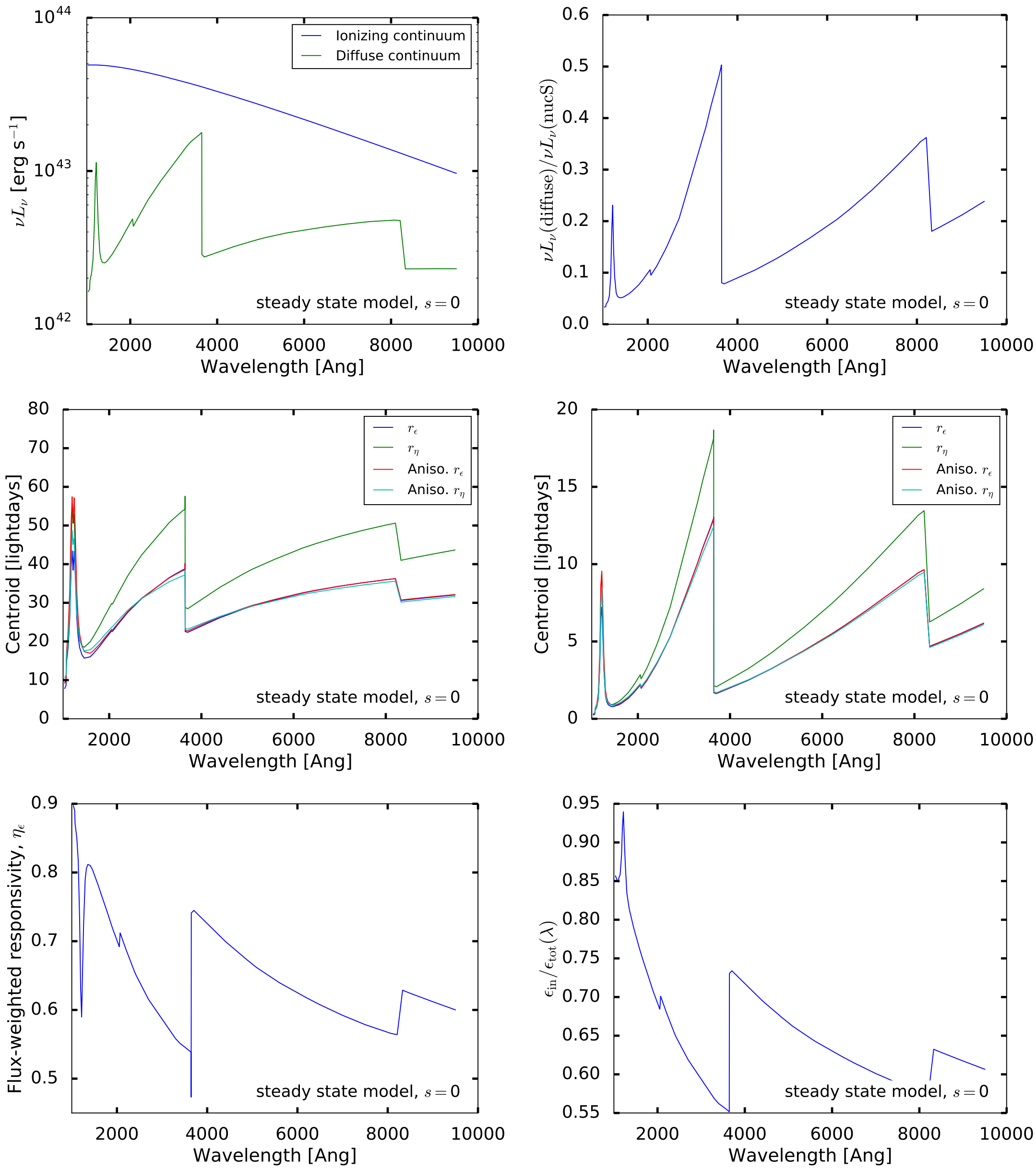

Figure 4.5: Top left: diffuse BLR continuum νF_{nu} as a function of wavelength,for the $s = 0$ steady state model ($\log(N_{\mathrm{col}})$=22.5, $\log(n_{\mathrm{H}})$=10.75). Top right: Ratio of diffuse continuum to total (nuclear + diffuse) continuum luminosity, as a function of wavelength. Center left: Effective radii for the diffuse continuum. Center right: effective radii for the total + diffuse continua, assuming that the nuclear continuum is a point source at all wavelengths. Bottom left: the emissivity-weighted responsivity of the diffuse continuum. Bottom right: the ratio of inward to total emission for the diffuse continuum (i.e., the F factor, §3.3.)

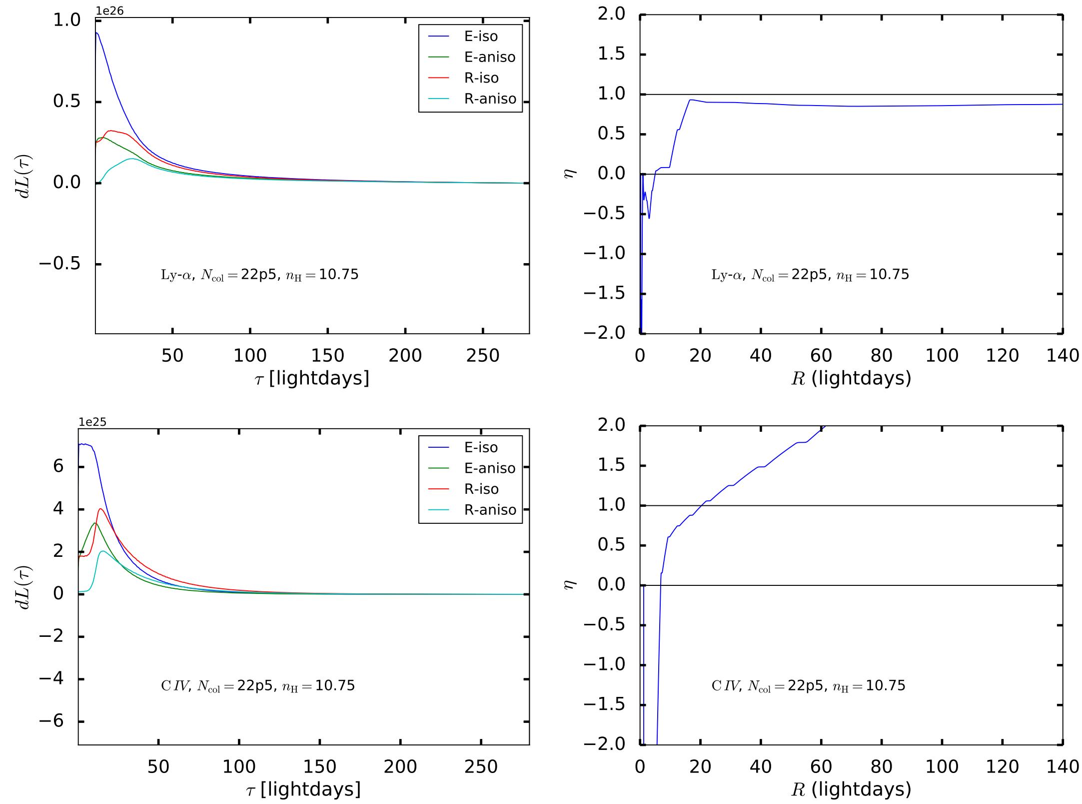

Figure 4.6: Top left: The line response function for Lyα, for our $s = 0$ steady state model, including various effects EXPAND!. Top right: The responsivity function for Lyα. Bottom row: same for CIV.

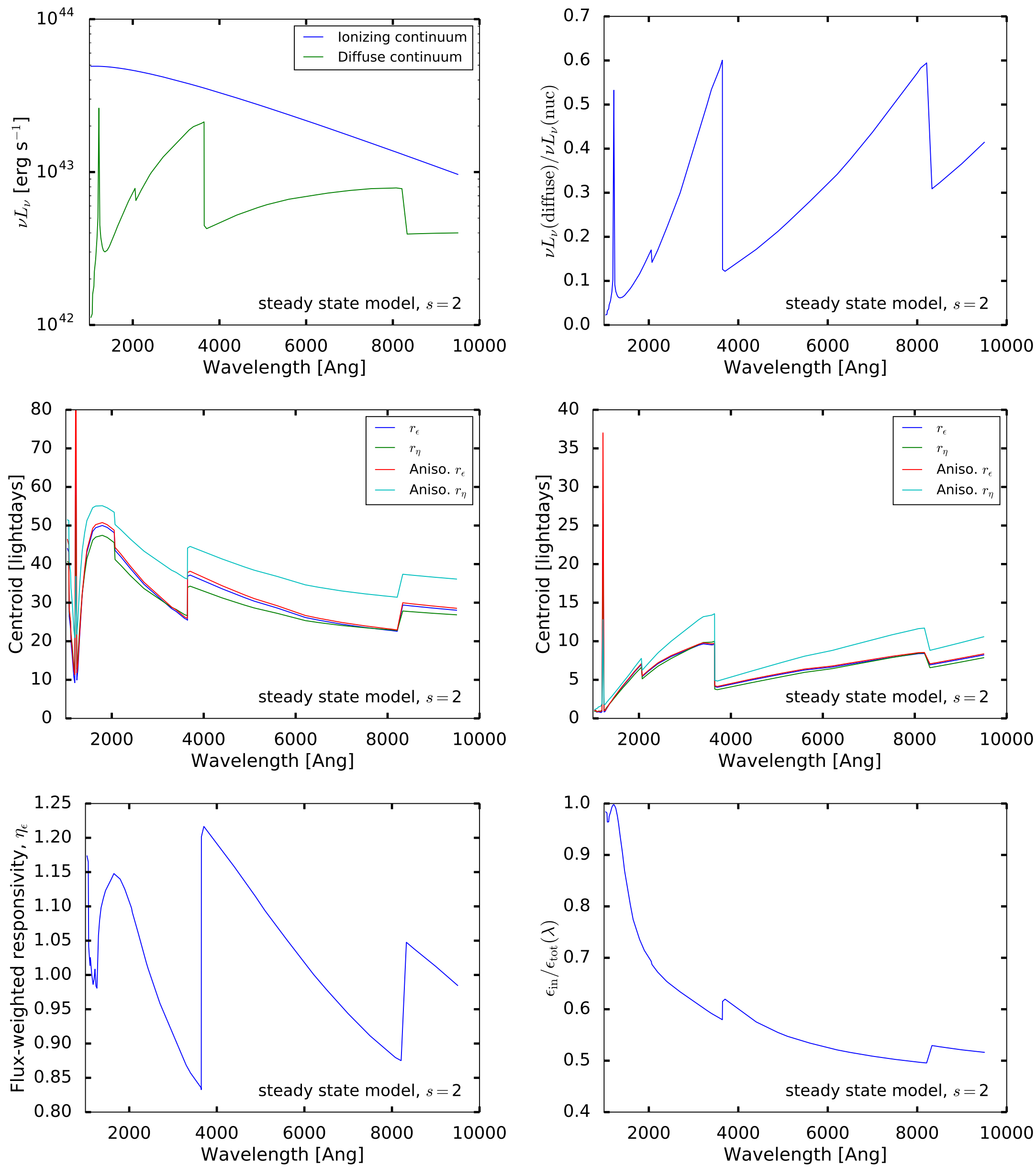

Figure 4.7: As Figure 4.6, but for the $s = 2$ steady state model ($\log(U) = -1.23$, $\log(N_{\mathrm{col}})r_{20} = 22.5$).