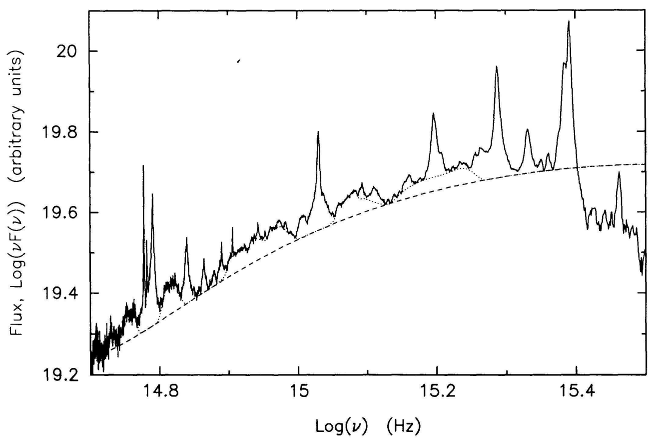
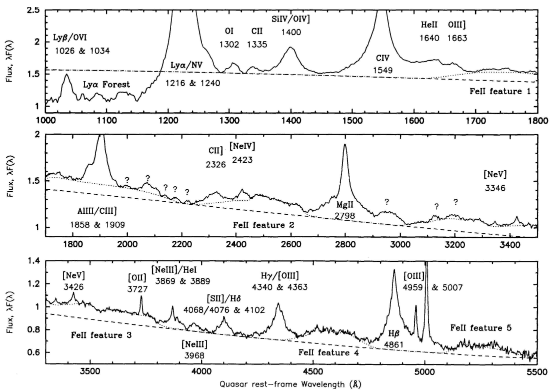
Introduction



(average quasar spectrum Francis et al., 1991, Fig. 6)

Reminder: The average optical spectrum of AGN is dominated by broad and narrow lines.

Introduction



(average quasar spectrum Francis et al., 1991, Fig. 7)

Typical spectra of AGN (and planetary nebulae) are dominated by Hydrogen lines, plus emission from O III at 5007 Å (“nebulium”).

Physics: gas is in photoionization equilibrium with radiation of the vicinity of the central black hole.

Introduction

Ionization structure of gas in AGN determined from the rate equations:

Atoms can be ionized and can recombine

$\Longrightarrow$ number density of ions can change with time.

Define

$n_Z(z)$: number density of species Z in ionization stage z (units: cm^{-3}).
$\lambda(z, z+1)$: transition rate from stage z to $z+1$ (units: s^{-1}).

then

$$\frac{\mathrm{d}n_Z(z)}{\mathrm{d}t} = n_Z(z-1)\lambda(z-1,z) - n_Z(z)\left(\lambda(z,z+1)+\lambda(z,z-1)\right) + n_Z(z+1)\lambda(z+1,z) \quad (5.5)$$

In equilibrium: $\mathrm{d}n_Z/\,\mathrm{d}t = 0$ and thus

$$\frac{n_Z(z+1)}{n_Z(z)} = \frac{\lambda(z,z+1)}{\lambda(z+1,z)} \quad (5.6)$$

In Eq. (5.5) only adjacent ionization stages are connected, calculation gets (much) more complicated if also $z, z+2$, etc. are connected.

Introduction

The rate equations are determined from all physical processes with result in ionization or recombination.

- Most important processes for ionization:
  - Photoionization
  - Collisional Ionization
- Most important processes for recombination:
  - Radiative Recombination
  - Dielectronic Recombination

Real calculations are very complicated

$\Longrightarrow$ Modeling with photoionization codes such as XSTAR Kallman & Bautista (2001) or CLOUDY Ferland et al. (1998).

Introduction

Assume: cloud irradiated by photons

Simplification: only source for ionization: photoionization

Equilibrium: number ionizations = number of recombinations $\Longrightarrow$

$$\int_{\nu_{\text{ion}}}^{\infty} n(Z^z)\sigma_{\text{bf}}(\nu)\frac{F_\nu}{h\nu}\mathrm{d}\nu = \alpha(T)n_{\text{e}}n(Z^{z+1}) \quad (5.7)$$

where

$\sigma_{\text{bf}}(\nu)$: photoionization cross section (cm^2; $\propto E^{-3}$)
$\alpha(T_{\text{e}})$: total recombination coefficent (cm^3 s^{-1})
n_i: particle density (cm^{-3})
F_ν: local photon flux (erg cm^{-2} s^{-1} keV^{-1})

where F_ν is related to the source luminosity via

$$F_\nu = \frac{L_\nu}{4\pi D^2} \quad (5.8)$$

Introduction

Since $\sigma_{\text{bf}}(\nu)$ is a strongly peaked function, we can write Eq. (5.7) as

$$n(Z^z)\sigma_{\text{bf}}(\nu_{\text{ion}})\frac{F_{\nu_{\text{ion}}}}{h\nu_{\text{ion}}} \sim \alpha(T)n_{\text{e}}n(Z^{z+1}) \quad (5.9)$$

and therefore

$$\frac{n(Z^{z+1})}{n(Z^z)} \sim \frac{\sigma_{\text{bf}}(\nu_{\text{ion}})}{\alpha(T)}\frac{L}{4\pi D^2 n_{\text{e}}}\frac{1}{h\nu_{\text{ion}}} \quad (5.10)$$

i.e., ionization equilibrium mainly depends on

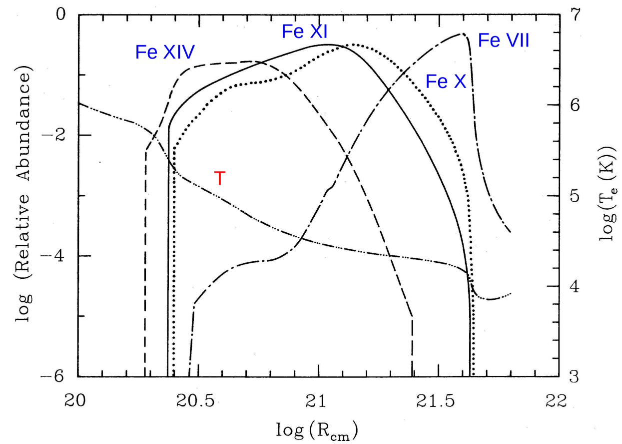
$$U = \frac{L/4\pi D^2 h\nu_{\text{ion}}}{n_{\text{e}}}\frac{1}{c} = \frac{\#\ \text{ionizing photons/cm}^3}{\#\ \text{electrons/cm}^3} \quad (5.11)$$

where U is called the ionization parameter

many other definitions available! Theorists prefer $\xi = L_{\text{ion}}/n_{\text{H}}R^2$

Example: For the BLR: $D \sim$ 10 light days, $L/h\nu \sim 10^{51}$ photons, and $n = 10^{11}$ cm^{-3} gives $U \sim 0.1$.

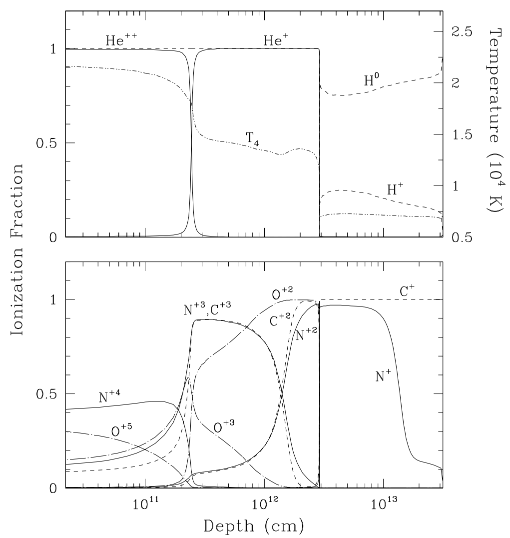
Introduction



(Korista & Ferland, 1989, Fig. 5)

Fe ionization structure and temperature profile of a cloud with $n_{\text{H}} = 1$ cm^{-3} as a function of distance from a central source with a typical AGN continuum.

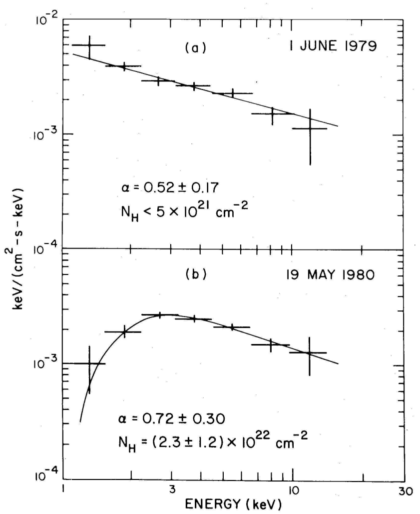
Introduction



“Strömgren sphere” like structure of a cloud irradiated with a typical AGN spectrum (Mathews & Ferland, 1987) with $U = 0.1$, and $n_{\text{H}} = 10^{10}$ cm^{-3} (typical for BLR). Distance is “into” cloud.

(Hamann et al., 2002, Fig. 1)

Warm Absorbers

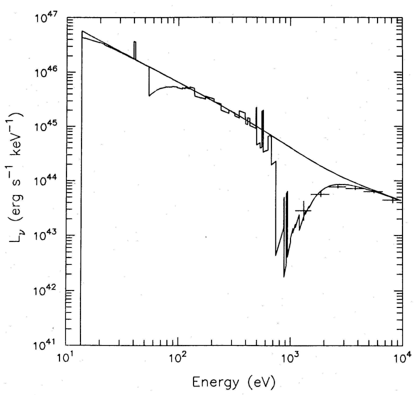


Halpern (1984): Quasar MR 2251−178 shows variable absorption due to warm absorber which changes its ionization.

At that time alternative interpretation: clouds moving through line of sight.

(Halpern, 1984, Fig. 1)

Warm Absorbers



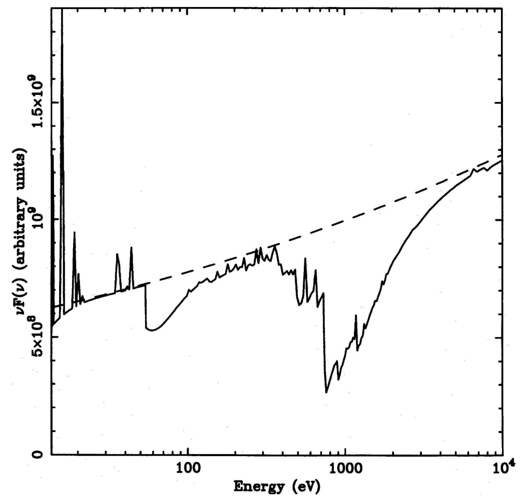
Halpern (1984): Quasar MR 2251−178 shows variable absorption due to warm absorber which changes its ionization.

At that time alternative interpretation: clouds moving through line of sight.

"Warm absorber": photoionized gas much colder (only $10^5 \ldots 10^{6.5}$ K than a collisionally ionized plasma of same degree of ionization.

(theoretical warm absorber model with $\log U = 0$ and $N_{\rm H} = 6.2\times10^{22}\,\mathrm{cm}^{-2}$ Halpern, 1984, Fig. 3)

Warm Absorbers



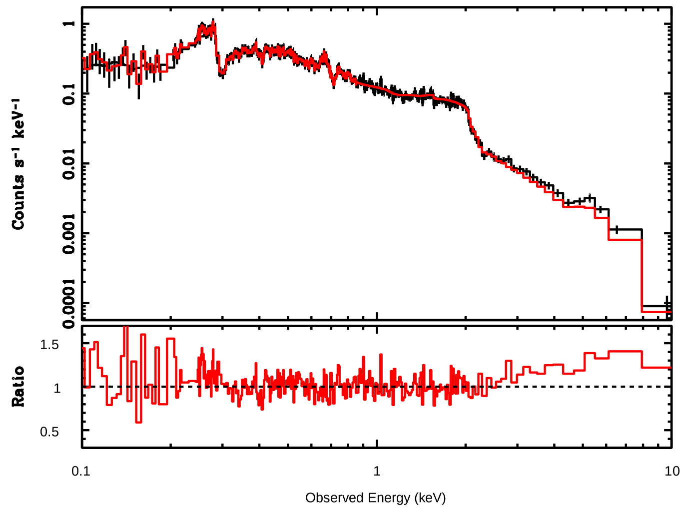
(Reynolds & Fabian, 1995, Fig. 1)

Photoionization calculations: Warm absorbers show strong O VII and O VIII edges at 739 eV and 839 eV.

First resolvable in 1990s with *ASCA*:

Nandra & Pounds (1994): Warm absorbers are found in ∼50% of all Seyfert 1s.

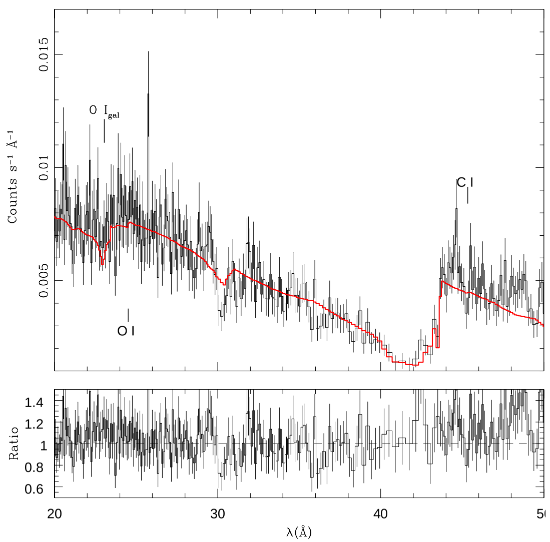
MR 2251-178



(MR 2251−178; Ramírez et al., 2008, PL+2 O-edge fit)

With high-resolution gratings spectroscopy on *XMM* and *Chandra*, warm absorber can be studied in much greater detail than before.

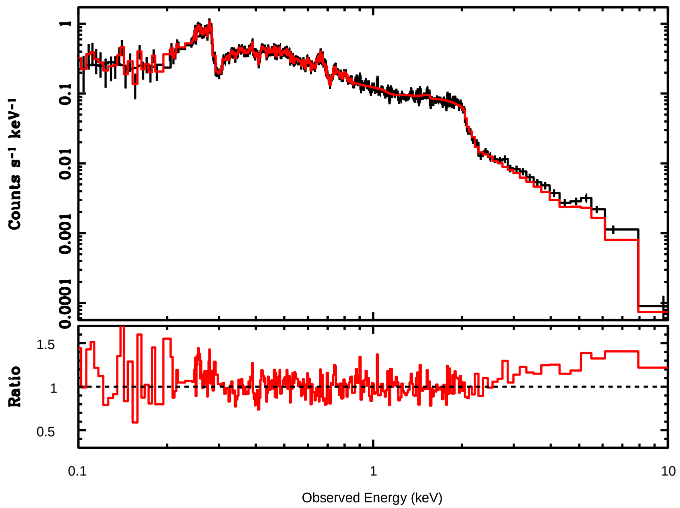
MR 2251-178



(MR 2251−178; Ramírez et al., 2008, O edge region)

With high-resolution gratings spectroscopy on *XMM* and *Chandra*, warm absorber can be studied in much greater detail than before.

MR 2251-178



(MR 2251−178; Ramírez et al., 2008)

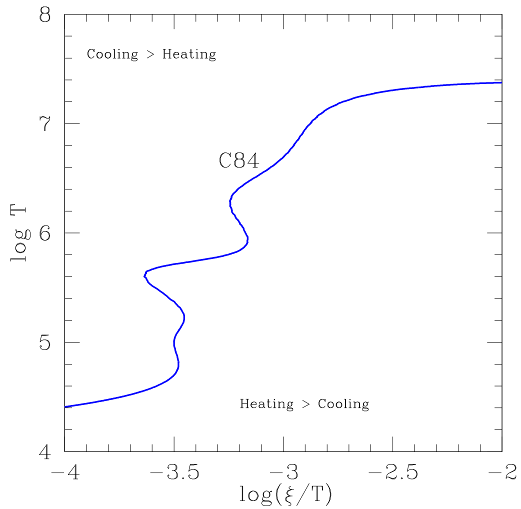
Warm absorber models fit observations well.

For MR 2251−178:

- $\Gamma = 1.66^{+0.02}_{-0.02}$
- $kT_{BB} = 89.5^{+2.5}_{-2.5}$ eV
- $N_H = 2.25^{+0.28}_{-0.25} \times 10^{21}\,\mathrm{cm}^{-2}$
- $\log(\xi) = 0.63^{+0.06}_{-0.06}$
- $v_{out} = -1100^{+60}_{-210}\,\mathrm{km\,s}^{-1}$
- $\chi^2_\nu/(\mathrm{dof}) = 1.22/(584)$

note: includes *outflow*!

Two Phase Gas?



Chakravorty et al. (after 2008, Fig. 2)

Properties of warm absorber gas define a stability curve: gas on curve is in equilibrium (=cooling equals heating), gas away from curve will cool/heat towards curve.

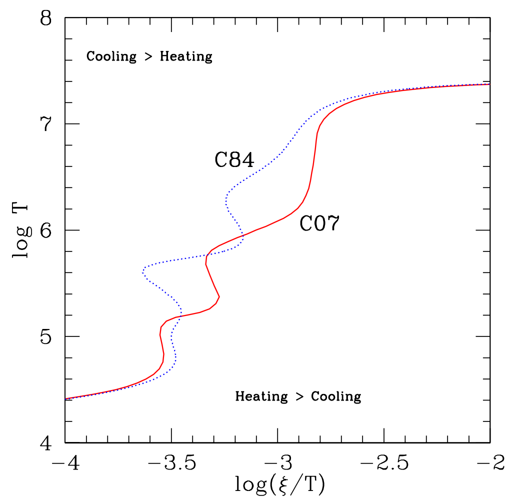
Traditionally plotted: ξ vs. ξ/T, since

$$\frac{\xi}{T} = \frac{L_{ion}}{n_H T R^2} \propto \frac{L_{ion}}{p_{gas}} \quad (5.12)$$

Early work (Krolik, McKee & Tarter, 1981): For hard X-ray spectra, there are regions where a two-phase equilibrium exists, i.e., two phases of gas with different T in pressure equilibrium.

Interpretation: Broad line region clouds in equilibrium with hot warm absorber gas.

Two Phase Gas?



Chakravorty et al. (2008, Fig. 2)

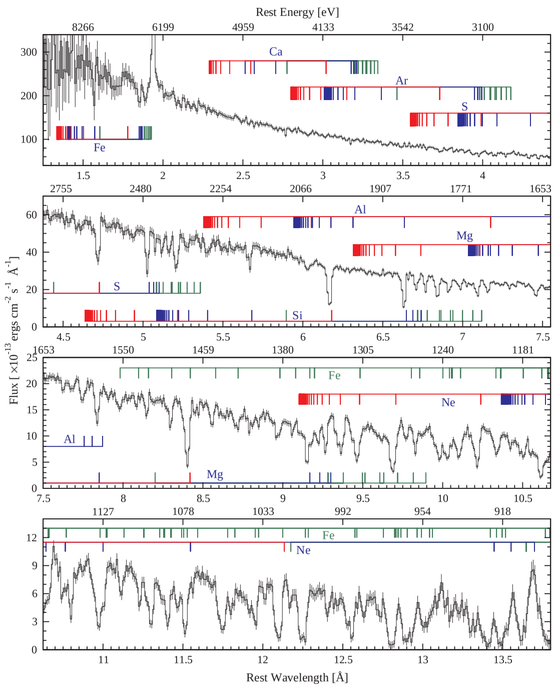
New results: Location of two-phase equilibria in new calculations with better atomic physics are *not* in the range where warm absorber / BLR are seen.

Main influences on location of equilibria:

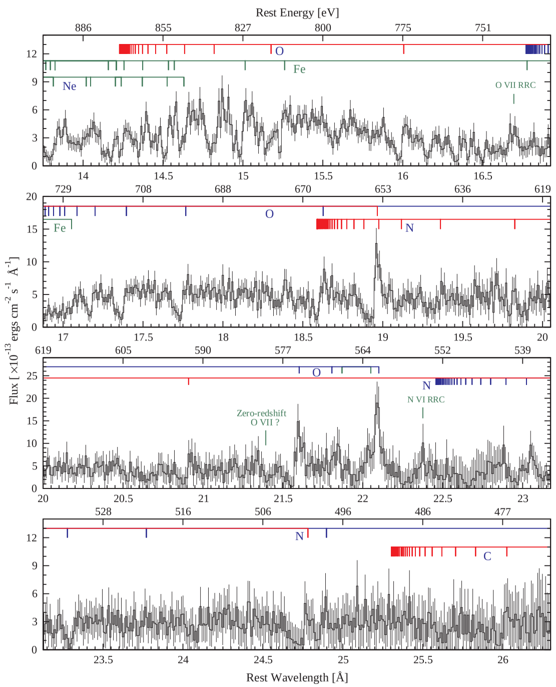
- spectral shape (slope, location of exponential cutoff)
- abundances
- density of medium

$\Longrightarrow$ Current work mainly assumes WA in outflows.

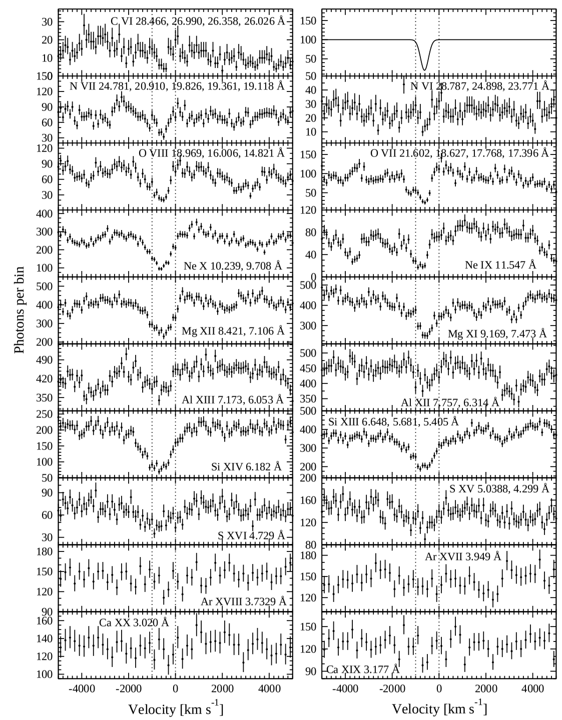
see also Różańska, Kowalska & Gonçalves (2008)



(NGC 3783, *Chandra*; H- and He-like series; Kaspi et al., 2002, Fig. 1a)



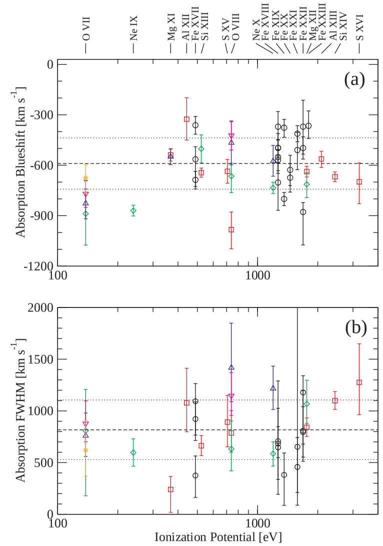
(NGC 3783, *Chandra*; H- and He-like series; Kaspi et al., 2002, Fig. 1b)



NGC 3783: lines are asymmetric, blueshifted

(Kaspi et al., 2002, Fig. 1b)

NGC 3783



The highly ionized lines in warm absorber spectra are blueshifted.

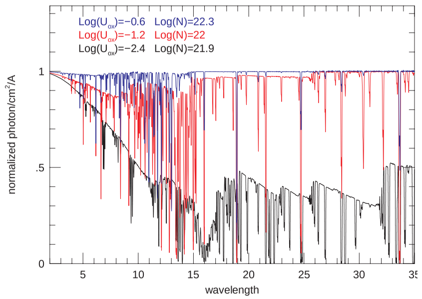
For NGC 3783, in O-lines two systems with $v \sim 630\,\mathrm{km\,s^{-1}}$ and $v \sim 1300\,\mathrm{km\,s^{-1}}$ are seen, consistent with line shifts in UV.

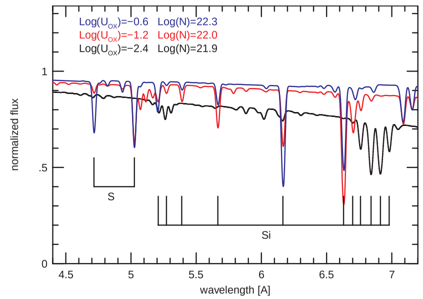
$\Longrightarrow$ Warm absorber is an outflowing medium!

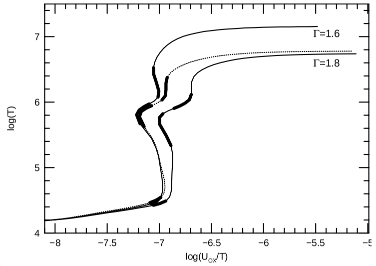
Possible explanation: photoionized accretion disk wind?

(Kaspi et al., 2002)

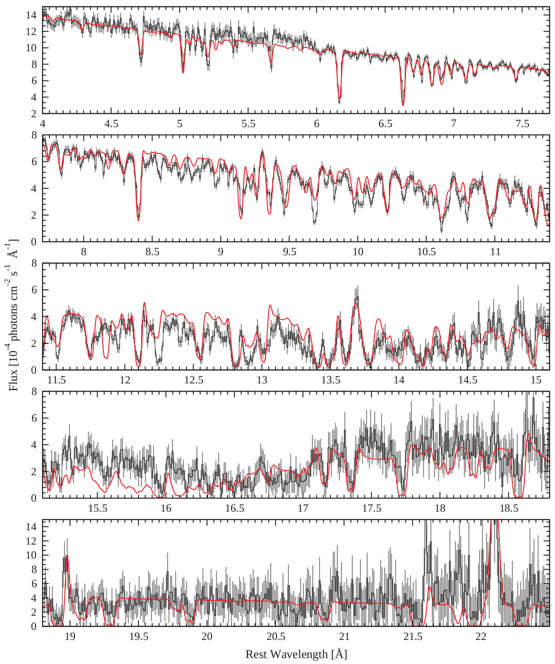
NGC 3783







Netzer et al. (2003): Modeling of Warm Absorber in NGC 3783 requires three absorbing components, which are in pressure equilibrium.



(NGC 3783, Fit of warm absorber model to data; Netzer et al., 2003, Fig. 7)

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