Chandra Detections of Two Quiescent Black Hole X-Ray Transients

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1 Summary

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} erg 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 (although we note that the secondary star is probably not viable for most of the systems).

Using *Chandra* observations between 2002 August and 2003 February, we have detected the black hole transients V4641 Sgr and XTE J1859+226 in their low luminosity, quiescent states, and obtained the following results:

- $L_{\rm V4641 Sgr}$ (0.3-8 keV) = $(4.0^{+3.3}_{-2.4}) \times 10^{31}$ $(d/7$ kpc$)^2$ erg s^{-1}
- $L_{\rm XTE J1859+226}$ = $(4.2^{+4.8}_{-2.2}) \times 10^{31}$ $(d/11$ kpc$)^2$ erg s^{-1}
- Now, 14 out of the 15 transients with confirmed black holes have measured quiescent luminosities or sensitive upper limits.
- The luminosities for V4641 Sgr and XTE J1859+226 are consistent with the median luminosity of 2×10^{31} erg 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.

2 Targets, Detections, and Spectral Results

V4641 Sgr and XTE J1859+226 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 the source undergoing an extremely bright (12 Crab) outburst lasting only 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).

Figures 1 and 2 show the *Chandra* images for the V4641 Sgr and XTE J1859+226 fields, respectively. For V4641 Sgr, we measured 9 counts in 29.5 ks, and for XTE J1859+226, we measured 6 counts in 24.8 ks.

Although the number of counts detected for both V4641 Sgr and XTE J1859+226 is small, we extracted energy spectra. We fitted the energy spectra with a power-law model with interstellar absorption (i.e., $N_{\rm H}$ fixed). 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). Although the V4641 Sgr value for Γ is harder than the typical values for quiescent BHs ($\Gamma = 1.3$-2.3), when $N_{\rm H}$ is left free, we find 90% confidence upper limits on Γ and $N_{\rm H}$ of 2.5 and 3.3×10^{22} cm^{-2}, respectively. **Thus, we conclude that either the V4641 Sgr is intrinsically hard or that $N_{\rm H}$ is higher than the interstellar value.**

3 Quiescent Black Hole Luminosities

The X-ray luminosity (L_x) measurements for the confirmed transient BH systems are summarized in Figure 3. We include a new low X-ray flux measurement for XTE J1550–564 (Kaaret et al., 2003), that 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., 2002; Corbel et al., 2003), and we assume a distance of 4 kpc. The median luminosity is 2×10^{31} erg s^{-1} for the 9 systems with previous detections, and the measured luminosities for V4641 Sgr and XTE J1859+226 are consistent with the median.

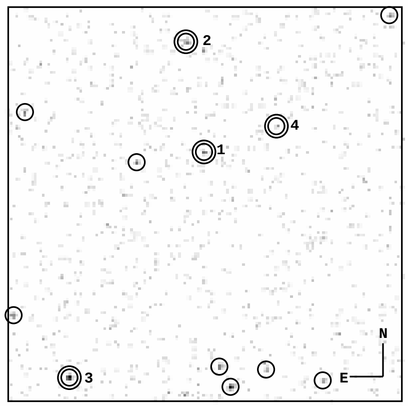

FIGURE 1: 0.3-8 keV *Chandra* image of the V4641 Sgr field. The exposure time is 29.5 ks, and the image size is 1.968 arcmin^2. The N and E lines are $10''$. The 12 detected sources are circled, and sources 1-4 (marked with 2 circles) have 2MASS identifications. Source 1 is V4641 Sgr.

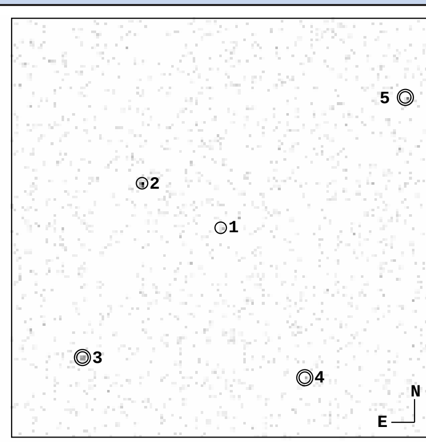

FIGURE 2: 0.3-8 keV *Chandra* image of the XTE J1859+226 field. The exposure time is 24.8 ks, and the image size is 3 arcmin^2. The N and E lines are $10''$. The 5 detected sources are circled, and and the 3 sources marked with 2 circles have 2MASS identifications. Source 1 is XTE J1859+226.

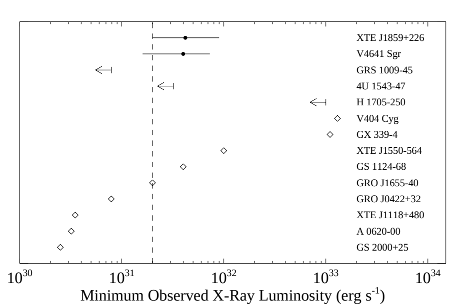

FIGURE 3: Quiescent black hole X-ray luminosities. The points with error bars mark the 0.3-8 keV luminosities of XTE J1859+226 and V4641 Sgr from our *Chandra* measurements, assuming distances of 11 kpc and 7 kpc for the two sources, respectively. The diamonds and upper limits are the minimum X-ray luminosities 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., 2002; Kaaret et al., 2003; Corbel et al., 2003). The dashed line is the median luminosity for the previous detections.

4 Discussion

Jet Emission? The V4641 Sgr source distance along with the proper motion of the one-sided radio jet seen in 1999 indicate that the angle between the jet and our line of sight is $<8^\circ$ (Orosz et al., 2001). Thus, if the X-ray emission originates in a fast-moving jet, one expects V4641 Sgr to be brighter due to 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 are either 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, Falcke & Fender, 2001), it is unlikely that the bulk-motion Lorentz factor could be higher than $\sim$1.5 as this would cause the source to be brighter than an unbeamed source by a factor of $\sim$10 for a jet that is 8° from our line of sight (Mirabel & Rodríguez, 1999). This calculation assumes a spectrum with a photon index of 1.5, which is in the range of values that can be produced within the Markoff, Falcke & Fender (2001) model. Assuming a photon index of 0.2 (our best estimate for V4641 Sgr) would lead to a somewhat higher limit on the Lorentz factor, but it is unclear whether such a hard spectrum could have a synchrotron origin. Also, we note that the Lorentz factor constraint is similar for models where X-rays are produced in jets via inverse Comptonization (Georganopoulos, Aharonian & Kirk, 2002). The V4641 Sgr constraint on the Lorentz factor ($\lesssim$1.5) is consistent with recent results for BH systems in the canonical low-hard state (Gallo, Fender & Pooley, 2003; Maccarone, 2003).

Accretion Disk? 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.

Secondary Star? 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 for V4641 Sgr is $\sim 3 \times 10^{-5}$ based on the X-ray luminosity reported here and the optical luminosity of the secondary (Orosz et al., in prep.). 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 a some contribution to the soft X-ray flux below $\sim$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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