CHANDRA DETECTION OF XTE J1650−500 IN QUIESCENCE AND THE MINIMUM LUMINOSITY OF BLACK HOLE X-RAY BINARIES

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ABSTRACT

The Galactic black hole X-ray binary XTE J1650−500 entered a quiescent regime following the decline from the 2001–2002 outburst that led to its discovery. Here we report on the first detection of its quiescent counterpart in a 36 ks observation taken in 2007 July with the Chandra X-Ray Observatory. The inferred 0.5–10 keV unabsorbed flux is in the range (2.5–5.0) × 10−15 erg s−1 cm−2. Notwithstanding large distance uncertainties, the measured luminosity is comparable to that of the faintest detected black hole X-ray binaries, all having orbital periods close to the expected bifurcation period between j- and n-driven low-mass X-ray binaries. This suggests that a few 10^30 erg s^{-1} might be a limiting luminosity value for quiescent black holes.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (XTE J1650−500) — X-rays: binaries

Online material: color figure

1. INTRODUCTION

Black hole (BH) X-ray transients—close binary systems in which a low-mass donor transfers mass via Roche lobe overflow onto a black hole accretor—spend most of their lifetimes in a low-luminosity state, where the boundary between “quiescence” and a more active regime can be set around 10^{33.5} erg s^{-1}, corresponding to a few 10^{-6} times the Eddington luminosity (L_{Ed}) for a 10 M_{\odot} object (e.g., McClintock & Remillard 2006). Broadly speaking, the low Eddington ratios can be due to low radiative efficiency or low net accretion rate in the inner regions, or a combination of the two (see, e.g., Narayan 2005 and references therein). First explored in their basic ideas by Ichimaru (1977) and Rees et al. (1984), stable, radiatively inefficient accretion flow models were later formalized in the popular works of Narayan & Yi (1994, 1995) and Abramowicz et al. (1995). Since the mid 1990s, they have been widely employed to account for the broadband (radio/optical/UV/X-ray) spectra of low-luminosity BH candidates, such as A0620−00, GS 1124−68, and V404 Cyg (Narayan et al. 1996, 1997a), as well as the Galactic center source Sgr A* (Narayan et al. 1995). The increased sensitivity of Chandra and XMM-Newton with respect to previous flying X-ray telescopes has eventually permitted detailed X-ray studies of quiescent Galactic BHs down to Eddington ratios as low as a few 10^{-9} (Garcia et al. 2001; Kong et al. 2002; Hameury et al. 2003; Tomsick et al. 2003; McClintock et al. 2003; Gallo et al. 2006; Homan et al. 2006; Corbel et al. 2004; Bradley et al. 2007). In the framework of advection-dominated accretion flow models (ADAF; Narayan & Yi 1994, 1995), the observed luminosity difference between quiescent BHs and quiescent neutron stars—the former being fainter by 1 order of magnitude at comparable orbital periods—has been interpreted as evidence for the existence for an event horizon in BHs (Narayan et al. 1997b; Menou et al. 1999; Garcia et al. 2001; Narayan & McClintock 2008). At the same time, recent studies at lower frequencies, in the radio and mid-infrared bands, suggest that BHs and neutron stars may channel different fractions of the total accretion power into relativistic outflows, with a substantially reduced jet contribution in quiescent neutron stars with respect to BHs (Fender et al. 2003; Gallo et al. 2006, 2007; Migliari et al. 2006; Körding et al. 2007).

Of the 40 candidate BH X-ray binaries listed by Remillard & McClintock (2006), 15 have sensitive measurements/upper limits on their quiescent X-ray luminosities. In this Letter, we report on a 36 ks observation of the quiescent BH XTE J1650−500 performed in 2007 July with the Chandra X-Ray Observatory, and briefly discuss it in the context of quiescent BH X-ray binaries and how the advent of high-sensitivity/high-resolution X-ray telescopes has improved our understanding of such systems.

The Galactic X-ray binary system XTE J1650−500 entered a quiescent regime following the 2001–2002 outburst that led to its discovery with the Rossi X-Ray Timing Explorer (Remillard 2001). Observations conducted with XMM-Newton and BeppoSAX in late 2001, right after the outburst peak, revealed a broad, asymmetric Fe Kα emission line, interpreted as due to a irradiation of the inner accretion disk around a rapidly spinning Kerr BH (Miller et al. 2002; Miniutti et al. 2004; see Done & Gierliński 2006 for a different interpretation). The prolonged quiescent regime has allowed for the derivation of the system orbital period and optical mass function: P_{orb} = 7.7 hr and f(M) = 2.73 ± 0.56 M_{\odot}, respectively (Orosz et al. 2004). The mass of the BH in XTE J1650−500 is highly uncertain. The amplitude of the phased R-band light curve results in a lower bound to the orbital inclination i > 50° ± 3°, which, in the limiting case of no disk contribution, implies in an upper limit of 7.3 M_{\odot} to the accretor mass (Orosz et al. 2004). However—although with the caveat of the poor signal-to-noise ratio...
TABLE 1

| Source (1) | Name (CXOU) (2) | R.A. (3) | Decl. (4) | Count Rate (5) |
|------------|-----------------|----------|-----------|----------------|
| J165007.6−495623 | 16 50 07.69 | −49 56 23.8 | 1.9 (0.7) |
| J165000.2−495723 | 16 50 00.21 | −49 57 23.4 | 1.9 (0.7) |
| XTE J1650−500 | 16 50 00.92 | −49 57 44.1 | 2.0 (0.7) |
| J165000.3−495814 | 16 50 06.37 | −49 58 14.3 | 2.0 (0.7) |
| J165013.1−495709 | 16 50 13.14 | −49 57 09.1 | 2.0 (0.7) |
| J165005.4−495427 | 16 50 05.48 | −49 54 27.6 | 2.1 (0.8) |
| J165002.5−495333 | 16 50 02.56 | −49 53 34.0 | 2.2 (0.8) |
| J164943.9−495901 | 16 49 43.97 | −49 59 01.3 | 2.2 (0.8) |
| J165012.1−495715 | 16 50 12.12 | −49 57 15.2 | 2.4 (0.8) |
| J165000.3−495659 | 16 50 00.38 | −49 56 55.9 | 2.5 (0.8) |
| J165006.0−495455 | 16 50 06.05 | −49 54 37.5 | 2.7 (0.8) |
| J165021.3−495632 | 16 50 21.38 | −49 56 32.0 | 3.0 (0.9) |
| J164950.3−495931 | 16 49 50.30 | −49 59 31.0 | 3.1 (0.9) |
| J165006.3−495743 | 16 50 06.35 | −49 57 44.0 | 3.6 (1.0) |
| J165009.1−495442 | 16 50 09.10 | −49 54 42.9 | 4.2 (1.1) |
| J164959.7−495518 | 16 49 59.77 | −49 55 18.7 | 4.2 (1.1) |
| J164958.5−495614 | 16 49 58.54 | −49 56 14.2 | 4.8 (1.2) |
| J164955.8−495653 | 16 49 51.87 | −49 56 33.8 | 5.2 (1.2) |
| J165013.9−495726 | 16 50 13.94 | −49 57 26.7 | 5.3 (1.2) |
| J164947.8−500119 | 16 49 47.82 | −50 01 19.9 | 5.4 (1.2) |
| J164955.5−495705 | 16 49 55.50 | −49 57 05.6 | 5.6 (1.2) |
| J165005.2−495622 | 16 50 05.27 | −49 56 22.6 | 5.9 (1.3) |
| J164943.2−495450 | 16 49 43.28 | −49 54 50.6 | 7.2 (1.4) |
| J165005.1−495624 | 16 50 05.13 | −49 56 24.3 | 7.2 (1.4) |
| J164956.0−495711 | 16 49 56.04 | −49 57 11.2 | 8.0 (1.5) |
| J164953.5−495747 | 16 49 53.59 | −49 57 47.6 | 8.6 (1.5) |
| J164948.8−495509 | 16 49 48.82 | −49 55 09.8 | 9.4 (1.6) |
| J164948.7−495936 | 16 49 48.72 | −49 59 36.2 | 11.5 (1.6) |

Notes.—Col. (1): Target number. An asterisk (*) indicates USNO B1. Col. (2): Source name following the Chandra convention. Col. (3): Units of right ascension (equinox J2000.0) are hours, minutes, seconds. Col. (4): Units of declination (equinox J2000.0) are degrees, arcminutes, and arcseconds. Col. (5): Net count rate, in units of 10−4 counts s−1, as measured by wavdetect, with errors given in parentheses, over the energy interval 0.3–7.0 keV. Note that wavdetect is designed to be used as a detection algorithm, and only secondarily as a source flux measurement tool. Count rates are generally reliable, but can be slightly underestimated for very low number of counts.

2. OBSERVATION AND DATA ANALYSIS

The field of view of XTE J1650−500 was observed with the Advanced CCD Imaging Spectrometer (ACIS) detector on board Chandra on 2007 June 30 at 23:46 UT for approximately 36 ks. The target was placed on the back-side-illuminated S3 chip in order to take advantage of the CCD sensitivity to low-energy X-rays. The data were telemetered in very faint (VF) mode with an upper energy cutoff at 13 keV (since 6 CCDs were activated in VF mode, the upper energy filters ensure avoiding telemetry saturation). We have reprocessed and analyzed the data using the Chandra Interactive Analysis Observation (CIAO) software version 3.4.1.1. The level 1 event lists were first cleaned following the standard threads to reduce the ACIS particle background for VF mode observations, including only ASCA grades 0, 2, 3, 4, and 6. Further analysis was restricted between 0.3 and 7.0 keV in order to avoid calibration uncertainties at low energies and to limit background contaminations at high energies. As Chandra is known to encounter periods of high background which especially affect the S1 and S3 chips, we first checked for background flares but found none, resulting in a net exposure of 35.65 ks. We applied a wavelet detection algorithm, using CIAO wavdetect with a sensitivity threshold that corresponds to a 3.8 × 10−1 chance of detecting a spurious source per point-spread function (PSF) element if the local background is uniformly distributed. We employed the default “Mexican Hat” wavelet, with scales increasing by a factor of \( \sqrt{2} \) between 1 and 16 pixels on a full-resolution circular region of 512 pixel radius centered on the nominal position of the target (restricting the circle to the S3 chip). Table 1 lists the 28 sources detected by the algorithm, in order of increasing count rate (the positions are given after correcting the Chandra image to the USNO B1 catalog; see below). Three of the detected X-ray sources have optical counterparts with positions listed in the US Naval Observatory (USNO) B1 catalog (Monet et al. 2003), which has an absolute positional error of 0.20″. The mean USNO-to-Chandra shifts in right ascension \( \alpha \) and declination \( \delta \) are 0.06″ ± 0.31″ and 0.08″ ± 0.31″, respectively, where the uncertainties account for the Chandra statistical errors as well as the USNO B1 position uncertainty. We thus registered the Chandra image by applying the above astrometric corrections, and ran wavdetect again on the registered image to obtain refined position of the X-ray sources.

The position of source 3, shown in Figure 1, is consistent...
FIG. 2.—Left: Quiescent X-ray luminosities/upper limits for 15 BH X-ray binaries with sensitive observations (down to a minimum threshold of ∼10^{35} erg s^{-1}). Right: The measured luminosities are plotted against the systems’ orbital periods. The faintest systems (GS 2000+25, A0620−00, and XTE J1650−500) have orbital periods close to 10 hr, the expected bifurcation period between j- and n-driven low-mass X-ray binaries according to Menou et al. (1999).

3. DISCUSSION

As illustrated in Figure 2 (updated from Tomsick et al. 2003 after Corbel et al. 2004, Gallo et al. 2006, and Homan et al. 2006), the quiescent X-ray luminosity of XTE J1650−500 as measured by Chandra sits in the range of values inferred for systems with similar orbital periods. Out of 15 candidate BH X-ray binary systems with sensitive observations while in the quiescent regime, 12 have now been detected in X-rays. For those 12, the quiescent luminosities range between a few 10^{30} and 10^{33} erg s^{-1}. The nearest BH, A0620−00, has been steadily emitting at ∼(2–3) × 10^{30} erg s^{-1} at least for the past 5 years (Kong et al. 2002; Gallo et al. 2006); this is approximately the same luminosity level as XTE J1650−500 (this work), XTE J1118+480 (McClintock et al. 2003), and GS 2000+25 (Garcia et al. 2001), suggesting that this might be some kind of limiting value.

Indeed, for low-mass X-ray binaries one can make use of binary evolution theory, combined with a given accretion flow solution, to predict a relation between the minimum quiescent luminosity and the system orbital period \( P_{\text{orb}} \) (see, e.g., Menou et al. 1999; Lasota 2000). As an example, Figure 4 of Menou et al. (1999) illustrates how the predicted luminosity of quiescent BHs powered by ADAFs depends on the ratio between the outer mass transfer rate and the ADAF accretion rate. The lower band, which roughly reproduces the observed luminosities of three representative systems spanning the whole range of detected luminosities (A0620−00, GRO J1655−40, and V404 Cyg), corresponds to ∼1/3 of the mass transferred being accreted via the ADAF, whereas the remaining 2/3 would be either accumulated in an outer thin disk or lost to an outflow. Most importantly, independently of the actual solution for the accretion flow in quiescence, the existence of a minimum luminosity in low-mass X-ray binaries stems directly from the existence of a bifurcation period, \( P_{\text{bif}} \), below which the mass transfer rate is driven by gravitational wave radiation (j-driven...
systems), and above which it is dominated by the nuclear evolution of the secondary star (n-driven systems). Specifically, the outer mass transfer rate $M_f$ increases with decreasing orbital period below $P_{\text{orb}}$, while it increases with increasing orbital period above $P_{\text{orb}}$ (the same applies to quiescent neutron star X-ray binaries, although with higher normalization). For a wide range of donor masses, Menou et al. find $P_{\text{orb}} \approx 10$ hr. As long as the luminosity expected from a given accretion flow model scales with a positive power of $M_f$, systems with orbital periods $\dot{M}_T$ in a drastically reduced $\dot{M}_T$, making the direct comparison between quiescent ultracompact and longer period binaries somewhat dubious (see Jonker et al. 2006, 2007, and related discussion in Lasota 2007). For long orbital period systems, the ideal testbed would be obviously provided by the power-off of the as yet superluminous GRS 1915+105, with an orbital period of over 800 hr. Similarly, the newly discovered BH candidate Swift J1753.5—0127, with an inferred orbital period of 3.2 hr (Zurita et al. 2008), represents the ideal short-period target.

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