X-ray Spectra From Weakly Magnetized Accretion Flows

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ABSTRACT

In this paper, we expand upon previous work that argued for the possibility of a sub-equipartition magnetic field in the accretion flow of a black hole binary system. Using X-ray observations of the three well-known sources A0620-00, XTE J1118+480 and V404 Cyg during the quiescent state, we compare the theoretically expected spectral shape with the observed data in order to verify that the parameters of the sub-equipartition model are plausible. In all three cases, we find that it is possible to reproduce the spectral shape of the X-ray observations with a sub-equipartition flow. These findings support the idea that the quiescent state spectrum of X-ray binary systems is produced by a weakly-magnetized accretion flow. A sub-equipartition flow would pose a significant challenge to our current understanding of jet-launching, which relies on the presence of a strong magnetic field to power the jet.

Keywords: X-ray binary stars; Jets; Stellar mass black holes; Magnetic fields

1. INTRODUCTION

Black hole binaries (BHBs) are luminous sources consisting of a central black hole, accreting from an orbiting companion star. These sources are generally observed in one of four main spectral states, named for their X-ray luminosity and spectral hardness: The high/soft state (HSS), very high state/intermediate state (VHS/IS), low/hard state (LHS) and quiescent state (QS) (Esin et al. 1997; Zdziarski & Gierliński 2004; Remillard & McClintock 2006; Narayan & McClintock 2008).

BHBs spend most of their lifetime in the extremely low luminosity regime known as the quiescent state (Belloni 2010). In this state, the low observed luminosity poses an observational challenge, in spite of the large number of sources that have been discovered. On the other hand, the influence of a jet on observations in this state is likely to be greatly reduced (Narayan & McClintock 2008), making it an ideal laboratory to probe the properties of the accretion flow itself.

Despite a large number of observed sources (around 75, see Tetarenko et al. 2016, for a recent survey), there is still no clear consensus on the structure of the accreting system or its radiative properties in each spectral state. The most common model of such systems consists of two main regions — an inner, hot flow which is optically thin and geometrically thick and an outer, geometrically thin disk, which is optically thick (Esin et al. 1997). In each
of their spectral states, BHBs are also believed to launch jets from their innermost regions (Narayan & McClintock 2008), however the mechanism by which this occurs is still subject to some debate.

Multiwavelength observations and modeling of X-ray binary spectra play an important role in developing our understanding of the structure and properties of the environment surrounding the central black hole (Gallo et al. 2007; Plotkin et al. 2015; Rana et al. 2016; Dinçer et al. 2018, for example). Understanding the parameters of the accretion flow in its inner regions is crucial in uncovering the extreme physics there. In particular, the magnetic field configuration is of utmost importance in models of jet-launching such as the Blandford-Znajek and Blandford-Payne mechanisms (Blandford & Znajek 1977; Blandford & Payne 1982).

In Wallace & Pe’er (2021, hereafter WP21), we showed that the optical/infrared (OIR) spectra of three quiescent sources could be well explained by the standard two-component accretion flow, consisting of an outer thin disk, surrounding an inner, hot accretion flow. In that work, we found that the spectrum at these frequencies was consistent with a sub-equipartition magnetic field strength in the inner flow. In addition, radio observations of the three sources also suggest the presence of a flat-spectrum radio jet (Gallo et al. 2007). These observations, in combination with the sub-equipartition field found in WP21, create a tension with our current understanding of jet-launching, which requires a large magnetic field strength to power and maintain such a jet.

In this paper, we extend our previous work to include X-ray data, in order to verify that the values used in our previous work are plausible, using the observed value of the X-ray spectral index. X-ray observations of quiescent BHB sources generally reveal a power-law slope with spectral index around 2 (Kong et al. 2002; Corbel et al. 2006; Remillard & McClintock 2006). This power-law arises naturally from scattering of soft photons by a population of thermal electrons (Rybicki & Lightman 1979; Zdziarski 1985). The spectral index of the X-ray spectrum is tied to the temperature and density of the emitting plasma and therefore we can use it to confirm that the parameters used to argue for a weak magnetic field in WP21 are consistent with the observed X-ray spectral slope. This offers further support for a sub-equipartition field configuration, that not only poses a challenge for models of jet-launching, but also raises questions about the dissipation mechanisms necessary to maintain the weakly magnetized state of the disk.

2. X-RAY DATA

We extend the analysis of WP21 using the data described in the following sections. In each case, we estimate the Compton $y$-parameter and the optical depth by $y = (\nu F_{\nu, IC}) / (\nu F_{\nu, \text{sync}})$ and $\tau = (F_{\nu, IC}) / (F_{\nu, \text{sync}})$ (see, for example, Pe’er & Loeb 2012). This can be used to extract information about the temperature of the plasma, for example, which allows for a cross-check of our results with the observational data. The model spectra are constructed according to the procedure described in WP21.

2.1. A0620-00

A0620-00 is a soft X-ray transient source, consisting of a 6.6 $M_\odot$ black hole, orbited by a 0.4 $M_\odot$ K-type companion, with an orbital period of 7.75 hr (McClintock & Remillard 1986; Cantrell et al. 2010). It is one of the most extensively observed BHB systems to date.

Several X-ray observations of A0620-00 in quiescence have been carried out using Chandra, with observations carried out in 2000, 2005 and 2013, as reported in Dinçer et al. (2018). The observed spectral index, $\Gamma_{\text{obs}}$, varies slightly
across different observations, falling in the range 2.07 ± 0.13 – 2.32 ± 0.16. For our purposes, we make use of the 2005 observations, originally reported by Gallo et al. (2007) (with $\Gamma_{\text{obs}} = 2.24 \pm 0.16$), which are strictly simultaneous in radio and X-ray, and are nearly simultaneous with optical data from the Small and Moderate Aperture Research Telescope (SMARTS). The optical observations were taken one day before the radio/X-ray data, while infrared data was taken 5 months beforehand (March 2005 vs. August 2005) with Spitzer. This non-simultaneity is important to note when evaluating the conclusions of our study, given that a variability timescale of months is typical of BHB systems (Remillard & McClintock 2006). However, A0620-00 has not been observed to undergo an outburst between 1996 and 2015 (Tetarenko et al. 2016), combined with the consistent measurements of $\Gamma_{\text{obs}}$ over this time frame, we therefore believe it is reasonable to assume that its radiative properties are relatively stable over this period of observation.

### 2.2. XTE J1118+480

XTE J1118+480 is another soft X-ray transient source, consisting of a 7.3 $M_\odot$ black hole orbited by a 0.2 $M_\odot$ companion, with an orbital period of 4.1 hr. We use the X-ray observations reported in Plotkin et al. (2015), which were carried out using Chandra in 2013. The observed spectral index, $\Gamma_{\text{obs}}$, is reported to be 2.02 ± 0.41.

These observations were carried out nearly-simultaneously with radio, near infrared (NIR)/optical and ultraviolet (UV) measurements. The radio measurements were obtained by the Very Large Array (VLA), the NIR/optical by the William Herschel Telescope (WHT) and the UV by Swift. In addition to the simultaneous data, there are also several non-simultaneous measurements available for XTE J1118+480, detailed in Plotkin et al. (2015).

### Figure 1.

Spectral energy distributions of A0620-00 (left) and XTE J1118+480 (right). These figures are similar to those in WP21, but with the addition of X-ray data from Chandra. The X-ray emission calculated for the sub-equipartition model shows good agreement with the X-ray data in both cases. Typical values of the equipartition ratio $\varepsilon_B$ here are $10^{-8}$, indicating a very weakly-magnetized disk.

### 2.3. V404 Cygni

V404 Cyg consists of a 9 $M_\odot$ black hole orbited by a 0.7 $M_\odot$ K-type companion, with an orbital period of 155 hr (Bernardini et al. 2016). There are several X-ray observations of V404 Cyg in its quiescent state, that are all generally in agreement. Here, we use the observations compiled by Hynes et al. (2009), which are primarily based on a simultaneous observing campaign carried out in 2003, supplemented by archival (non-simultaneous) data. Radio data were obtained using both the VLA and the Westerbork Synthesis Radio Telescope (WSRT), the optical measurements are from WHT, the UV from the Hubble Space Telescope (HST) and the X-ray from Chandra.

### 3. RESULTS

In the cases of A0620-00 and XTE J1118+480 (see fig. 1), we find good agreement with the observational data from infrared to X-rays. For A0620-00, a Compton $y$-parameter of $5 \times 10^4$ closely reproduces the observed X-ray data, corresponding to a plasma optical depth $\tau$ of $\sim 10^{-5}$. In XTE J1118+480, we find that $y = 2 \times 10^4$ and $\tau \sim 10^{-5}$ give good agreement with observations. These values are sensible, given that the synchrotron emission in this
model is assumed to come from a very hot, optically thin flow.

The accretion rate we used for A0620-00 is on the order of $10^{-9} M_\odot \text{yr}^{-1}$, which corresponds to around 0.5% of the Eddington value. In XTE J1118+480, the accretion rate is around $10^{-10} M_\odot \text{yr}^{-1}$, or $5 \times 10^{-4} M_\text{Edd}$. The temperature at the inner boundary of the hot accretion flow in each case is on the order of $10^{11} K$, falling to around $10^9 K$ at the transition to the thin disk.

In the case of V404 Cyg (fig. 2), it was not possible to directly match the observations with a purely two-component model. This is most likely due to contamination of the spectrum by the companion star. It was, however, possible to constrain the accretion rate to below $10^{-8} M_\odot \text{yr}^{-1}$ (5% of the Eddington value), which then allows us to carry out the same analysis on this source. Again, we find that the magnetic field must be strongly sub-equipartition in order to reproduce the spectral features seen in observations at OIR frequencies. For the X-ray emission, we find that in this case, the emission is better explained by upscattering of the thin disk photons by the hot inner flow, rather than upscattering of the synchrotron photons as in the other two sources. This gives good agreement with the X-ray data for $y = 2 \times 10^3$ and $\tau = 1.5 \times 10^{-2}$.

Therefore in all cases, we find that the parameters used here are in good agreement with the available spectral data, offering further support to the sub-equipartition magnetic field configuration as a potential model for the emission in BHB sources. In all three cases, the data used here are simultaneous, or at least nearly-simultaneous across the different frequencies. This is important due to the time-varying nature of these objects, with typical variation timescales of hours to days. Thus even observations that occur close together, but not simultaneously, may exhibit different spectral features depending on the source and its properties.

4. DISCUSSION

In each case, we found that the X-ray emission in our model is in good agreement with observed values. This backs up the conclusion of WP21, that the emission from these sources in their quiescent states (in particular their optical and infrared emission) can be explained using synchrotron emission from a thermal population of electrons in a weakly-magnetized inner disk.

Given the extensive observations of A0620-00 and XTE J1118+480 and their similarity to other quiescent sources, the viability of a sub-equipartition magnetic field in those sources raises the prospect that such a configuration may be common across other sources in the quiescent state. The parameters used in WP21 are typical of weakly accreting binaries in their quiescent states and so in combination with the available X-ray data, the results of this paper...
further support the sub-equipartition model as an explanation for the broadband spectrum of not just A0620-00 and XTE J1118+480, but potentially quiescent sources more broadly.

Since BHB sources are readily observed in the X-ray bands, including in quiescence, it is vital that any model of their emission be consistent with observations in that range. In each case, the results obtained here show that the X-ray data supports the sub-equipartition model, thus passing an important test. An accretion flow with a sub-equipartition magnetic field can therefore explain the entire observed spectral energy distribution, from optical to X-ray, assuming that radio emission from a jet exists (for which there is strong observational evidence).

These findings underscore the fact that the requirement for such a low magnetic field has important consequences for our understanding of the physical processes at play in accretion flows. As discussed in WP21, maintaining the magnetic field at such low values would require a large amount of dissipation throughout the flow, which may in turn have dynamical or radiative consequences on the structure of the system. This also raises issues around jet-launching, given that the magnetic field is central to that process and there is clear evidence for the presence of at least weak jet emission in each of these sources.

On the other hand, for V404 Cyg, we find that the X-ray emission is better explained by upscattering of thin disk photons rather than those from the synchrotron-emitting inner region. The spectral shape of the observed X-ray emission here is somewhat harder than the standard value of $\sim 2$, but in line with observations reported by Kong et al. (2002), Corbel et al. (2006) and Hynes et al. (2009). The behaviour of V404 Cyg is unusual compared to the other two sources considered here, and its higher luminosity has led to some suggestions that it may be on the boundary between the quiescent state and the hard state (Gallo et al. 2007).

V404 Cyg is also observed to experience “hard-only” outbursts, undergoing one such outburst in 2015 (Tetarenko et al. 2016), which is after the period of observations of Rana et al. (2016), but given the long period of quiescence that preceded the outburst, from 1989-2015, this may offer an explanation for the change in spectral parameters. These hard-only outbursts generally do not follow the standard path along the hardness-intensity diagram, never reaching the soft state and instead transitioning only between the hard state and quiescence.

Corbel et al. (2006) note that V404 Cyg may not soften between the LHS and QS, as other sources do, but may even harden. This behavior is unusual in BHBs, where a softening of the X-ray spectrum is generally observed between the LHS and quiescence. This absence of softening is also observed to occur in a small subset of sources, suggesting that perhaps there is a sub-population of BHBs whose accretion structure does not follow the canonical model. Corbel et al. (2006) suggest that the difference in spectral index may arise from differences in the mass transfer rate between long- and short-period binaries.

Indeed, V404 Cyg has a much longer orbital period (155 hr) than both XTE J1118+480 and A0620-00 (4.1 hr and 7.75 hr respectively). The mass transfer rate (i.e. the accretion rate) is correspondingly higher in V404 Cyg, which is in line with theoretical expectations for a binary system accreting by Roche lobe overflow (Frank et al. 2002). This difference arises due to the fact that the mass transfer may be driven by one of two separate mechanisms: evolutionary expansion of the donor star — known as $n$-driven systems — or angular momentum losses through gravitational radiation and magnetic braking — known as $j$-driven. Due to constraints on the size of the Roche lobe for $n$-
driven systems, this mechanism can only operate in long period systems. Menou et al. (1999) find that there is a “bifurcation period” separating the range of operation of the two mechanisms, occurring at $P_{\text{bif}} = 0.5 - 2$ days. This places V404 Cyg firmly in the $n$-driven regime and the other two sources in the $j$-driven regime. Similarly, GRO 1665-40 is another long-period source, with an orbital period of around 2.5 days (Tetarenko et al. 2016). Its spectral index has been observed to be around 1.3 (Corbel et al. 2006, see), again harder than the short-period sources considered here.

We therefore conclude that in all three sources considered, the results obtained here support the findings of WP21, namely a sub-equipartition magnetic field in the accretion flow. Under this sub-equipartition framework, we are still left with the challenge of how a jet could be launched by such a weakly-magnetized disk, as well as how an accretion flow could efficiently dissipate the magnetic field to maintain such a weak magnetization. As noted in WP21, the flat/inverted shape of the spectrum in radio observations of BHBs seem to indicate the presence of a weak jet even at the low luminosities of the quiescent state. Given that that the Blandford-Znajek mechanism — which is the usual mechanism invoked to explain the launching of jets from around black holes — requires the presence of a strong magnetic field, it is not clear that it can operate efficiently in these scenarios.

5. CONCLUSIONS

In this paper, we have extended the analysis of WP21, using X-ray observational data for the three sources considered in that work to further support the possibility of a sub-equipartition flow as a model for the observed spectra in quiescent X-ray binary systems. We find that in each case, the parameters of the accretion flows used in WP21 are consistent with X-ray observations of those sources, reproducing the observed X-ray spectral index in each case. This finding further supports our previous result, namely that the emission can be described by a weakly-magnetized, two-component accretion flow.

As noted in our previous work however, we require jet emission to adequately explain the spectrum at radio frequencies, suggesting that jets are still launched despite this low magnetization. Given the important role played by the magnetic field in the current understanding of jet-launching, the possible existence of jets launched by weakly-magnetized accretion flows raises important questions about the limits of those models, as well as the dissipation processes necessary within the accretion flow in order to maintain this low magnetic field strength.

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