Assessing the X-ray Contribution from Jets in X-ray Binaries

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Abstract. Astrophysical jets exist from the stellar scale up to AGN, and seem to share common features particularly in the radio. But 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, and it seems likely that some form of outflow is present whenever this state is achieved. 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 also 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.

1. Introduction

Active galactic nuclei (AGN) jets have been extensively imaged in the radio, and also emit significantly at higher frequencies including the X-rays via synchrotron and inverse Compton (IC). It turns out that black hole candidate (BHC) X-ray binaries (XRBs) also produce collimated outflows, at least when in the low/hard state (LHS) [1]. The jets in several persistent Galactic sources have already been resolved in the radio (e.g., 1E1740.7-2942, [2]; Cyg X-1, [3]).

Analogous to the "signature" emission of compact radio cores in AGN (e.g., [4]), XRB jets contribute a flat-to-inverted radio synchrotron component to the LHS spectra. Beyond this radio signature, a typical LHS spectrum shows a weak thermal contribution and a hard power-law at higher frequencies. This has generally been interpreted in terms of a Standard Thin Disk (SD; [5]) which either transitions at some radius to an optically thin, non-radiative flow, or is underlying a corona (for reviews see [6, 7]). The hotter plasma is believed to account for the hard power-law via IC upscattering of the thermal SD photons.

While variations of this picture can successfully explain the X-ray features, there is increasing evidence that—at least in the LHS and likely also the quiescent state—the jet is also playing a role outside the radio band. The extent of this role is not yet clear, but we have found that emission from the jets alone can actually account for the majority of the broadband LHS spectrum (excluding the thermal SD contribution) in sources where simultaneous radio, X-ray and sometimes infrared (IR)/optical data are available. The models for these various sources also show a surprising degree of similarity in their input parameters, and is the only model yet which can explain the multi-wavelength correlations which are now being seen in several sources. It is therefore important to begin exploring ways in which the jets can be incorporated into the previously disk-only X-ray picture, and to know the extent to which they can reasonably contribute.

2. Brief Model Summary

We first considered a jet model for the BHC XTE J1118+480, because of the excellent broadband observational coverage. Details of the model, data references and figures can be found in [8]. The basic idea is that a small fraction of the charge-neutral accreting plasma from the inner disk, which we take to be optically thin and hot, escapes the black hole and is collimated into a jet. The energy in the jet is divided equally between the kinetic energy and the internal energy, dominated by hot electrons and the magnetic fields. Under these assumptions, to explain the radio/IR spectra with a realistic jet power, $Q_{\rm j} = q_{\rm j}\dot{M}c^2$ where $q_{\rm j} \sim 0.01 - 0.1$, the thermal plasma must encounter some acceleration region within the jet (see, e.g., [9]). This process is also inferred because of the observed optically thin synchrotron power-law seen during radio outbursts, indicating the presence of nonthermal particles.

The question of whether jet synchrotron will contribute to the X-rays is thus a matter of the maximum energy to which the particles can be accelerated. Synchrotron cooling will dominate as long as the SD does not extend too close to the base of the jet ($\lesssim 10r_g$). In the specific case of Fermi acceleration, the location of the maximum cutoff is not dependent on the magnetic field, the jet power, or the shock location but is instead dependent on two plasma parameters: the mean free path for diffusive scattering and the speed of the shock in the plasma frame. Because we would expect XRBs to have similar shock structures, we should get roughly similar cutoffs for different sources and accretion rates. In cases where the photon field from the SD is high enough, however, IC from the jet could instead dominate.

3. Some Applications

We have applied this model so far to 4 LHS sources with simultaneous or quasi-simultaneous data, in addition to XTE J1118+480. One of the most interesting data sets comes from the 1981 observations of the Galactic BHC GX 339-4, presented in [10]. The IR/optical wavebands seem to indicate the clear presence of both jet and disk components, which has not been seen explicitly in any other source. The first component at lower frequencies has a negative slope, suggesting that we are seeing the expected turnover from the optically thick to optically thin regimes. The shape of this spectrum at higher frequencies is hidden under a component which is likely due to thermal emission from the SD, as indicated by the sharp rise in the optical points. However, if the simultaneously measured X-rays are traced back to the IR, they line up with the turnover remarkably well, supporting their interpretation as synchrotron emission. We present one possible model fit in Fig. 1a.

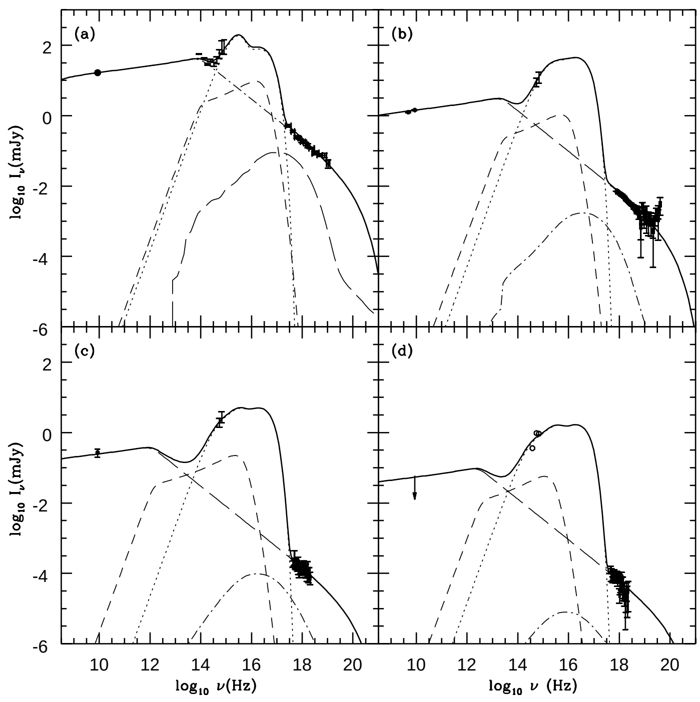

Figure 1. Jet model fit to four representative broadband spectra for GX 339-4, with details and data references in [9]. Solid thick line: total spectrum, dotted line: multi-temperature blackbody outer disk plus single blackbody irradiation contribution, short-dashed: synchrotron emission from the jet before acceleration, dot-dashed: synchrotron emission from jet regions after acceleration, and long-dashed: inverse Compton upscattered disk and jet photons. (a) 1981 IR/X-ray data set, with extrapolated radio point, (b) May 14, 1999 data set, (c) August 17, 1999 data set, (d) Sept. 15, 2000 data set (in quiescence), radio is a 3σ upper limit.

A special feature of GX 339-4 is that its radio emission has been observed to tightly correlate with the X-ray emission over the entire range of LHS luminosities, and also down to a very weak level of emission in the "off" state [11, 12]. This also suggests that the plasma emitting the synchrotron radiation plays a role at higher energy. In Fig. 1b-d we show representative fits to three of the 13 simultaneous data sets (see [9]), which cover almost three orders of magnitude in X-ray luminosity.

The correlation data of [11, 12] can be seen explicitly in Fig. 2. The solid line is the prediction of the synchrotron-dominated jet model, with the power as the only changing parameter. The two "outliers" may be due to a reflaring at the time of the observation. If we ignore them, the slope of the correlation is ~ 1.4, which is predicted analytically from the dependence of the radio and X-ray luminosities on jet power in our model.

In Fig. 3 we show two other applications which are not as well constrained due to the non-simultaneity. Simultaneous radio and X-ray data are critical for understanding this model. At this preliminary stage, however, we seem to be discovering a few trends beyond the correlations. For instance, in all sources

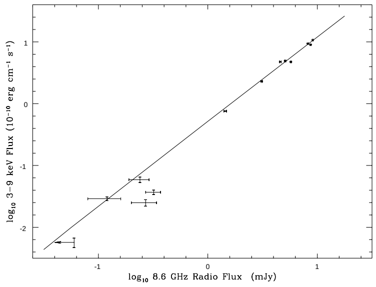

Figure 2. The jet model-predicted radio (8.6 GHz)/X-ray (integrated 3-9 keV emission) correlation (solid line). The data are from [11, 12]. The only changing parameter is the jet power. The arrow represents 3σ upper limits. See [9] for details.

the shock acceleration zone seems to fall $\sim 10^2\ r_g$, which is roughly where the reconfinement shock is thought to occur in AGN (e.g., [14]). This means that the "turnover coincidence" where the X-rays always trace back to the IR could be a signature of acceleration from this shock zone.

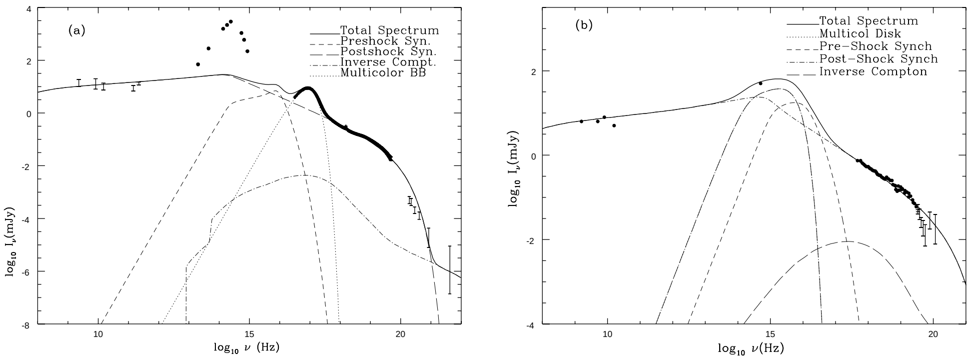

Figure 3. Two other applications: (a) Cyg X-1, non-simultaneous LHS data compiled by S. Tigelaar, the IR excess is due to the companion; (b) GRO J0422+32, simultaneous radio and IR compiled by C. Brocksopp, X-rays quasi-simultaneous from Mir-Kvant but averaged over 5 decaying days by [13].

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