Jet-Disc coupling in the accreting black hole XTEJ1118+480

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Abstract. We interpret the rapid correlated UV/optical/ X-ray variability of XTE J1118+480 as a signature of the coupling between the X-ray corona and a jet emitting synchrotron radiation in the optical band. We propose a scenario in which the jet and the X-ray corona are fed by the same energy reservoir where large amounts of accretion power are stored before being channelled into either the jet or the high energy radiation. This time dependent model reproduces the main features of the rapid multi-wavelength variability of XTE J1118+480. A strong requirement of the model is that the total jet power should be at least a few times larger than the observed X-ray luminosity, implying a radiative efficiency for the jet $\epsilon_j \gtrsim 3 \times 10^{-3}$. This would be consistent with the overall low radiative efficiency of the source. We present independent arguments showing that the jet probably dominates the energetic output of all accreting black holes in the low-hard state.

Keywords: accretion, black hole physics, star: XTE J1118+480, X-rays: binaries

1. INTRODUCTION

The X-ray nova XTE J1118+480, was discovered by the Rossi X-Ray Timing Explorer (RXTE) All-Sky Monitor (ASM) on 2000 March 29 (Remillard et al. 2000). The optical spectrophotometry proved a low mass X-ray binary system containing a black hole of at least 6 solar masses (McClintock al. 2001a, Wagner et al. 2001). The interstellar extinction towards the source is exceptionally low (Garcia et al. 2000). This fact allowed an unprecedented wavelength coverage (Mauche et al. 2000; Hynes et al. 2000; McClintock et al. 2001b; Hynes et al. 2003; Chaty et al. 2003 and references therein). In the radio to optical bands, a strong non-thermal component was associated with synchrotron emission from a powerful jet or outflow (Fender et al. 2001). In the optical to EUV bands the spectral energy distribution is dominated by a thermal component from the accretion disc. The X-ray emission consists of a typical powerlaw spectrum with photon index $\Gamma \sim 1.8$. Such a spectrum is generally associated with Comptonisation in the hot inner
part of the disc or corona. During the whole outburst duration, the X-ray properties of the source, as well as the presence of strong radio emission, were typical of black hole binaries in the hard state.

2. Optical X-ray correlations

Interestingly, fast optical and UV photometry allowed by the weak extinction, revealed a rapid optical/UV flickering presenting complex correlations with the X-ray variability (Kanbach et al. 2001; Hynes et al. 2003, hereafter K01 and H03 respectively). This correlated variability cannot be caused by reprocessing of the X-rays in the external parts of the disc. Indeed, the optical flickering occurs on average on shorter time-scales than the X-ray one (K01), and reprocessing models fail to fit the complicated shape of the X-ray/optical cross correlation function (H03). Spectrally, the jet emission seems to extend at least up to the optical band (McClintock et al. 2001b; Chaty et al. 2003, hereafter C03), although the external parts of the disc may provide an important contribution to the observed flux at such wavelengths. The jet activity is thus the most likely explanation for the rapid observed optical flickering. For this reason, the properties of the optical/X-ray correlation in XTE J1118+480 might be of primary importance for the understanding of the jet-corona coupling and the ejection process.

The simultaneous optical/X-ray observations are described at length in a number of papers (K01; Spruit & Kanbach 2001; H03; Malzac et al. 2003, hereafter M03). As discussed in these works, the observations are very challenging for any accretion model. The most puzzling pieces of evidence are the following: (a) the optical/X-ray Cross-Correlation Function (CCF) shows the optical band lagging the X-ray by 0.5 s, but with a dip 2-5 seconds in advance of the X-rays (K01); (b) the correlation between X-ray and optical light curves appears to have timescale-invariant properties: the X-ray/optical CCF maintains a similar, but rescaled, shape on timescales ranging at least from 0.1 s to few tens of sec (M03); (c) the correlation does not appear to be triggered by a single type of event (dip or flare) in the light curves; instead, as was shown by M03, optical and X-ray fluctuations of very different shapes, amplitudes and timescales are correlated in a similar way, such that the optical light curve is related to the time derivative of the X-ray one. Indeed, in the range of timescales where the coherence is maximum, the optical/X-ray phase lag are close to $\pi/2$, indicating that the two lightcurves are related through a differential relation. Namely, if the optical variability is representative of fluctuations in the jet power output
$P_j$, the data suggest that the jet power scales roughly like $P_j \propto -\frac{dP_x}{dt}$, where $P_x$ is the X-ray power.

### 3. The energy reservoir model

Malzac, Merloni & Fabian (2004, hereafter MMF04) have shown that the complex X-ray/optical correlations could be understood in terms of an energy reservoir model. In this picture, it is assumed that large amounts of accretion power are stored in the accretion flow before being channeled either into the jet (responsible for the variable optical emission) or into particle acceleration/heating in the Comptonizing region responsible for the X-rays. MMF04 have developed a time dependent model which is complicated in operation and behaviour. However, its essence can be understood using a simple analogue: Consider a tall water tank with an input pipe and two output pipes, one of which is much smaller than the other. The larger output pipe has a tap on it. The flow in the input pipe represents the power injected in the reservoir $P_i$, that in the small output pipe the X-ray power $P_x$ and in the large output pipe the jet power $P_j$. If the system is left alone the water level rises until the pressure causes $P_i = P_j + P_x$. Now consider what happens when the tap is opened more, causing $P_j$ to rise. The water level and pressure (proportional to $E$) drop causing $P_x$ to reduce. If the tap is then partly closed, the water level rises, $P_j$ decreases and $P_x$ increases. The rate $P_x$ depends upon the past history, or integral of $P_j$. Identifying the optical flux as a marker of $P_j$ and the X-ray flux as a marker of $P_x$ we obtain the basic behaviour seen in XTEJ1118+480. In the real situation, we envisage that the variations in the tap are stochastically controlled by a shot noise process. There are also stochastically-controlled taps on the input and other output pipes as well. The overall behaviour is therefore complex. The model shows however that the observed complex behaviour of XTEJ1118+480 can be explained by a relatively simple basic model involving several energy flows and an energy reservoir. This simple model is largely independent of the physical nature of the energy reservoir. In a real accretion flow, the reservoir could take the form of either electromagnetic energy stored in the X-ray emitting region, or thermal (hot protons) or turbulent motions. The material in the disc could also constitute a reservoir of gravitational or rotational energy behaving as described above. In a stationary flow, the extracted power $P_j + P_x$ would be perfectly balanced by the power injected, which is, in the most general case, given by the difference between the accretion power and the power advected into the hole and/or stored in convective motions: $P_i \simeq \dot{M}c^2 - P_{\text{adv,conv}}$. However, observations of strong
variability on short time scale clearly indicate that the heating and cooling of the X-ray (and optical) emitting plasma are highly transient phenomena, and the corona is unlikely to be in complete energy balance on short timescales. We therefore introduce a time-dependent equation governing the evolution of its total energy $E$:

$$\dot{E} = P_i - P_j - P_x,$$

and we assume that all the three terms on the right hand side are time dependent. The optical variability is produced mainly from synchrotron emission in the inner part of the jet at distances of a few thousands gravitational radii from the hole. We assume that at any time the optical flux $O_{opt}$ (resp. X-ray flux) scales like the jet power $P_j$ (plasma heating power $P_x$). We introduce the instantaneous dissipation rates $K_j$ and $K_x$:

$$P_j(t) = K_j(t)E(t), \quad P_x(t) = K_x(t)E(t).$$

For a specific set of parameters we generate random independent fluctuations (time series) for $K_x$, $K_j$ and $P_i$, solve the time evolution of the energy reservoir $E$ and then use the solution to derive the the resulting optical and X-ray light curves (see MMF04 for details).

Combining equations (1) and (2) we obtain the following relation for the total instantaneous jet power:

$$P_j = P_i - (1 + \dot{K}_x K_x^{-2}) P_x - \dot{P}_x / K_x.$$  \hspace{1cm} (3)

We can see from this equation that the differential scaling $P_j \propto -\dot{P}_x$, observed in XTEJ1118+480, will be rigorously reproduced provided that: (1 ) $K_x$ is a constant; (2 ) $P_i - P_x$ is a constant. It is physically unlikely that those conditions will be exactly verified. In particular, $P_x$ is observed to have a large RMS amplitude of variability of about 30 percent. However, the observed differential relation holds only roughly and only for fluctuations within a relatively narrow range of time-scales $1 - 10s$. Therefore, the above conditions need only to be fulfilled approximatively and for low frequency fluctuations ($> 1s$). In practice, the following requirements will be enough to make sure that the low frequency fluctuations of the right hand side of equation 3 are dominated by $\dot{P}_x$:

- $P_x \ll P_i$, implying that the jet power, on average, dominates over the X-ray luminosity;
- the amplitude of variability of $K_x$ and $P_j$ in the 1-10 s range is low compared to that of $P_i$. In other words the 1-10 s fluctuations
of the system are mainly driven by the jet activity, implying that the mechanisms for dissipation in the jet and the corona occur on quite different time-scales.

Figure 1 shows the results of a simulation matching the main timing properties of XTE J1118+480. In this simulation jet power was set to be 10 times larger than the X-ray power. The model produces an X-ray power spectrum with a plateau up to \( \sim 0.1 \) Hz and a power-law component with slope \( \sim 1.4 \) above that frequency, with most of the X-ray variability occurring around 0.1 Hz. The optical PDS power-law has a flatter slope \( \sim 1 \) up to 1 Hz and then softens to a slope similar to that of the X-ray PDS. The resulting optical ACF is significantly narrower than the X-ray one. The full-width-at-half-maximum (FWHM) of the two ACFs differs by a factor > 2. The overall coherence is low \(< 0.4\): reaching a maximum in the 0.1–1 Hz range and decreasing rapidly both at lower and higher frequency. The phase-lags are close to \( \pi/2 \) in the 0.1–1 Hz range and increase from 0 at low frequencies up to \( \pi \) at around 6 Hz. At higher frequencies the phase lags spectrum is characterized by large oscillations. Finally the resulting CCF rises very quickly at positive optical lags, peaks around 0.5 s (this is the post-peak) and then declines slowly at larger lags. The two bands appear to be anti-correlated at negative optical lags indicating a systematic optical dip 1-2 s before the X-rays reach their maximum (pre-dip). All these characteristics are observed in XTE J1118+480.

4. Jet dominance in XTE J1118+480 and other low-luminosity sources

The total mass accretion rate onto the black hole can be estimated from the observed luminosity of the cold disc component which in the case of XTE J1118+480 can be estimated from fits to the optical, UV and EUV spectra (see e.g. Chaty et al. 2003). The result depends on several assumptions regarding the geometry and the physical mechanisms for energy dissipation in the disc and the hot comptonising medium. However, for reasonable parameters, the estimated accretion rate is much larger than the observed bolometric luminosity (by at least a factor of ten). The important issue, however, would be to determine whether the missing accretion power escapes the system in the (low radiative efficiency) jet or in other forms of non-radiative losses, such as a slow wind, or large scale convective motions, or advection into the black hole. The answer to this question resides in the exact determination of the jet kinetic power. Unfortunately, there are major uncertainties in this determination, mainly because the jet radiative efficiency is not
Figure 1. Sample input time series (panel a) and power spectra (panel b) of $P_i$, $K_i$, $K_x$, resulting X-ray and optical fluxes light curves (panel c), X-ray/optical autocorrelation and cross-correlation functions (panel d), power spectra, coherence and phase-lags (panel e).

known. The jet is expected to be a poor radiator because most of the energy is lost in adiabatic expansion. Thus, although the radiation from the jet represents a small fraction of the bolometric luminosity the jet could dominate the energetics. For the case of XTE J1118+480, typical efficiency $\epsilon_j \sim 0.01$ would already imply that the total jet power dominates over the X-ray luminosity. As discussed above, the analysis of
our time dependent modeling strongly requires \( f_x \lesssim 0.1 \), corresponding to a jet efficiency \( \epsilon_j \lesssim 3 \times 10^{-3} \).

There are additional independent arguments in favour of jet dominance in low/hard state sources and in XTE J1118+480 in particular. Based on the observed radio flux \( (L_R) \) and X-ray correlation observed in hard states sources (Falcke & Biermann 1996; Gallo, Fender & Pooley, 2003), as well as on standard synchrotron formulae (Heinz & Sunyaev, 2003), Fender, Gallo & Jonker (2003, hereafter FGP03) have shown that, provided that advection into the black hole horizon and/or convective motions do not store a large fraction of the accretion power, there should exist a critical accretion rate, \( \dot{m}_{\text{cr}} \), below which an accreting black hole is jet-dominated. The exact value for the critical accretion rate could be inferred from the observations, if we knew the total jet power at a certain X-ray luminosity, and is given by \( \dot{m}_{\text{cr}} = 2P_j^2/L_x \), corresponding to a critical X-ray luminosity \( L_{x,\text{cr}} = \dot{m}_{\text{cr}}/2 \). Fender et al. (2001) derived a lower limit for the jet to X-ray power ratio in XTE J1118+480: \( P_j/L_x = 0.2 \), and FGP03 used this conservative estimates to determine the value of the critical rate \( \dot{m}_{\text{cr}} \simeq 7 \times 10^{-5} \). However such a low value of the critical luminosity leads to several problems.

First, as shown in FGJ03, during the transition from a disc to a jet-dominated state, the dependence of the X-ray luminosity on the accretion rate changes from being \( L_x \propto \dot{m}^2 \), the right scaling for \textit{radiatively inefficient flows}, to \( L_x \propto \dot{m} \), the scaling for \textit{radiatively efficient flows} (see Fig. 1 of FGJ03). This would imply that with \( L_x \sim 10^{-3} \), XTE J1118+480 should be a \textit{radiatively efficient} system. As discussed above, there is however strong observational evidence of the contrary.

Furthermore, black holes in the hard state should show some kind of spectral transition in the X-ray band at the critical luminosity \( L_{x,\text{cr}} \approx 3 \times 10^{-5} \), due to the drastic changes in emission mechanisms that are needed to account for the different scalings of \( L_x \) with the accretion rate. The observations of low/hard state sources at such low luminosities are few and hard to perform, however no indication of any dramatic spectral change in any hard state source down to quiescent level has ever been reported (Kong et al., 2002; Hameury et al., 2003) In fact, the only physical transition that we do actually observe is the transition between the hard and the soft state that occurs at luminosities of at least a few percent of Eddington luminosity (Maccarone 2003). We believe that, if the above mentioned difficulties are to be solved, then \( \dot{m}_{\text{cr}} \) has to correspond to luminosities that are comparable to, or larger than, hard-to-soft state transition luminosities. For the case of XTE J1118+480, instead of using the lower limit for the jet to X-ray power \( (P_j/L_x = 0.2) \), we can adopt the much larger value
$P_j/L_x \sim 10$ required by our variability model. Then we find $\dot{m}_{ct} \sim 0.2$, involving a transition at $L_{x,ct} = \dot{m}_{ct}/2 \sim 0.1$. This is in agreement with the idea that the transition from jet dominated to X-ray dominated states occurs at luminosities similar or slightly higher than the hard to soft state transition. Thus, if the arguments of FGJ03 are correct, an important consequence of the jet dominance in XTE J1118+480 is that all hard state sources are jet-dominated (in the sense that the jet power dominates over the X-ray power). This jet dominance also implies that all hard state sources should be radiatively inefficient. The reason for this inefficiency could be advection into the jet as well as advection into the black hole.

5. Conclusions

The puzzling optical/X-ray correlations of XTE J1118+480, can be understood in terms of a common energy reservoir for both the jet and the Comptonizing electrons. Any energy reservoir model for XTE J1118+480 requires that the total jet power dominates over the X-ray luminosity. Following the same line of arguments as FGJ03, we showed that this situation is likely and probably represents a common feature of all black holes in the low-hard state.

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