Detection of Hard State Spectral and Timing Signatures from the Black Hole X-Ray Transient XTE J1650-500 at Low X-Ray Luminosities

John A. Tomsick[1], Emrah Kalemci[2], Philip Kaaret[3]

[1] Center for Astrophysics and Space Sciences, Code 0424, University of California at San Diego, La Jolla, CA, 92093 (e-mail: jtomsick@ucsd.edu)
[2] Space Sciences Laboratory, University of California, Berkeley, CA, 94702-7450
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, 02138

1 Summary

In order to constrain theoretical models for X-ray emission from black holes in the low-hard state and, potentially, quiescence, we have studied the black hole candidate (BHC) XTE J1650–500 with *Chandra* and *RXTE* near the end of its 2001-2002 outburst (see Figure 1) after its transition to the low-hard state at X-ray luminosities down to $L = 1.5 \times 10^{34}$ erg s^{-1} $(d/4\ \mathrm{kpc})^2$. Our results include a characterization of the spectral and timing properties. At the lowest sampled luminosity, we used an 18 ks Chandra observation to measure the power spectrum at low frequencies. The 0.5-20 keV energy spectra are consistent with a power-law model with interstellar absorption, and the source softens at the lowest luminosity. The power spectra are characterized by strong (20-35% fractional rms) band-limited noise, which we model as a zero-centered Lorentzian. In the context of theoretical models for accreting BHCs and observations of other BHCs, our results have implications for the following questions:

- **Is the "quiescent" black hole state fundamentally different from the "low-hard" state?**
- **Does the inner edge of the accretion disk move away from the black hole in the low-hard state?**
- **Is there spectral evolution in the low-hard state at low luminosities?**
- **What is the origin of short-term optical variability for black holes in quiescence?**
- **What are the implications for theoretical models, including ADAF/sphere+disk (Esin, McClintock & Narayan, 1997; Nowak, Wilms & Dove, 2002), Magnetic corona (Merloni & Fabian, 2002), and Jet-based models (Markoff, Falcke & Fender, 2001)?**

2 Results

- BHC Characteristic Frequencies: For XTE J1650–500 the Lorentzian half-width drops by a factor of 1200 while the source is in the hard state (see Figures 2 and 3). For A 0620–00 and Nova Mus 1991, optical observations (Hynes et al., 2003) suggest that this trend extends into quiescence (see Figure 4).
- BHC Spectral Evolution: For several BHCs, including XTE J1650–500 (this work), XTE J1118+480 (Kalemci, 2002), and XTE J1550–564 (Tomsick, Corbel & Kaaret, 2001; Kalemci, 2002), spectral softening is seen at low luminosities (see Figure 5).
- Frequency vs. Γ: While, for XTE J1650–500, frequency and Γ are strongly correlated above 0.25-1 Hz (see Figure 6), our results show that this trend does not continue at lower frequencies.

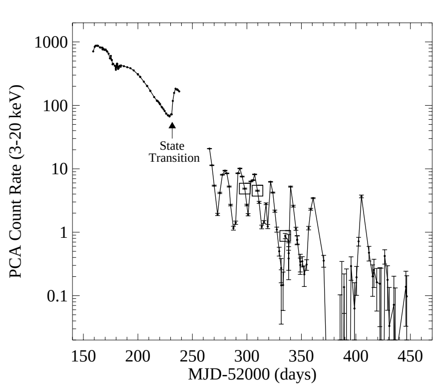

FIGURE 1: The 3-20 keV light curve for the 2001-2002 XTE J1650–500 outburst using PCA data from all the *RXTE* observations. The time of the soft-to-hard state transition, which occurred on MJD 52231.5, is marked, and the gap in observations that is centered near MJD 52250 is due to solar angle constraints. After the gap, the source exhibited 14 day oscillations (Tomsick et al., 2003). The 3 *Chandra* observations occurred during these oscillations and are marked with squares.

JAT acknowledges useful discussions with Mike Nowak, Joern Wilms, and Biff Heindl. We thank Mike Garcia and Harvey Tananbaum for assistance in scheduling the *Chandra* observations. JAT acknowledges partial support from NASA grant NAG5-13055 and *Chandra* award number GO2-3056X issued by the *Chandra* X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-39073. EK acknowledges partial support of TÜBİTAK. PK acknowledges partial support from NASA grant NAG5-7405.

2.1 Characteristic Frequencies

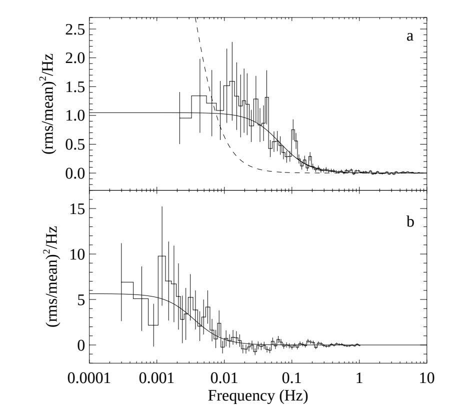

FIGURE 2: (a) PCA power spectrum for observations 1 and 2 combined. The solid line shows the best fit zero-centered Lorentzian, and the power spectrum shows marginal (between 2 and 3-σ) evidence for a QPO at 0.11 Hz. (b) ACIS power spectrum for observation 3 with the best fit zero-centered Lorentzian. In panel a, the dashed line shows the model used for observation 3 to illustrate that the power shifts to lower frequency for observation 3.

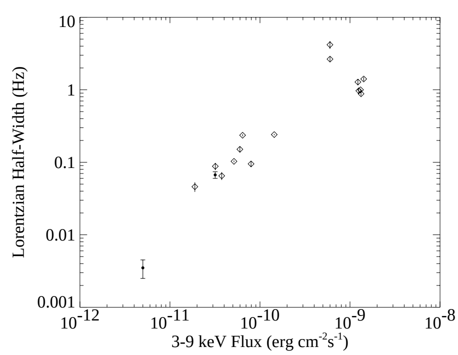

FIGURE 3: The values for XTE J1650–500 from *Chandra* (filled circles) and *RXTE* (diamonds) of the Lorentzian half-width vs. the flux in the 3-9 keV energy band. The higher flux *RXTE* measurements come from (Kalemci et al., 2003).

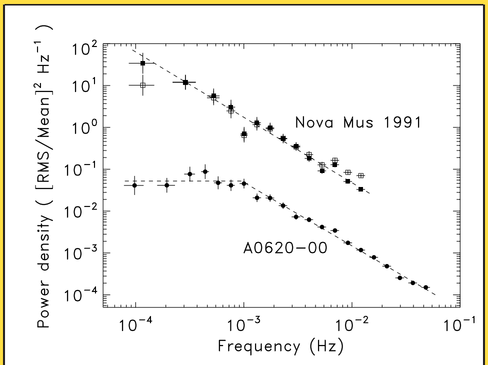

FIGURE 4: Quiescent optical power spectra for the black hole transients A 0620–00 and Nova Mus 1991. From Hynes et al. (2003).

References

Esin, A. A., McClintock, J. E., & Narayan, R., 1997, ApJ, 489, 865
Hynes, R. I., Charles, P. A., Casares, J., Haswell, C. A., Zurita, C., & Shahbaz, T., 2003, MNRAS, 340, 447
Kalemci, E., 2002, Ph.D. Thesis, Temporal Studies of Black Hole X-Ray Transients During Outburst Decay
Kalemci, E., Tomsick, J. A., Rothschild, R. E., Pottschmidt, K., Corbel, S., Wijnands, R., Miller, J. M., & Kaaret, P., 2003, ApJ, 586, 419
Markoff, S., Falcke, H., & Fender, R., 2001, A&A, 372, L25
Merloni, A., & Fabian, A. C., 2002, MNRAS, 332, 165
Nowak, M. A., Wilms, J., & Dove, J. B., 2002, MNRAS, 332, 856
Tomsick, J. A., Corbel, S., & Kaaret, P., 2001, ApJ, 563, 229
Tomsick, J. A., Kalemci, E., Corbel, S., & Kaaret, P., 2003, ApJ, 592, 1100

2.2 Spectral Evolution

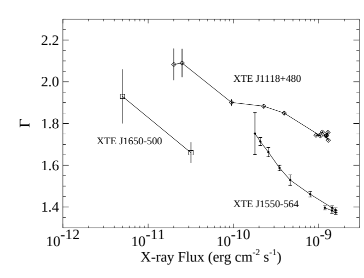

FIGURE 5: The power-law photon index (Γ) vs. the flux for three accreting BHCs at the ends of their outbursts. For XTE J1118+480 and XTE J1550–564 (Kalemci, 2002), the 3-25 keV flux from *RXTE* measurements is shown, and for XTE J1650–500, the 3-9 keV *Chandra* flux is shown.

2.3 Frequency vs. Γ for XTE J1650–500

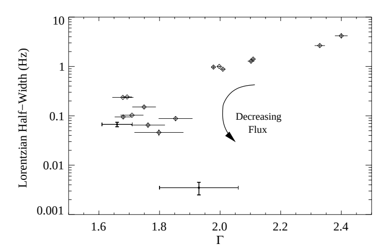

FIGURE 6: The values for XTE J1650–500 from *Chandra* (filled circles) and *RXTE* (diamonds) of the half-width vs. the power-law photon index (Γ). The arrow shows the direction of decreasing flux.

3 Discussion

- Quiescence and the Low-Hard State: For XTE J1650–500, the general shape of the low-hard state X-ray energy and power spectra remain the same to low luminosities. Furthermore, the quiescent optical power spectra of BHCs (Hynes et al., 2003) are also similar, suggesting a connection between the two states and that the optical and X-ray emission mechanisms may be related.

- Implications for ADAF/SD models: ADAF/sphere+disk (SD) models, where the inner edge of the accretion disk (at R_{in}) increases when the source is in the hard state, provide natural explanations for many of our results. Within this model the drop in frequency corresponds to an increase in R_{in}, the correlation between Γ and frequency above 0.25-1 Hz is due a lower level of coronal cooling as the disk moves out, and the softening of the energy spectrum at low luminosities is due to a drop in the coronal y-parameter as the mass accretion rate drops. However, ADAF/SD models do not currently incorporate outflows, and, even for XTE J1650–500, radio emission that is probably from a jet is detected in the hard state (Corbel et al., in prep.).

- Implications for Magnetic corona models: The magnetic corona model of Merloni & Fabian (2002) incorporates outflows, and also can explain some of our results. The softening of the spectrum occurs as more of the coronal energy is carried away from the outflow. Merloni & Fabian (2002) do not address the question of what characteristic frequencies might be detected, but it is likely that time scales would be set by the size of the corona.

- Implications for Jet-based models: Markoff, Falcke & Fender (2001) have suggested that the X-ray emission may be dominated by synchrotron emission from a jet. X-rays are produced when electrons are accelerated at a shock that is $z_{sh} \sim 10^3 R_g$ from the black hole. The X-ray spectrum is predicted to have a power-law shape out to a cutoff energy, and the power-law index is set by the index of the electron energy distribution, p, where $dN/dE \propto E^{-p}$. Thus, a softening of the energy spectrum implies a change in p. One would expect that the characteristic frequencies of the system would be related to the size of the source. Assuming that the size of the X-ray emitting region is related to the location of the shock, z_{sh}, it may be difficult for the jet-dominated model to explain the large range of characteristic frequencies we observe for XTE J1650–500.