Theory and Observations Of Accretion Disk Spectra Across Mass Scales

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Summary

• How we model radiatively efficient accretion

• Applications to X-ray binaries and ULXs in the high soft state

• How models seem to fail in AGN

• What physics might be driving these differences between X-ray binaries and AGN
Amazingly, there is a simple self-consistent model for disk accretion which includes relativistic effects: the relativistic, radiatively-efficient, thin $\alpha$-disk:
Shakura & Sunyaev (1973), Novikov & Thorne (1973)

**Thin disk**

- H/R << 1
- Constant accretion rate
- Gravitational binding energy radiated locally

\[
F = -H \tau_{R\phi} R \frac{\partial \Omega}{\partial R}
\]

\[
\dot{M} \frac{\partial (R^2 \Omega)}{\partial R} = \frac{\partial}{\partial R} \left( 4\pi R^2 H \tau_{R\phi} \right)
\]

**$\alpha$-disk**

- Need surface density $\Sigma$ (g/cm²) as function of R

Computed via stress prescription:

\[
\tau_{R\phi} = \alpha P
\]
Computing a Simple Disk Spectrum

Integrate from radii with different temperature

\[ T \propto R^{-3/4} \]

Essentially the DISKBB model

Color correction – shifting the peak to mimic the influence of Compton scattering

\[ I_\nu = f^{-4} B_\nu(fT) \]
Self-consistent models of spectra at the disk surface must perform stellar atmospheres-like calculations:

- Solve for hydrostatic equilibrium

\[
\frac{\partial P_{\text{tot}}}{\partial z} = \rho \Omega^2 z
\]

- Solve for radiative equilibrium

\[
\nabla \cdot F = \epsilon
\]

- Solve equations of radiative transfer and statistical equilibrium (with Compton scattering, Bremsstrahlung, and atomic opacities)

Solving large system of coupled PDE’s: typically involves iterative methods: use TLUSTY
Significant deviations from blackbody shape due to edges & electron scattering.

Color correction (generally) increases with $T_{\text{eff}}$

X-ray binaries (Davis & Hubeny, 2006)

AGN (Hubeny et al. 2001)
Putting it All Together (e.g. BHSPEC/KERRBB)

Model Parameters

- \( M \): black hole mass
- \( L/L_{\text{edd}} \): luminosity/accretion rate
- \( a_\ast \): black hole spin
- \( \alpha \): stress parameter

Photons follow geodesics (KERRTRANS, Agol, 1997)

Radial structure/emission (Shakura & Sunyaev, 1973, Novikov & Thorne, 1973)

Vertical structure/radiative transfer (TLUSTY, Hubeny & Lanz, 1995)

i: inclination
BHSPEC: Full Disk Spectra

L/L_{Edd}

Inclination

Spin

Mass
X-ray Binary Spectral Fitting

BHSPEC yields more sensible fits to broadband data than DISKBB + POWERLAW

Fix M and i at known values: 0.1-10 keV spectrum fit with just 3 parameters!  $a^*$, $L/L_{edd}$, and $N_H$.

Davis et al. (2006)
Using DISKBB one finds $L \sim T^4$, where $T=T_{\text{in}}$. Radius is nearly, but not exactly constant.

Radius is now constant!

Use a color correction $f_{\text{col}}$ to "correct" the relations.

Shafee et al. (2006)
Models Can Fit Some, but not all, ULXs

Applications of our models to ULX’s somewhat limited – most luminous source not high/soft states (Thursday talks)

HLX-1 in ESO 243-49 (talk by Soria) is a notable exception: $L > 10^{42}$ erg/s – strong candidate IMBH
AGN generally poorly fit by disk models:
• UV slopes of real quasars are flatter
• Models do not predict X-ray emission
• No Lyman (Balmer?) edges

Exception? – NLS1s: some well fit by OPTXAGNF, but need additional heating to generate soft X-ray excess
Why are AGN and X-ray Binaries Different?

Some Possibilities:

• Environment? (obscuration?)

• Large UV opacities in AGN? (but not as simple as adding edges, etc.)

• Much higher ratio of $P_{\text{rad}}$ to $P_{\text{gas}}$?
Radiation Damping in MRI Numerical Simulations

Socrates, Davis & Blaes (2004): Spectrum may be affected via Compton scattering off of turbulent eddies.

Jiang, Stone & Davis (2013): Radiation damps turbulent motions in very radiation pressure dominated shearing box simulations.

\[ P_{\text{rad}} \sim 17P_{\text{gas}} \]
\[ P_{\text{rad}} \sim 1377P_{\text{gas}} \]
High $P_{\text{rad}}/P_{\text{gas}}$: Thermal Runaways

We see evidence of thermal runaways in simulations with vertical gravity. Implications for global flows and spectra remains unclear.

See talk by Omer Blaes
UV opacity is already included in TLUSTY models. Modifies spectra but doesn’t explain the narrow range in SED peaks.

However, the effect of (1000s of) strong UV lines is neglected. Most tangible affect of these lines in O stars is strong winds.

Same physics appears to drive BAL winds in quasars. See talk by Daniel Proga. Unfortunately, simulations can not yet model feedback on the disk.

O star mass loss determined primarily by flux (and g)!
What happens if we simply parameterize AGN mass loss (per unit area) by empirical O star relationship?

Strong dependence of mass loss on flux effectively caps $T_{\text{eff}}$, leading to SED peak always near 1000 ang, even for lower mass, high spin and high $L/L_{\text{edd}}$.

Implies rather high mass loss rates for low mass systems. Model may require a hot (X-ray emitting) and radiatively inefficient flow.

See talk by Ari Laor for more details!
Thin disk (Shakura & Sunyaev) spectral models fit the high/soft X-ray binaries (and a few ULXs) quite well (modulo some unseen edges)

Spectral models generally do poorly in AGN

Most promising physics (to my mind) is feedback on the emission from an outflow

Also of interest are the effect of a very high ratio of $P_{\text{rad}}$ to $P_{\text{gas}}$. But still not well understood how these affect spectra – soft X-ray excess? (optxagnf – talk by Chris Done)