Modeling the X-ray contribution of XRB jets

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Abstract

Astrophysical jets exist in both XRBs and AGN, and seem to share common features, particularly in the radio. While AGN jets are known to emit X-rays, the situation for XRB jets is not so clear. Radio jets have been resolved in several XRBs in the low/hard state, establishing that that some form of outflow is routinely present in this state. Interestingly, the flat-to-inverted radio synchrotron emission associated with these outflows strongly correlates with the X-ray emission in several sources, suggesting that the jet plasma plays a role at higher frequencies. In this same state, there is increasing evidence for a turnover in the IR/optical where the flat-to-inverted spectrum seems to connect to an optically thin component extending into the X-rays. We discuss how jet synchrotron emission is likely to contribute to the X-rays, in addition to inverse Compton up-scattering, providing a natural explanation for these correlations and the turnover in the IR/optical band. We present model parameters for fits to several sources, and address some common misconceptions about the jet model.

1 Introduction

While the jets in Active Galactic Nuclei (AGN) are known to radiate from the radio through the X-rays, the jets associated with low/hard state (LHS) X-ray binaries (XRBs) have only been conclusively identified as the source of the radio emission for a few sources (Fender 2001). However, these smaller jets do share the “signature” flat-to-inverted radio synchrotron spectrum seen from the compact inner jets in AGN, so it is likely that the same emission mechanism is at work even when the jets are as yet unresolved. Unlike in AGN, however, this optically thick synchrotron can extend well into the infrared (IR) and beyond (e.g., Corbel & Fender 2002).

At higher frequencies, the picture is not so clear. Although AGN jets
contribute to the X-rays via both synchrotron and inverse Compton (IC) emission, these processes have not been considered in the standard picture for the high-frequency emission of XRBs. Beyond the IR, a typical LHS spectrum shows a weak thermal contribution plus a hard power-law extending to typically $\sim 100$ keV. These have generally been interpreted in terms of a Standard Thin Disk (SD; Shakura & Sunyaev, 1973) in combination with an optically thin flow at smaller radii, or an overlying corona (for reviews see Poutanen, 1998; Nowak, Wilms & Dove, 2002). In this scenario, the hard power-law originates in IC upscattering of the thermal SD photons by the hotter plasma.

Although variations of this picture can successfully explain the X-ray features, they cannot address the very tight correlation between the X-ray and radio in the LHS extending down to the Quiescent State (QS), which has now been seen in several sources (e.g., Corbel et al., 2002; Gallo, Fender & Pooley, 2002). Similarly, in all XRBs with quasi-simultaneous or better broadband data, there seems to be a “turnover coincidence” in which the X-rays always trace back to the same decade of frequency between $\sim 10^{14} - 10^{15}$ Hz in the IR. This suggests some connection between the low and high frequencies which is present for all LHS sources.

An alternative model for the LHS emission, involving a combination of jet and thermal SD emission, has been applied to several sources (e.g., Markoff, Falcke & Fender, 2001; Markoff et al., 2003). It is currently the only model which can simultaneously fit the broadband spectrum, account for the radio/X-ray correlations (as well as analytically explain the slope of the correlations) and explain the turnover coincidence between the IR and X-rays. The X-rays can stem from synchrotron, IC, or both, processes depending on maximum energy to which the particles can be accelerated in the jet, which itself depends on cooling processes.

The details of the jet model have been discussed elsewhere, so we would like to briefly touch on the main points as well as a few common misconceptions about the workings of the model.

# 2 General results & discussion

We present the important model parameters for several sources in Tab. 1. While these results are preliminary in that they do not yet address the fine features in the X-rays (e.g., line emission and reflection components), some basic trends are revealing themselves. The jets can account for the entire broadband spectrum with 1-10% of the total Eddington luminosity of the source, assuming relativistic thermal electrons in the accreting plasma, and that a fraction of this plasma is accelerated. The location where the acceleration starts falls between $\sim 10^2 - 10^3 r_g$ with the exception of two sources. The first is Cyg X-1, where the data are not simultaneous, and for which we are currently working with a newer data set (R. Fender, priv.comm.) which will give better restraints. The binary parameters of the other outlier, XTE
Jet model parameters for several sources. The mass, distance and inclination are taken from observations, when available. The input total power in the jet, the initial electron plasma temperature and the location of the acceleration zone are found from fitting.

| Source               | \(M_{\text{bh}}\) (M\(_\odot\)) | D (kpc) | \(\theta_i\) | Jet power (L\(_{\text{Edd}}\)) | \(T_e\) (K) | \(z_{sh}\) (r\(_g\)) |
|----------------------|----------------------------------|---------|----------------|-----------------------------|-------------|----------------|
| XTE J1118+480        | 6                                | 1.8     | 31             | \(1.5 \times 10^{-2}\)     | 7 \times 10^9 | 150            |
| GX 339−4 (1981)      | 5                                | 4.0     | 55             | \(2.0 \times 10^{-1}\)     | 7 \times 10^9 | 1750           |
| Cyg X-1\(\ast\)     | 10                               | 2.5     | 35             | \(1.4 \times 10^{-2}\)     | 7 \times 10^9 | 47             |
| V404 Cyg\(\ast\)    | 12                               | 3.5     | 56             | \(1.4 \times 10^{-1}\)     | 7 \times 10^9 | 670            |
| GRO J0422+42         | 5                                | 2.5     | 41             | \(1.5 \times 10^{-2}\)     | 2 \times 10^{10} | 100            |
| XTE J1550-564        | 10                               | 4.0     | 75             | \(3.5 \times 10^{-2}\)     | 7 \times 10^9 | 215            |
| XTE J1650-500        | 10?                              | 3.0?    | 57?            | \(3.0 \times 10^{-2}\)     | 2 \times 10^{10} | 9000           |

* Non-simultaneous data set, ** No spectral info for X-ray flux.

J1650-500, are still unconstrained so we assumed reasonable values, which however could be contributing to this difference.

The location of \(z_{sh}\) is determined by fitting the turnover from the optically thick IR to the optically thin X-ray regime in the jet. The range of fit values is very small, considering that the jet must extend at least out to \(\sim 10^{10} r_g\) to fit the radio. This reflects the “turnover coincidence” seen in all LHS sources with flat-to-inverted radio and quasi-simultaneous X-rays, and suggests that all sources share a common structure where acceleration occurs. Synchrotron from the jet is a natural explanation for this coincidence, and can similarly explain the radio/soft X-ray correlations. If the synchrotron only extends into the soft X-rays and IC from the base of the jet dominates at hard X-rays, the model could also address the turnover coincidence and correlations. Interestingly, this turnover was explicitly resolved in GX 339−4 (Corbel & Fender, 2002). Furthermore, fits to spectral data from massive jets in blazars also show a similar scale for the dominant emission region (Beckmann et al., 2002), strengthening the argument that the basic physics of jets scale to some extent.

What is becoming clear is that the processes behind the radio/IR and X-ray emission can no longer be considered independent. This is not, however, incompatible with the standard picture if one considers that the idea of a hot, magnetized corona above the SD could be synonymous or the source of the jet base (see, e.g., Merloni & Fabian, 2002). Unifying these two types of models provides a challenge, however. In the case of GX 339−4, for example, a sphere-disk model can well explain the X-ray spectrum in many details (Nowak, Wilms & Dove, 2002), but not the radio/IR and the correlations. If the jet can explain the entire broadband spectrum, and if its base is somehow equivalent to, or contiguous with, the corona, there must be a self-consistent parameter range for combining these two pictures. This is problematic at first consideration, however, since the temperatures re-
quired at the jet model base are much higher than “typical” coronal values, while the scale of the jet base is a factor of $\sim 10$ smaller. It is possible that by combining these two scenarios, both models will be required to explore new parameter ranges to find a compatible solution. This is work we are currently exploring.

3 Addressing some common misconceptions

As a final note, we have noticed several misconceptions about the nature of the jet model in the literature and in the remaining space would like to touch on a few of these.

First, spectral pivoting in the X-ray would not result in orders of magnitude variability in the radio, which is of course not observed. If one takes self-absorption into account, as is integral to our model, the X-ray pivoting requires mainly a change in the location of the optically thick-to-thin turnover. Another point raised is that the jet model is incompatible with reflection features. As seen in Tab. 1, the X-ray emission originates close enough to the disk that beaming away from the disk is weak because near the base of the jet the plasma is near the local speed of sound. It is also important to note the increasing evidence for misaligned jets in XRBs, where the jet is in fact inclined towards the disk. This, along with disk warping, means that jets may be able to reproduce most reflection features. Along these lines, the location of the X-ray emitting region is also compatible with estimates based on the amplitude of reflection and the iron line. Finally, it has been argued that the shape of the cutoff itself argues against a non-thermal interpretation. The jet model can naturally explain the cutoff via synchrotron emission or IC from the jet—which process dominates is dependent on the photon field available for upscattering. Arguments based strictly on the shape of the cutoff are not necessarily valid, because the cutoff data is likely averaged over many variations (e.g., Poutanen & Fabian, 1999), and the statistics are not as good.

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