Continuum Spectra of Quasar Accretion Disk Models

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Abstract.
We have calculated the spectrum and polarization of a standard thin accretion disk with parameters appropriate for a bright quasar. This model improves upon previous work by including ultraviolet metal line opacities, assumed for now to be in LTE. Though not yet fully self-consistent, our calculations demonstrate that metal lines can change the spectral slope, reduce the polarization, and reduce the Lyman edge feature in accretion disk spectra. Some observational differences between quasar spectra and accretion disk models might be reconciled with the inclusion of metal lines.

The prodigious luminosities and compact sizes of quasars led theorists to a model in which gas falls into a supermassive black hole through a geometrically thin, optically thick accretion disk. If quasars contain a hole of about $10^{8-9} M_\odot$ which is accreting at near the Eddington limit, then their spectra should peak in the ultraviolet, as observed [1]. However, so far this paradigm has failed to explain many other details of quasar spectra: the calculated spectra are too narrow in range of frequency (an extra power law is needed to fit the spectrum [2]); have too strong a feature at the Lyman edge [3]; and have too large polarization at the wrong polarization angle [4]. Part of the reason for the failure might be due to oversimplified disk spectra calculations, which until now have neglected the effects of metal line opacity. We present here a preliminary calculation including metal line opacities; the calculation, however, is not fully self-consistent, but simply illustrates that the opacity of metal lines can play an important role in shaping accretion disk spectra.

We have computed the spectrum and polarization of a disk with the following parameters: mass of black hole $M_{BH} = 2 \times 10^9 M_\odot$, accretion rate $\dot{M} = 1 M_\odot/\text{year}$, and spin of black hole $a = 0.998 M_{BH}$. This corresponds to a luminosity of 0.072 $L_{Edd}$. We computed the vertical structure at each radius using TLUSDISK [5]. Using this structure, we then computed the spectrum and polarization using the code SYNSPEC [6] combined with the polarization code of Blaes and Agol [7]. Finally,
we convolved the spectra from each radius with a relativistic transfer function [8]. The vertical structure (i.e. temperature, density, flux) is computed taking into account the continuum opacity of hydrogen and helium in non-LTE, and then this structure is used to compute the opacity due to metal lines assumed to be in LTE at the calculated temperature and density. We assume a 30 km/s Doppler width for all lines. We take the outer edge of the disk to be \(50GM_{BH}/c^{2}\). We take into account departures from LTE for the 9 levels of HI, 14 levels of HeI, and 14 levels of HeII. So far, we have only included metal lines between 200 – 3000\(\AA\), assuming solar abundance. We have not yet taken into account the effects of bound-bound transitions on the hydrogen and helium number densities. Because the atmosphere structure calculation did not include metal lines in the radiative equilibrium condition, the spectrum is not fully self-consistent. Hence there is an artificial reduction in flux. The spectra for different inclination angles are presented in figure 1, comparing spectra models with and without metal lines. The flux falls more steeply in the UV when metals are included; above \(10^{14.8}\) Hz for the face-on disk, \(f_{\nu} \propto \nu^{-0.3}\) approximately. This may change when the calculation is done self-consistently (i.e. when flux is conserved). The models are identical below \(10^{15}\) Hz since metal lines are not included in that wavelength range. The spectral slope at smaller frequencies changes due to the small outer cutoff radius we used.

The ultraviolet polarization is decreased significantly by the line opacity (figure 2). For this nearly edge-on disk, the polarization is between 1.2-1.8% in the observable region. This is reduced from the maximum value of 3-4% assuming pure
FIGURE 2. Comparison of the flux ($\lambda F_\lambda$) and percent polarization for the model viewed nearly edge-on. The polarization angle is not shown since it stays roughly constant within 5° for all three models in this wavelength range. Note that for this viewing angle, the Lyman edge is so highly smeared that it is not visible, and the continuum is quite hard.

electron scattering with relativistic effects included. If quasars are preferentially seen closer to face-on, then their ultraviolet polarization will be even lower, and the small observed polarization could be due to scattering off of material at larger radii.

Inclusion of metal opacity reduces the bump near the Lyman edge which is present in the H/He continuum-only face-on disk model (figure 3). This may be why it is difficult to find Lyman edge features in quasars. The main contributors to the metal line opacity in this region are Fe, Ni, Mn, and S. There is a broader dip blueward of the Lyman edge due to metal lines, mostly Fe. Note that the flux is different in the two cases because we haven’t included the lines in the atmosphere structure calculation, so the total flux is not constant.

In summary, metal line opacities can reduce the polarization, change the spectral shape, and reduce the Lyman edge jump in accretion disk model spectra for quasars. We need to see whether these effects still occur in models which include the lines in calculating the disk structure. To make a better comparison of the models with and without metals, we will construct line-blanketed disk structure models including lines from a wider range of wavelengths and bound-bound transitions for H and He, and we will include the contribution of the disk at larger radii. The metal line opacity will change the temperature equilibrium and the radiative acceleration,
FIGURE 3. Flux versus wavelength near the Lyman edge for a face-on ($\cos i = 0.98$) disk. The Lyman edge feature is in emission in the inner parts of the disk (which are strongly redshifted), and absorption in the outer parts (which are less redshifted), which causes the bump redward of the Lyman edge. When metal lines are included, the photosphere redward of the Lyman edge is brought closer to the surface where the temperature is higher/lower for an edge in emission/absorption, reducing the contrast across the Lyman edge.

and thus will be important for calculating the disk structure, which will in turn affect the continuum shape.

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