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CHANDRA DETECTIONS OF TWO QUIESCENT BLACK HOLE X-RAY TRANSIENTS

John A. Tomsick,[1] Stéphane Corbel,[2] Rob Fender,[3] Jon M. Miller,[4,5] Jerome A. Orosz,[6] Michael P. Rupen,[7] Tasso Tzioumis,[8] Rudy Wijnands,[9] and Philip Kaaret[4]
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ABSTRACT

Using the *Chandra X-Ray Observatory*, we have detected the black hole transients V4641 Sgr and XTE J1859+226 in their low-luminosity quiescent states. The 0.3–8 keV luminosities are $(4.0^{+3.3}_{-2.4}) \times 10^{31}$ $(d/7\ \mathrm{kpc})^2$ ergs s^{-1} and $(4.2^{+4.8}_{-2.2}) \times 10^{31}$ $(d/11\ \mathrm{kpc})^2$ ergs s^{-1} for V4641 Sgr and XTE J1859+226, respectively. With the addition of these two systems, 14 out of the 15 transients with confirmed black holes (via compact object mass measurements) now have measured quiescent luminosities or sensitive upper limits. The only exception is GRS 1915+105, which has not been in quiescence since its discovery in 1992. The luminosities for V4641 Sgr and XTE J1859+226 are consistent with the median luminosity of 2×10^{31} ergs s^{-1} for the systems with previous detections. Our analysis suggests that the quiescent X-ray spectrum of V4641 Sgr is harder than for the other systems in this group, but because of the low statistical quality of the spectrum, it is not clear if V4641 Sgr is intrinsically hard or if the column density is higher than the interstellar value. Focusing on V4641 Sgr, we compare our results to theoretical models for X-ray emission from black holes in quiescence. Also, we obtain precise X-ray positions for V4641 Sgr and XTE J1859+226 via cross-correlation of the X-ray sources detected near our targets with IR sources in the Two Micron All Sky Survey catalog.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (V4641 Sgr, XTE J1859+226) — stars: winds, outflows — X-rays: stars

1. INTRODUCTION

Previous measurements of black hole (BH) X-ray transients in quiescence show that the BH systems have X-ray luminosities ranging from 10^{30} to 10^{33} ergs s^{-1} (Garcia et al. 2001; Hameury et al. 2003). As in outburst, there is evidence for the presence of an accretion disk in quiescence (Orosz & Bailyn 1997; McClintock et al. 2003), but the accretion rate onto the BH itself is unclear, as is the nature of the accretion flow. Although there is currently no consensus on the origin of the quiescent X-ray emission, three emission sites are considered to be viable for at least some systems: the accretion disk, the putative outflow or jet, and the secondary star.

One picture for the quiescent accretion flow is that of an inner quasi-spherical and optically thin region surrounded by an optically thick disk as in the advection-dominated accretion flow (ADAF) model (Narayan, McClintock, & Yi 1996). This model explains the faintness of quiescent BHs as being due to advection of radiation across the BH event horizon (Garcia et al. 2001). However, it has been determined that ADAFs are convectively unstable for certain viscosity ranges, leading to convection-dominated accretion flows (CDAFs; Quataert & Gruzinov 2000). Such a model can explain the low BH luminosities without the need for advection across an event horizon. In addition, BH advection may not be necessary if outflows or jets transport the accretion energy out of the system (Blandford & Begelman 1999; Gliozzi, Bodo, & Ghisellini 1999; Fender, Gallo, & Jonker 2003). There is evidence for the presence of compact radio jets from BH systems at low X-ray luminosities (Fender 2001; Corbel et al. 2003), and these may persist in quiescence. Such jets may possibly contribute to the X-ray emission (Markoff, Falcke, & Fender 2001). Finally, Bildsten & Rutledge (2000) suggested the secondary as an X-ray emission site, but we note that this possibility has been ruled out for most systems (Kong et al. 2002b).

In this work, we describe results of observations of the BH transients V4641 Sgr and XTE J1859+226 in quiescence made using the *Chandra X-Ray Observatory* (Weisskopf et al. 2002). These systems both had major X-ray outbursts in 1999 (Wood et al. 1999; Smith, Levine, & Morgan 1999). While the XTE J1859+226 outburst was typical of BH transients, the behavior of V4641 Sgr was unusual, with a long period of low-level activity punctuated by a 12 crab flare lasting 1–2 days. From optical observations covering the 67.6 hr V4641 Sgr orbit and the (likely) 9.16 hr XTE J1859+226 orbit, the compact object masses are above 3 $M_\odot$, indicating that these systems contain BHs (Orosz et al. 2001; Filippenko & Chornock 2001). At the time of the outburst, V4641 Sgr exhibited a one-sided, rapidly evolving relativistic radio jet (Hjellming et al. 2000; Orosz et al. 2001), and there is evidence that XTE J1859+226 also produced a radio jet (Brocksopp et al. 2002). The main motivations of our *Chandra* observations are to study the BHs in quiescence and to search for large-scale X-ray jets such as those detected for XTE J1550−564 (Corbel et al. 2002) and 4U 1755−338 (Angelini & White 2003). Here, we report on the detection of the BHs in quiescence, and we will report on the X-ray jet search and the consequences of the nondetection of those jets in a future paper.

[1] Center for Astrophysics and Space Sciences, Code 0424, University of California at San Diego, La Jolla, CA 92093; jtomsick@ucsd.edu.
[2] Université Paris VII and Service d'Astrophysique, CEA Saclay, 91191 Gif sur Yvette, France.
[3] Astronomical Institute "Anton Pannekoek," University of Amsterdam and Center for High Energy Astrophysics, Kruislaan 403, NL-1098 SJ Amsterdam, Netherlands.
[4] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[5] National Science Foundation Astronomy and Astrophysics Fellow.
[6] Department of Astronomy, San Diego State University, San Diego, CA 92182.
[7] National Radio Astronomy Observatory, 1003 Lopezville Road, Soccoro, NM 87801.
[8] Australia Telescope National Facility, Commonwealth Scientific and Industrial Research Organization, P.O. Box 76, Epping, NSW 1710, Australia.
[9] School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, UK.

2. OBSERVATIONS

We obtained two *Chandra* observations of V4641 Sgr in 2002: a 4.3 ks observation on UT August 5 (observation 1a) and a 25.3 ks observation on UT October 21 (observation 1b). For both observations, we used the Advanced CCD Imaging Spectrometer (ACIS) in imaging mode, and the target was placed on one of the back-illuminated ACIS chips (S3). Observation 1a was carried out under Director's Discretionary Time and was prompted by X-ray, optical, and radio activity from the source during 2002 May and June (Markwardt & Swank 2002; Uemura et al. 2002; Rupen, Dhawan, & Mioduszewski 2002). Considering the possibility that the source might still be active in X-rays during observation 1a, we used a $\frac{1}{4}$ CCD subarray to mitigate photon pileup effects. We found that the source was not bright (Tomsick et al. 2002), and we used the full CCD for observation 1b. We also obtained a 24.8 ks *Chandra* observation of XTE J1859+226 on 2003 February 5 (observation 2) using ACIS in imaging mode. The last known X-ray activity from XTE J1859+226 was in 2000 (Tomsick & Heindl 2000). For all three observations, the background levels remain low throughout, allowing us to use the full exposure time. Very Large Array (VLA) radio observations occurred within 1 week of observations 1a and 1b and within 2 weeks of observation 2. V4641 Sgr and XTE J1859+226 showed no radio emission with rms noise levels near 0.1 mJy beam^{-1} at 4 and 6 cm.

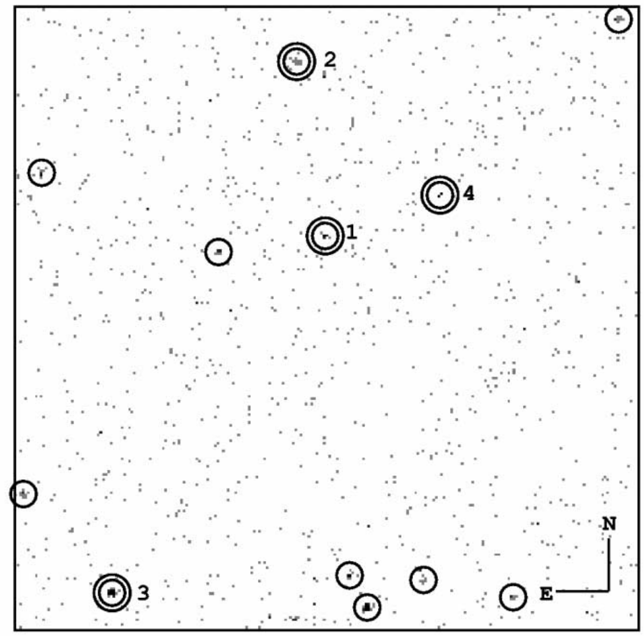

FIG. 1.—The 0.3–8 keV *Chandra* image of the V4641 Sgr field. The exposure time is 29.5 ks, and the image size is 1.968 arcmin^2. The north and east lines are 10″. The 12 detected sources are circled, and sources 1–4 (marked with two circles) have 2MASS identifications. Source 1 is V4641 Sgr.

3. SOURCE DETECTIONS AND 2MASS/*CHANDRA* CROSS-CORRELATION

We produced 0.3–8 keV ACIS images using the "level 2" event lists from the standard data processing. For the analysis described below, we used the *Chandra* Interactive Analysis of Observations (CIAO) version 2.3 software and Calibration Data Base version 2.21. To obtain the maximum sensitivity for source detection in the V4641 Sgr field, we combined the data for observations 1a and 1b. We restricted our search for sources to a 2 arcmin^2 region containing the position of V4641 Sgr. This region, which is shown in Figure 1, is fully covered by both observations giving a spatially uniform exposure time of 29.5 ks. We used the CIAO routine *wavdetect* with a detection threshold of 10^{-6} (Freeman et al. 2002) to search for sources in the combined image, leading to the detection of 12 sources with between 6 and 36 counts per source. A source with 9 counts (labeled 1 in Fig. 1) is detected at a position consistent with the V4641 Sgr radio position.

As the V4641 Sgr radio position is known to 0″.1 (Hjellming et al. 2000), it is worthwhile to obtain the best possible X-ray position in order to test whether *Chandra* source 1 is, in fact, V4641 Sgr. To register the image, we cross-correlated the *Chandra* source positions with the Two Micron All Sky Survey (2MASS) IR sources in the field. We determined that four of the 12 *Chandra* sources have 2MASS sources within the *Chandra* pointing uncertainty of 0″.6. For these four sources, the angular separations between the 2MASS and *Chandra* positions range from 0″.03 to 0″.25. Given the surface density of 2MASS sources (7×10^{-3} sources arcsec^{-2} down to $K_s \sim 14$), there is a 0.14% probability that a match with the largest separation is spurious. As source 1 (the V4641 Sgr candidate) is identified as one of the 2MASS sources (2MASS 18192163−2524258 with IR magnitudes $J = 12.532 \pm 0.029$, $H = 12.364 \pm 0.027$, and $K_s = 12.270 \pm 0.030$), we used the other three sources to register the image. For these three sources, the average 2MASS to *Chandra* differences in R.A. and decl. are −0″.05 ± 0″.13 and 0″.10 ± 0″.13, respectively, where the uncertainties account for the *Chandra* statistical position error as well as the 0″.2 position uncertainties for 2MASS.[10] We performed the indicated shifts (0″.05 east and 0″.1 south) to complete the registration of the *Chandra* image to the 2MASS positions. The position of source 1 is R.A. = $18^h19^m21^s.641$, decl. = −25°24′25″.87 (equinox J2000.0, systematic uncertainty = 0″.13, statistical uncertainty = 0″.13). The best *Chandra* position is 0″.12 from the 2MASS position and 0″.06 from the radio position obtained from a VLA image obtained on 1999 September 17, for which Hjellming et al. (2000) interpreted the emission as coming from the BH rather than the extended jet. After registering the image, we find that all 9 ACIS counts are contained within 1″ of the radio position, while the expected number of background counts in a 1″ circle is 0.28. Thus, the Poisson probability that the detection is spurious is 2×10^{-11}.

We carried out a similar analysis for XTE J1859+226. We searched for *Chandra* sources in a 3 arcmin^2 region centered on the XTE J1859+226 radio position (Pooley & Hjellming 1999) using *wavdetect*. As shown in Figure 2, we detected five *Chandra* sources with between 6 (source 1) and 113 (source 2) counts. Source 1 is consistent with the XTE J1859+226 radio position. We cross-correlated the *Chandra* positions with the 2MASS positions and found that sources 3–5 have likely IR counterparts. For these three sources, the maximum separation between the *Chandra* and 2MASS positions is 0″.33, and there is a 0.07% probability that a match with this separation is spurious. Using the 2MASS identifications, we determined the position shifts required to register the *Chandra* image, and these are 0″.09 ± 0″.12 and 0″.25 ± 0″.14 in R.A. and decl., respectively. After shifting the *Chandra* image by 0″.09 west and 0″.25 south, the position of source 1 is R.A. = $18^h58^m41^s.485$, decl. = +22°39′29″.88 (equinox J2000.0, systematic uncer-

[10] See http://www.ipac.caltech.edu/2mass/releases/second/doc.

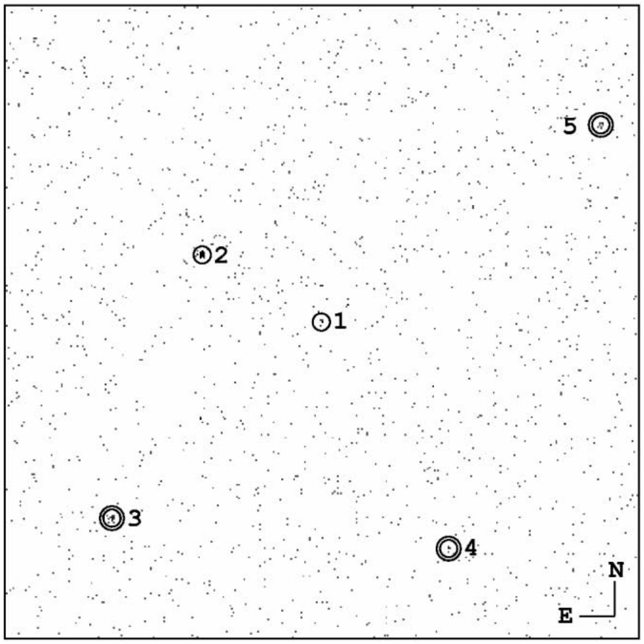

FIG. 2.—The 0.3–8 keV *Chandra* image of the XTE J1859+226 field. The exposure time is 24.8 ks, and the image size is 3 arcmin². The north and east lines are 10″. The five detected sources are circled, and the three sources marked with two circles have 2MASS identifications. Source 1 is XTE J1859+226.

tainty is 0.″14, statistical uncertainty is 0.″10 in R.A. and 0.″20 in decl.), which is consistent with the 0.″3 VLA radio position (Pooley & Hjellming 1999). All 6 ACIS counts are contained within 1″ of the radio position, while the expected number of background counts in a 1″ circle is 0.18. Thus, the Poisson probability that the detection is spurious is 4×10^{-8}.

4. QUIESCENT BLACK HOLE PROPERTIES

Although the number of counts detected for both V4641 Sgr and XTE J1859+226 is small, we extracted energy spectra (with 9 and 6 counts, respectively). For V4641 Sgr, the photon energies range from 0.87 to 7.0 keV, and the mean photon energy is 3.5 keV. For XTE J1859+226, the photon energies range from 0.75 to 2.7 keV, and the mean photon energy is 1.5 keV. We fitted the energy spectra with a power-law model with interstellar absorption. We used this model because this spectral shape is typically seen for quiescent BH systems (Garcia et al. 2001; Kong et al. 2002b), but we emphasize that we cannot rule out other spectral shapes. We fitted the spectra using Cash statistics (Cash 1979), and we fixed the column density (N_H) to the H I values from Dickey & Lockman (1990): 2.3×10^{21} and 2.2×10^{21} cm^{-2} for V4641 Sgr and XTE J1859+226, respectively. We determined the errors on the parameters by producing and fitting 10,000 simulated spectra. We used the best-fit parameters from the fits to the actual data as input to the simulations. The power-law photon indices are $\Gamma = 0.2^{+0.9}_{-1.0}$ for V4641 Sgr and $\Gamma = 2.4^{+1.5}_{-1.3}$ for XTE J1859+226 (90% confidence errors).

The energy spectra of quiescent BHs are typically well described by an absorbed power law with a photon index of $\Gamma = 1.3$–2.3 (Kong et al. 2002b; Hameury et al. 2003; McClintock et al. 2003). Although a (much) better V4641 Sgr spectrum should be obtained to confirm its spectral shape, the best estimate of $\Gamma = 0.2$ is well outside the typical range, and even at the upper limit of $\Gamma = 1.1$, V4641 Sgr would be the hardest of the quiescent BHs. However, the uncertain column density is an important source of systematic error, and we refitted the V4641 Sgr spectrum leaving N_H as a free parameter. Our simulations indicate 90% confidence upper limits on Γ and N_H of 2.5 and 3.3×10^{22} cm^{-2}, respectively. Thus, we conclude that either the V4641 Sgr is intrinsically hard or N_H is higher than the interstellar value.

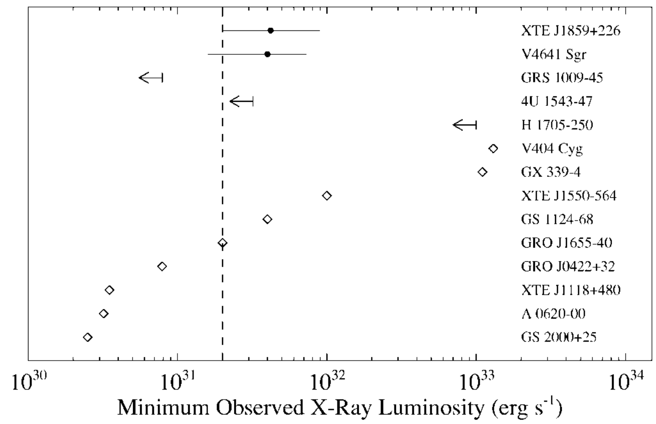

FIG. 3.—Quiescent BH X-ray luminosities. The points with error bars mark the 0.3–8 keV luminosities of XTE J1859+226 and V4641 Sgr from our *Chandra* measurements, assuming distances of 11 and 7 kpc for the two sources, respectively. The diamonds and upper limits are the minimum X-ray luminosities reported for the other 12 BH systems for which quiescent measurements have been possible (Garcia et al. 2001; Hameury et al. 2003; Sutaria et al. 2002; McClintock et al. 2003; Kong et al. 2002a; Kaaret et al. 2003; Corbel et al. 2003). The dashed line is the median luminosity for the previous detections.

We used the spectral fits to obtain flux and luminosity measurements for the sources. For V4641 Sgr, the absorbed 0.3–8 keV flux is $(6.5^{+5.7}_{-4.0}) \times 10^{-15}$ ergs cm^{-2} s^{-1} (90% confidence errors), and the unabsorbed luminosity in the same energy band is $(4.0^{+3.3}_{-2.4}) \times 10^{31}$ $(d/7\ \mathrm{kpc})^2$ ergs s^{-1}, where d is the source distance. Optical observations of V4641 Sgr in quiescence give a distance of 7.3 ± 1.2 kpc (J. A. Orosz et al. 2003, in preparation). For XTE J1859+226, the absorbed 0.3–8 keV flux is $(1.5^{+0.2}_{-0.7}) \times 10^{-15}$ ergs cm^{-2} s^{-1}, and the luminosity is $(4.2^{+4.8}_{-2.2}) \times 10^{31}$ $(d/11\ \mathrm{kpc})^2$ ergs s^{-1}. The distance estimate of 11 kpc comes from the X-ray and optical properties of the source (Zurita et al. 2002).

5. DISCUSSION

As confirmed BH systems (based on compact object mass measurements), V4641 Sgr and XTE J1859+226 represent important additions to the group of BHs that have previously been detected in X-rays in quiescence. Of the 15 confirmed (McClintock & Remillard 2003) transient BH systems, 14 now have quiescent X-ray detections or sensitive upper limits, and only GRS 1915+105, which has been in outburst since its discovery in 1992, does not. The X-ray luminosity (L_X) measurements are summarized in Figure 3. We include a new low X-ray flux measurement for XTE J1550−564 (Kaaret et al. 2003), which has not been previously considered in the context of studies of quiescent BHs, and we assume a distance of 5.3 kpc (Orosz et al. 2002) to convert from flux to luminosity. We also include the lowest flux measurements for the recurrent transient GX 339−4

(Kong et al. 2002a; Corbel et al. 2003), and we assume a distance of 4 kpc. The median luminosity is 2×10^{31} ergs s^{-1} for the nine systems with previous detections, and the measured luminosities for V4641 Sgr and XTE J1859+226 are consistent with the median.

For quiescent BHs, the X-ray emission is thought to originate from the accretion flow, a jet, or the secondary star, and here we discuss how our results for V4641 Sgr may constrain theoretical models for X-ray production. The V4641 Sgr source distance (7 kpc) along with the proper motion of the one-sided radio jet seen in 1999 (0″.36 per day) indicate that the angle between the jet axis and our line of sight is less than 8° (Orosz et al. 2001). Thus, if the X-ray emission originates in a fast-moving jet, one expects V4641 Sgr to be brighter because of relativistic beaming. However, the V4641 Sgr X-ray luminosity (assuming isotropic emission) is similar to the luminosities of the other BH systems, for which the jet axes either are not known or are known to be relatively far from our line of sight, indicating that the X-ray emission is not highly beamed and limiting the velocity of a putative X-ray emitting jet. For a continuous synchrotron X-ray jet (Markoff et al. 2001), it is unlikely that the bulk-motion Lorentz factor could be higher than ∼1.5, as this would cause the source to be brighter than an unbeamed source by a factor of ∼10 for a jet that is 8° from our line of sight (Mirabel & Rodríguez 1999). This calculation assumes a spectrum with a photon index of 1.5, which is in the range of values that can be produced within the Markoff et al. (2001) model. Assuming a photon index of 0.2 (our best estimate for V4641 Sgr) would lead to a somewhat higher limit on the Lorentz factor, but it is unclear whether such a hard spectrum could have a synchrotron origin. Also, we note that the Lorentz factor constraint is similar for models in which X-rays are produced in jets via inverse Comptonization (Georganopoulos, Aharonian, & Kirk 2002). The V4641 Sgr constraint on the Lorentz factor ($\lesssim 1.5$) is consistent with recent results for BH systems in the canonical low-hard state (Gallo, Fender, & Pooley 2003; Maccarone 2003).

For accretion disk models such as the ADAF model, the quiescent X-ray luminosity depends mainly on mass accretion rate rather than on system orientation. Thus, the luminosities of V4641 Sgr and XTE J1859+226 would be expected to be similar to the other BH systems, as observed. If the hard V4641 Sgr X-ray spectrum is confirmed and is intrinsic to the source, it would suggest that another parameter besides accretion rate is important. Hard spectra can be produced by ADAFs (McClintock et al. 2003) and CDAFs (Quataert & Gruzinov 2000), but it is unclear why one system at close to the median luminosity would be intrinsically much harder than the others.

The spectral type of the V4641 Sgr secondary is B9 III (Orosz et al. 2001), making it the most luminous of the BH transients. In quiescence, the ratio of the X-ray to bolometric luminosity (L_X/L_{bol}) for V4641 Sgr is $\sim 3 \times 10^{-5}$ based on the X-ray luminosity reported here and the optical luminosity of the secondary (J. A. Orosz et al. 2003, in preparation). The V4641 Sgr ratio is higher than the average value but comparable to the highest values measured by *ROSAT* for late B-type stars (Berghoefer et al. 1997). While it is unlikely that the hard X-ray flux from V4641 Sgr comes from the secondary, we cannot rule out the possibility that the secondary makes some contribution to the soft X-ray flux below ∼2 keV. The early-type secondary could also be important if it has a strong wind. The wind could collide with accretion disk material, leading to additional X-ray production, or it could cause extra X-ray absorption, explaining the hard V4641 Sgr spectrum.

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