Accretion Flows in X–Ray Binaries and Active Galactic Nuclei

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Abstract. Hard X–ray emission is ubiquitous in accreting black holes, both in Galactic binary systems and in Active Galactic Nuclei. I review the different spectra which can be seen from these systems, and possible ways of producing this emission. X–ray reflection should give an observational test of these scenarios, but we need better models before this can give an unambiguous diagnostic of the accretion geometry.

1. Introduction

Accretion onto a black hole is observed to produce copious X–ray emission. For the Galactic binary systems, then at high mass accretion rates (luminosity close to the Eddington limit, \( L_{\text{Edd}} \)) the spectra are dominated by a soft component at \( kT \sim 1 \) keV which is strongly (very high state) or weakly (high state) Comptonized by low temperature thermal (or quasi–thermal) electrons with \( kT \sim 5–20 \) keV (e.g. Gierliński et al. 1999; ˙Zycki, Done & Smith 2001; Kubota et al. 2001). There is also a rather steep power law tail (\( \Gamma \sim 2–3 \)) which extends out beyond 511 keV in the few objects with good high energy data (e.g. Grove et al. 1998). At lower mass accretion rates, below \( \sim 0.02–0.03L_{\text{Edd}} \) (˙Zycki, Done & Smith 1998; Gierliński et al. 1999), there is a rather abrupt transition when the soft component drops in temperature and luminosity. These low state spectra are dominated by the hard component with \( \Gamma < 1.9 \), rolling over at energies of \( \sim 150 \) keV (see e.g. the reviews by Tanaka & Lewin 1995; Nowak 1995). This spectral form continues to the very low luminosities of the quiescent state (\( \sim 10^{-4}L_{\text{Edd}} \) e.g. Kong et al. 2000).

In AGN, nearby Seyfert galaxies generally have hard X–ray spectra which are rather similar to the low state spectra from Galactic black holes (Zdziarski et al. 1995), while the (probably higher mass accretion rate) Narrow Line Seyfert 1 galaxies and radio–quiet quasars look more similar to the high/very high state spectra (Pounds, Done & Osborne 1995; Sultentic et al. 2000; Kurazkiewicz et al. 2000), as do the ultraluminous off–nuclear sources in nearby galaxies (compare spectra in Makashima et al. 2000 with those of e.g ˙Zycki et al. 2001).

2. Hard X–ray Emission Mechanisms

The low state (and quiescent) continuum spectra are adequately described by thermal Compton scattering of UV/soft X–ray seed photons in an X–ray hot
plasma (e.g. Sunyaev & Treuher 1979) which has temperature $\sim 100$ keV, and optical depth $\sim 1$ (e.g. Gierliński et al. 1997). This is often modelled by a power law with exponential cutoff, but true Compton spectra can be subtly curved from any anisotropy of the seed photons (e.g. if they come from a disk: Haardt & Maraschi 1993) rather than a power law. The high energy cutoff is also much sharper than exponential at these temperatures (Poutanen & Svensson 1996).

By contrast, the high/very high state continuum spectra cannot be fit by seed photons from a disk Comptonized by a single temperature plasma. The data require complex curvature, best described by a two component electron distribution, which is quasi–thermal at low energies, and a power law at higher energies (Poutanen & Coppi 1998; Gierliński et al. 1999; Wilson & Done 2001).

There are several proposed mechanisms to heat the electrons. The advective flow models assume that the accretion energy is given mainly to the protons and is mostly carried along with the flow with only a fraction being given to the electrons via Coulomb collisions (e.g. the review by Narayan et al. 1998). This gives a natural spectral switch at a few percent of Eddington as at high densities (i.e. high mass accretion rates) the electrons efficiently drain energy from the protons and the flow collapses back into an Shakura–Sunyaev disk (e.g. Esin, McClintock & Narayan 1997). These models can easily give continuity of spectral form between quiescence and low state, and give the spectral switch to the high state, but cannot produce the X–ray emission seen in the high states.

An alternative mechanism for the low state emission is magnetic reconnection, releasing the accretion energy in a flaring corona above the disk. This seems plausible as the disk viscosity is known to be connected to an MHD dynamo (Balbus & Hawley 1991). However, explaining the similarity of the low state and quiescent spectra may then be difficult as it is likely that the magnetic viscosity cannot operate at extremely low accretion rates (Gammie & Menou 1998). Another problem is that the only known potential mechanism for the emission in the high states is magnetic reconnection. The spectra change dramatically between the high and low states, which seems difficult to explain if they are both powered by the same mechanism. The radiation pressure instability probably does not offer a potential spectral switch as it is suppressed by a magnetic corona (Zdziarski & Svensson 1994).

The increased Comptonization in the very high state could be caused either by the inner disk becoming effectively optically thin (Shakura & Sunyaev 1973), or by incomplete thermalization in the magnetic reconnection process leading to a hybrid (thermal plus nonthermal tail) electron distribution (Poutanen & Coppi 1998). These possibilities are shown in Figure 1.

3. Observational Tests using X–ray Reflection

The potential emission mechanisms shown in Figure 1 imply very different geometries. X–ray reflection is an observable diagnostic of the geometry, as the amount of reflection depends on the solid angle of optically thick material (disk) as seen from the hard X–ray source, while the amount of relativistic smearing of the reflected spectral features shows how far the material extends down into the gravitational potential (see e.g. the review by Fabian et al. 2000).
The solid angle subtended by the reflecting disk in AGN seems to be correlated with spectral index (Zdziarski et al. 1999), and also with the amount of relativistic smearing (Lubiński & Zdziarski 2001). However, these observational results are currently controversial. The broad line profiles are sensitive to details of the ASCA (re)calibration (Weaver, Gellbord & Yaqoob 2001), and to the extent of any narrow line component from material further out such as the molecular torus or broad line region. The correlation of reflection with the illuminating power law index could be affected by details of the spectral decomposition (and background subtraction) for faint AGN (Nandra et al. 2001). But this is not a problem with the Galactic black holes, as their typical fluxes are much higher. Yet these again show the same correlation between the spectral index and amount of reflection (Ueda et al. 1994; Życki et al. 1999; Zdziarski et al. 1999; Gilfanov et al. 1999). They also show a correlation of the amount of smearing of the spectral features with amount of reflection/spectral index (Gilfanov et al 2000), and again this cannot be due to any of the problems seen in AGN (the data are from RXTE rather than ASCA, and there is no molecular torus to produce a narrow line component). These correlations in the Galactic binaries must be telling us something real about the X-ray accretion geometry.

4. Reflection Constraints on the Accretion Geometry?

These results can rather naturally be explained in an advective flow/truncated disk geometry if the inner disk radius moves inwards as a function of mass accretion rate. This automatically gives more relativistic broadening. If this is accompanied by an increasing overlap between the disk and advective flow then this increases the solid angle subtended by the disk, so increasing the amount of reflection. It also increases the amount of seed photons which are intercepted by the X-ray hot plasma, so leads to a steeper Comptonized spectrum (Poutanen et al. 1997; Zdziarski et al. 1999; Życki et al. 1999; Gilfanov et al. 1999). More evidence for this interpretation comes from the fact that a hole in the quiescent disk may be required to make the long inter–outburst timescale in the black hole transient systems (Dubus et al. 2001), while the variable frequency QPO seen in these sources argues for a variable radius for the inner disk edge.

However, this is not a unique interpretation of these correlations. The magnetic flares model can give similar correlations if the flares are accompanied by relativistic outflow away from the disk: the faster the outflow the more the emission is beamed away from the disk so the lower the reflection and the lower the seed photon flux seen by the X-ray plasma (Beloborodov 1999).

Alternatively, the magnetic flares can be static if they irradiate the disk to an extent that the X-ray heating substantially changes the vertical structure of the disk. Material at the top of the disk is heated by the illumination, and so can expand, lowering its density and increasing its ionization. This self–consistent density structure is especially important for the low state systems, as the intense hard spectral illumination causes an ionization instability in the disk. This results in an abrupt transition from a hot, intensely ionised skin (where X-ray heating is balanced by Compton and bremsstrahlung cooling) to low temperature, high density, low ionization material (where X-ray heating is balanced mainly by line cooling: see e.g. Nayakshin, Kazanas & Kallman 2000).
Figure 1. Potential X–ray emission mechanisms. In quiescence the disk is NOT in steady state (dotted line). The MHD dynamo probably cannot operate, so advective flows may be the only feasible way to power the X–ray emission. In the low state the accretion flow is probably in (quasi)steady state and the MHD dynamo works. If most of the reconnection takes place above the optically thick material then this can power the observed X–ray emission. Alternatively, if quiescence if powered by an advective flow then maybe the low state is also. In the high and very high states the only serious contender for the hard power law tail is magnetic reconnection leading to a non–thermal electron distribution (indicated by the black loops), while the thermal electrons could be part of the same mechanism (grey loops) or could be associated with the inner disk.

Models with this X–ray illuminated disk structure can show an apparent correlation between the spectral index and amount of reflection as inferred from using the standard constant disk ionization state reflection models (Done & Nayakshin 2001a), although the models depend on (unknown) physics of magnetic flares, e.g. any sideways expansion of the X–ray heated patch of disk underneath a reconnecting region (Done & Nayakshin 2001b).

5. Reflection in the high/very high states

The complex curvature of the high energy spectrum (sum of thermal and non–thermal Compton components) seen in the high/very high states makes it difficult to determine the reflected continuum. The Galactic black hole systems are further complicated by the dominance of the disk spectrum in the observed X–ray bandpass. Relativistic smearing (e.g. Ebisawa et al. 1991) and weak Compton scattering in the upper layers of the disk (e.g. Ross, Fabian & Mineshige 1992) should broaden the optically thick disk spectrum. However, much stronger Compton scattering is implied by data, which probably dominates over any relativistic broadening in the thermal disk spectrum (Życki, Done & Smith 2001; Kubota et al. 2001). This (poorly known) disk spectrum is the seed photon source, so there is a low energy cutoff in the Compton continuum spectrum.

Despite these uncertainties, there are some robust results. Reflection is always present and is always highly ionised (Życki et al. 1998; 2001; Gierliński
et al. 1999; Wilson & Done 2001). However, the amount of reflection is not easy to constrain: strong ionization means that there can be strong Comptonization of the reflected features which makes reflection much harder to identify (e.g. Ross, Fabian & Young 1999). Radial ionization gradients can also be important: there could be material in the inner disk which has even higher ionization than the material which we see. This would be completely reflective so would lead to an underestimate of the solid angle of the disk (Zycki et al. 1998).

6. Concluding Questions

• **Theory Issues:** Can the Balbus–Hawley viscosity work in quiescent disks? Can it transport most of the accretion energy into an optically thin corona to power the low state emission? What happens to the vertical structure of the disk under such intense illumination? For the alternative accretion geometry, can the advective flow models exist i.e. can the accretion energy really be given mainly to the protons and are (slow) Coulomb collisions the only process by which the electrons can gain this energy? And what controls the tranisition radius between the disk and advective flow? How much Comptonisation can be produced in the disk at high mass accretion rates? And a topic which I completely ignored: what role does the jet play in the X–ray emission from any of the spectral states?

• **Modelling Issues:** We need to fit proper reflection models to the data (not smeared edges and broad gaussian lines!). These models should include the self-consistently calculated vertical ionization structure of the X–ray illuminated accretion disk, especially in low state spectra where the thermal ionization instability is expected to develop. They should also include Compton upscattering of the reflected emission in the hot, ionised upper disk. And we need to use proper Comptonisation models of the continuum (including both high and low energy cutoffs) rather than a power law with exponential rollover!

• **Data issues** We need high signal to noise spectra of all states with good energy resolution around the iron K features, and broad bandpass to disentangle the continuum from the reflected emission. This is especially important for the rather faint spectra from AGN and quiescent Galactic black holes.

Chandra, XMM and especially ASTRO-E2 will address the observational deficiencies. The challenge is now for both theorists and observers to develop and fit physical models to these X–ray spectra.

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