Origin of X-ray Emission from Transient Black Hole Candidates in Quiescence

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ABSTRACT
We report results from a systematic study of X-ray emission from black hole transients in quiescence. In this state, mass accretion is thought to follow the geometry of an outer optically thick, geometrically thin disc and an inner optically thin, geometrically thick radiatively inefficient accretion flow (RIAF). The inner flow is likely also coupled to the jets near the black hole that are often seen in such systems. The goal of the study is to see whether the X-ray emission in the quiescent state is mainly powered by the accretion flow or the jets. Using data from deep XMM-Newton observations of selected black hole transients, we have found that the quiescent X-ray spectra are, to a high precision, of power-law shape in the cases of GRO J1655\(-\)40 and V404 Cyg. Such spectra deviate significantly from the expected X-ray spectrum of the RIAF at very low accretion rates. On the other hand, they can naturally be explained by emission from the jets, if the emitting electrons follow a power-law spectral distribution (as is often assumed). The situation remains ambiguous in the case of XTE J1550\(-\)564, due to the relatively poorer quality of the data. We discuss the implication of the results.

Key words: accretion, accretion discs — black hole physics — radiation mechanisms: thermal, non-thermal — stars: individual (XTE J1550\(-\)564, GRO J1655\(-\)40, V404 Cyg) — X-rays: binaries

1 INTRODUCTION
The majority of X-ray binaries that are known to contain a stellar-mass black hole are transient X-ray sources. They spend most of their time in the quiescent state, in which the mass accretion rate is thought to be extremely low. Occasionally, they undergo an outburst during which they may become the brightest X-ray sources in the sky. The exact mechanism that triggers such an outburst is not entirely understood but is thought to be related to a sudden surge in the accretion rate that is caused by a thermal instability in the accretion disc (see reviews, e.g., by King 1995 and Lasota 2001). During an outburst, the X-ray properties of a black hole transient is often described empirically in terms of spectral states (e.g., McClintock & Remillard 2006; Xue, Wu, & Cui 2008).

It is proposed that the spectral states may correspond to different configurations of the underlying accretion process at different mass accretion rates (Narayan 1996; Narayan, McClintock & Yi 1996; Esin, McClintock, & Narayan 1997). Specifically, when the accretion rate is high in the high-soft state, the accretion flow is thought to follow the geometry of the Shakura & Sunyaev (1973) disk (SSD), which is geometrically thin and optically thick. This can naturally explain the observed blackbody-like X-ray spectrum that is characteristic of the high-soft state. As the accretion rate decreases, the source evolves towards the low-hard state. In the process, a phase transition is thought to occur in the inner portion of the disc, in which the accreted matter is heated to nearly local virial temperatures and may also form an outflow wind (see Narayan 2005 for a comprehensive review of the models, their evolution, and their applications to black hole candidates and active galactic nuclei). The accretion flows in this region is a geometrically thick but optically thin configuration, and is radiatively inefficient. The accretion power is mostly advected into the black hole or carried away by the outflow (Blandford & Begelman 1999). Such a radiatively inefficient accretion flow (RIAF) is capable of producing hard X-rays by up-scattering ambient soft photons. This can naturally explain the increasing dominance of the power-law component of the X-ray spectrum, as the source approaches the low-hard state. The RIAF model predicts that the trend continues towards even lower accretion rates, as more of the accretion flow becomes advection dominated, and that the X-rays in the quiescent state originate entirely from the RIAF (Narayan, McClintock, & Yi 1996).
A more recent development is the realization of the potentially critical role of jets, which seem to be ubiquitous in black hole transients (see review by Fender 2006 and references therein). Yuan, Cui & Narayan (2005) demonstrated that it would be nearly impossible for the RIAF model, which is quite successful in explaining the X-ray emission from black hole transients in the low-hard state, to also account for the observed emission at longer wavelengths (radio and IR in particular). In order to describe the broadband spectral energy distribution (SED) in the low-hard state, they showed that contributions from both accretion flow and jets would be needed, with the formerly mainly responsible for emission at UV/X-ray wave-lengths, the latter for emission at radio/IR wavelengths, and both for emission in between (cf. Malzac, Merloni, & Fabian 2004, who argued that the optical emission might be dominated by the jets), when the accretion rates are relatively high. Extrapolating the result of Yuan et al. (2005) to lower accretion rates, Yuan & Cui (2005) predicted that the X-ray emission from the jets would eventually exceed that from the hot flow (because the former is proportional to the accretion rate $\dot{m}$, normalized to the Eddington rate, and the latter roughly to $\dot{m}^{\frac{3}{2}}$). In the quiescent state, the X-ray emission should, therefore, be mainly powered by the jets, at variance with the prediction of the RIAF model. Falcke, Kording & Markoff (2004) also postulated that the X-ray emission of the quiescent state would be dominated by the jets. But, in contrast to Yuan & Cui (2005), they argued that this would be the case even for the low-hard state. Is it the accretion flow or jets that power the X-ray emission from black hole transients in the quiescent state? Yuan & Cui (2005) proposed two observational tests to answer the question. If the quiescent X-rays are powered by the jets, they predicted: (1) the radio/X-ray correlation would steepen when the X-ray flux drops below a characteristic value and (2) the X-ray spectrum would be of power-law shape. It has been claimed that the observation of A0620-00 is at odds with the first prediction (Gallo et al. 2006). However, the conclusion hinged critically on a radio/X-ray correlation that had been thought to hold for all black hole candidates. The universality of the radio/X-ray correlation has since been brought into question (Xue & Cui 2007). The second prediction is a viable test because the X-ray spectrum of an RIAF should deviate strongly from power-law shape at sufficiently low accretion rates, when the density of the flows becomes so low that Comptonization is dominated by single scattering (Narayan, McClintock, & Yi 1996; Quataert & Narayan 1999; McClintock et al. 2003; Yuan, Cui, & Narayan 2005).

In this work, we present results from a systematic study of black hole transients in quiescence. A number of such sources had been observed and detected earlier with Chandra and XMM-Newton (Kong et al. 2002; Hameury et al. 2003) but none of the X-ray spectra obtained are of sufficiently high quality that would allow us to distinguish jet-based and accretion-based models. To improve the situation, we carried out deep observations of selected sources with XMM-Newton. The results reported here are based on data from these as well as an archival XMM-Newton observation.

2 OBSERVATIONS AND DATA ANALYSIS

Based on information on the quiescent X-ray fluxes of transient black holes from previous works (Kong et al. 2002; Hameury et al. 2003), we selected V404 Cyg, XTE J1550–564, and GRO J1655–40 for this pilot study. V404 Cyg is the brightest in X-rays among all black hole transients that have been observed in the quiescent state and is thus the best source for our investigation. It had already been observed with XMM-Newton for about 40 ks, with the EPIC detectors in the full-window mode and the medium filter used. We estimated that the quality of the data from that observation would be sufficient for our purposes. For this work, therefore, we simply used the archival data.

XTE J1550–564 had never been observed with XMM-Newton before, despite being the first black hole candidate to have its jets directly imaged in X-rays and also being one of the most active, producing an outburst (of varying magnitude) every couple of years. The quiescent X-ray luminosity of XTE J1550–564 is nearly the same as that of V404 Cyg ($\sim 10^{33}$ ergs s$^{-1}$; Kong et al. 2002) but it lies at a larger distance. It seems to have a harder X-ray spectrum than V404 Cyg but the uncertainty is quite large (Kong et al. 2002). We observed XTE J1550–564 in quiescence with XMM-Newton for about 60 ks in 2007, with the EPIC detectors in the full-window mode but the thin filter was used. Unfortunately, the observation suffered from severe contamination by solar flares. The standard filtering procedure (as described in the XMM-Newton Data Analysis Cookbook) removed the large flares but smaller ones were still visible after the filtering. We performed additional filtering, based on the 0.5–10 keV lightcurve of the whole chip, to minimize the effects of the contamination. The resulted effective exposure times are only about 14 ks and 24 ks for the pn and MOS detectors, respectively.

GRO J1655–40 is also relatively luminous in X-rays in the quiescent state but the luminosity seems to vary greatly, from about $3 \times 10^{31}$ to $10^{33}$ ergs/s (Hameury et al. 2003). The source is at roughly the same distance as V404 Cyg. It had already been observed by XMM-Newton for about 50 ks (Hameury et al. 2003). The X-ray flux measured is about a factor of 5 less than that of XTE J1550–564. Since a similar flux had been obtained earlier with Chandra (Kong et al. 2002), this is perhaps the more typical state for the source. The X-ray spectrum of GRO J1655–40 is quite similar to that of XTE J1550–564 but the spectrum lacks statistics for our purposes. We observed GRO J1655–40 in quiescence with XMM-Newton in 2007 for about 185 ks. The EPIC detectors were operated in the full-window mode with the thin filter. We should note that this observation was also partially contaminated by solar flares, but not as severely as in the case of XTE J1550-564.

Table 1 summarizes the key characteristics of the XMM-Newton observations. We followed the same procedures, as described in the Data Analysis Cookbook, for all observations in preparing and filtering data, making light curves, extracting spectra, and generating the corresponding response matrix files and ancillary response files for subsequent spectral modeling. Briefly, the source counts were extracted from within a circular region that is centered on each source and is of radius 40′′ (or roughly the 85% encircled-energy radius of the on-axis PSF), which is the largest source region that could be used without extending to a different CCD chip. The background counts were obtained from a different circular region of radius 80′′ that is located on the same chip, sufficiently far from any sources.

The raw pn and MOS spectra were re-binned such that each energy bin contains at least 16 counts. They were then filtered to cover the energy range of 0.5–10 keV. A 1% systematic error was added to the spectra. The initial modeling was carried out in XSPEC (Arnaud 1996). We chose to jointly fit the individual pn and MOS spectra. For XTE J1550–564, however, we only used}

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1 See [http://wave.xray.mpe.mpg.de/xmm/cookbook](http://wave.xray.mpe.mpg.de/xmm/cookbook)
the pn spectrum, because of the poorer statistics of the MOS data, and limited the energy range to 0.5–7.7 keV, where the signal-to-noise ratio is adequate. In all three cases, the X-ray spectrum can be fitted satisfactorily with a simple power law that is attenuated by interstellar absorption. Figure 1 shows the X-ray spectra of the three sources, along with the best-fit power law residuals and parameters. The model parameters are summarized in Table 2. Note that the hydrogen column density was fixed to the line-of-sight value in the case of XTE J1550–564; the actual value should be lower but it would hardly affect our results, again due to the poor quality of the data. Our results on V404 Cyg are in agreement with those previously obtained from the same dataset (Bradley et al. 2007).

In each case, we used the best-fit power law to compute unabsorbed photon and energy fluxes for a set of energy bins, to quantify the intrinsic X-ray spectrum of each source. The widths of the bins (typically 0.2–0.3 keV) were chosen to maintain sufficiently small error bars on the fluxes across the entire energy range. The error bars were derived (in XSPEC) by randomly drawing 1000 sets of parameters and taking the 1σ range of the resulted flux distribution. From the photon and energy fluxes we also computed the effective energy of each bin (Eeff = Fν/Φen). The unabsorbed X-ray spectra are shown in Figure 2. It is quite apparent that the quiescent spectra of GRO J1655–40 and V404 Cyg are, to a high precision, of power-law shape. The situation is a bit ambiguous in the case of XTE J1550–564, due to the limited statistics of the data.

3 MODELING RESULTS

We proceeded to examine the derived spectra with the same coupled accretion–jet model that has provided a good description of the SED of XTE J1118+480 over a broad spectral range (from radio to hard X-ray frequencies; Yuan, Cui, & Narayan 2005). In this model, the accretion flow is described as a standard thin disk outside a transition radius rtr and an RIAF inside this radius. For the quiescent state, rtr is expected to be very large (Narayan 2005), hence the disc is cool and likely contributes only to IR/optical emission. The effect of outflow/convection in the RIAF is taken into account in calculating the dynamics of the RIAF. The main parameters of RIAF are the viscous parameter α, a parameter describing the strength of the magnetic field β, and a parameter δ which determines the fraction of the turbulent dissipation which directly heats electrons. For the radiation processes in the RIAF, we considered synchrotron emission, bremsstrahlung emission, and inverse Compton scattering. Near the black hole, we assumed that a fraction of the accretion flow is transferred into the vertical direction to form a jet. Within the jet, internal shocks occur due to the collision of shells with different velocities. These shocks accelerate a fraction of the electrons into a power-law energy distribution. The steady-state energy distribution of the accelerated electrons is self-consistently determined, taking into account the effect of radiative cooling. The energy density of accelerated electrons and amplified magnetic field is determined by two parameters, εe and εB, which describe the fraction of the shock energy going into electrons and the magnetic field, respectively. Then the synchrotron radiation from these accelerated electrons can be calculated. We note that the effects of inverse Compton scattering of the synchrotron photons in the jet are negligible due to small scattering optical depth. We refer the readers to Yuan et al. (2005) for a detailed description of the model.

For this work, we fixed all model parameters to the values derived from fitting the SED of XTE J1118+480 (Yuan, Cui, & Narayan 2005), except for those that are source specific, such as distance, inclination angle, black hole mass, accretion rate, and rtr, which is presumed to depend on accretion rate. As before, we assume that the accretion rate is dependent of radius in the RIAF, $M = M_0(r/r_{tr})^{0.3}$ (Yuan, Cui, & Narayan 2005). However, we did not assume that the accretion rate is constant in the optically thick disc, because the disc is not expected to be in a steady state for the quiescent state (e.g., Lasota 2001). Instead, the accretion rate is expected to decrease with radius, resulting in a roughly isothermal temperature profile, which deviates significantly from the SSD. For this work, therefore, we adopted a constant-temperature disc for the model (although we also investigated scenarios in which the disc is assumed to be of SSD type). The results of this modeling are also shown in Fig. 2, with the model parameters summarized in Table 3.

We also explored the possibility of modeling the X-ray spectra with a pure accretion model (consisting only of disc plus RIAF). The results from our best attempts are also shown in Fig. 2 (insets); the values of the model parameters are shown in Table 3. We should note that in the cases of XTE J1550-564 and GRO J1655-40 we had to adopt a lower value for the viscous parameter in the RIAF (not shown in the table), $\alpha = 0.1$ as opposed to 0.3 (see Yuan, Cui, & Narayan 2005), to achieve better fits to the data. As is apparent from Fig. 2, the high-quality quiescent X-ray spectra of GRO J1655–40 and V404 Cyg cannot be accounted for by emission from the RIAF alone. We believe that this conclusion is robust, independent of theoretical uncertainties associated with the model adopted. Fundamentally, at very low accretion rates, contribution from multiple scatterings in the hot flows is negligible, so the Comptonized spectrum deviates strongly from a power law. On the other hand, the observed power-law shape of the quiescent X-ray spectra can be naturally explained by emission from the jets, if the spectral energy distribution of the emitting electrons is, as often assumed, of power-law shape. Therefore, our results are in favor of a jet origin of the X-ray emission from black hole transients in quiescence, lending support to the prediction of Yuan & Cui (2005).

The situation is still ambiguous in the case of XTE J1550–564, due to the relatively large uncertainties of the measurements. An RIAF origin of the X-ray emission cannot be ruled out in this case (see Fig. 2). A deeper XMM-Newton observation of the source in quiescence would provide the much needed data to resolve the ambiguity. In general, we believe that it is important to extend the effort to more black hole transients. The data would allow us to see whether the conclusion holds for such systems as a population.

For comparison, we also included in Fig. 2 the published results on the quiescent IR/optical fluxes of the disc (Casares et al. 1993; Orosz et al. 2002; Greene et al. 2001). It should, however, be stressed that these measurements were not made simultaneously with the X-ray measurements and should thus be taken with caution, because the sources can vary significantly even in the quiescent state (e.g., Bradley et al. 2007). Extrapolating our “best-fit” models to the IR/optical wavelength, we found that the predicted fluxes fall below the values from earlier measurements for XTE J1550–564 and V404 Cyg. We found that the discrepancy was worse when we replaced the constant-temperature disc with the SSD; the real disc is likely to fall in between these two extreme scenarios. The discrepancy could be attributed to the variability of the sources in the quiescent state. For instance, the accretion rates might have been higher during the IR/optical observations, so the discs were brighter then. Alternatively, there might be additional sources of IR/optical emission, for instance, hot spots where gas from the companion star impacts the accretion disc (cf. McClin-
trock et al. 2003). We should note, however, that in both cases we were able to find good fits also to the IR/optical data by adopting different values for the distance and inclination angle of the systems (that are still within measurement uncertainties).

4 DISCUSSION

Fender et al. (2003) argued, on the basis of the “universal radio/X-ray correlation”, that the energetics of the quiescent state ought to be dominated by the jets, in the sense that the kinetic power of the jet is much greater than the X-ray luminosity of the accretion flows. In their jet-dominated state, however, the X-ray luminosity of the jet is not necessarily also greater than that of the accretion flows, because the radiative power of the jet is only of the order of 1% of the kinetic power (see Yuan & Cui 2005 for a more detailed discussion). Here, we have shown that the quiescent X-rays from transient black hole candidates are likely to originate from the jets, as opposed to the accretion flows.

In summary, we have, for the first time, found direct evidence that the quiescent state may be fundamentally different from the low-hard state, as far as the source of X-ray emission is concerned. Contrary to the view that the former may be a simple extension of the latter towards lower accretion rates, our results suggest that the X-ray emission from transient black holes is dominated by contribution from the jets (or other sources of non-thermal electrons) in the quiescent state, while in the low-hard state it is likely dominated by contribution from the RIAF (e.g., Esin, McClintock, & Narayan 1997; Yuan et al. 2007).

Finally, we would like to emphasize that the prediction of Yuan & Cui (2005) is insensitive to the mass of black holes and might thus also hold for active galactic nuclei (AGN). Wu, Yuan & Cao (2007) has recently modeled a sample composed of eight FR I galaxies and found that their X-ray spectra should be dominated by jets, rather than by RIAFs, if their luminosities are below \( \sim 10^{-6} L_{\text{Edd}} \) and vice versa, as predicted by Yuan & Cui (2005). Wrobel, Terashima, & Ho (2008) observed two low-luminosity AGN at 8.5 GHz and found that the observed radio luminosity is within a factor of 3 of the value that is predicted from the observed X-ray luminosity and the radio–X-ray–mass relation derived by Yuan & Cui (2005).

ACKNOWLEDGMENTS

This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center. The work was supported in part by NASA through grants NNX07AQ29G and NNX07AH43G and by Natural Science Foundation of China through grant 10773024. F.Y. also acknowledges support from the Bairen Program of Chinese Academy of Sciences.

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### Table 1. Summary of Observations

| Obs. ID       | Source          | Date        | Duration (ks) | Effective Exposure (ks) |
|---------------|-----------------|-------------|---------------|-------------------------|
| 0400890201    | GRO J1655−40    | 2007.03.26  | 120           | 54.1 75.3 73.6          |
| 0400890301    | GRO J1655−40    | 2007.02.22  | 65            | 48.8 55.3 54.0          |
| 0400890101    | XTE J1550−564   | 2007.02.25  | 59            | 13.6 24.4 23.7          |
| 0304000201    | V404 Cyg       | 2005.11.08  | 40            | 31.0 36.8 36.4          |

### Table 2. Results of Power-Law Fitting

| Source          | $N_H$ (10^{21} cm^{-2}) | $\Gamma$ | $F_x$ (10^{-14} ergs^{-1} cm^{-2})^b | $\chi^2$/dof |
|-----------------|--------------------------|----------|--------------------------------------|--------------|
| GRO J1655−40    | 6.8^{+1.4}_{-1.1}        | 2.6^{+0.1}_{-0.2} | 5.8^{+0.8}_{-1.8}                       | 1.06/374     |
| XTE J1550−564   | 9 (fixed)^a              | 2.1^{+0.1}_{-0.5} | 4.9^{+2.1}_{-1.4}                       | 0.96/20      |
| V404 Cyg        | 9.4^{+0.8}_{-0.7}        | 2.11 ± 0.09  | 40^{+4}_{-5}                            | 0.90/285     |

^1 The errors shown represent 90% confidence intervals for a single parameter.
^a Dicky & Lockman 1990.
^b Measured X-ray flux in the 0.5–10 keV band.

### Table 3. RIAF+jet vs. pure RIAF modeling

| Source          | $d$ (kpc) | $M_{BH}^0$ ($M_\odot$) | $L_x/L_{Edd}$ ($10^{-7}$) | $i$ (°) | $r_{tr}/R_S$ | $\dot{m}(r_{tr})$ ($10^{-4}$) | $\theta_{jet}$ (°) | $\dot{m}_{jet}$ ($10^{-6}$) | $L_{kin}/\dot{M}(10R_S)c^2$ ($10^{-3}$) |
|-----------------|----------|------------------------|---------------------------|--------|-------------|-------------------------------|-------------------|---------------------------|----------------------------------|
| GRO J1655−40    | 3.2      | 6.3                    | 1.4                       | 70     | 5000        | 1.3                           | 85^c               | 2.35                      | 28                               |
| XTE J1550−564   | 5.3      | 9.6                    | 2.3                       | 73     | 5000        | 0.6                           | 73^d               | 2.4                       | 62                               |
| V404 Cyg        | 3.5      | 11.7                   | 7.0                       | 56     | 5000        | 5.0                           | 56^d               | 2.8                       | 8.6                              |

^1 The columns are: source name, distance, BH mass, Eddington scaled luminosity in the 0.5–10 keV band, binary inclination, RIAF/disc transition radius, accretion rate (in Eddington units) at $r = r_{tr}$, jet inclination, outflow rate (in Eddington units), and jet kinetic power $\Gamma_j (\Gamma_j - 1)\dot{M}_{jet}c^2$ (normalized to accretion power at $r = 10R_S$).
^c Pure accretion modeling.
^d McClintock & Remillard 2004, and references therein.
^e Hjellming & Rupen 1995.
^f The jet angle is assumed to be equal to the inclination angle of the binary orbit.
Figure 1. Power-law fit for GRO J1655−40 (top), XTE J1550−564 (middle), and V404 Cyg (bottom).

Figure 2. Spectral energy distribution (SED) for GRO J1655−40 (top), XTE J1550−564 (middle), and V404 Cyg (bottom). The solid lines show representative fits with the coupled accretion-jet model (see text). The dashed, dot-dashed, and dotted lines indicate individual contributions from the hot flows, jets, and the cool disc, respectively. For the purpose of illustration, the optical measurements from the literature are included. Since these measurements are not simultaneous with the X-ray measurements, one must exercise caution in drawing conclusions given the potential variability of the sources in the quiescent state. The insets show pure accretion modeling, that is clearly inconsistent with the SED in case of V404 Cyg and GRO J1655−40. The case is ambiguous for XTE J1550−564.

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