State transitions in the 2001/2002 outburst of XTE J1650–500

S. Rossi, J. Homan, J.M. Miller, T. Belloni

aINAF-Astronomical Observatory of Brera-Merate,
Via E.Bianchi 46, 23807 Merate (LC), Italy

bHarvard-Smithsonian Center for Astrophysics,
60 Garden Street, Cambridge, MA 02138, U.S.A.

We present a study of the X-ray transient and black hole candidate XTE J1650–500 during its 2001/2002 outburst. The source made two state transitions between the hard and soft states, at luminosity levels that differed by a factor of \( \sim 5-10 \). The first transition, between hard and soft, lasted for \( \sim 30 \) days and showed two parts; one part in which the spectral properties evolve smoothly away from the hard state and another that we identify as the 'steep power law state'. The two parts showed different behavior of the Fe K emission line and QPO frequencies. The second transition, from soft to hard, lasted only \( \sim 15 \) days and showed no evidence of the presence of the 'steep power law state'. Comparing observations from the early rise and the decay of the outburst, we conclude that the source can be in the hard state in a range of more than \( 10^4 \) in luminosity. We briefly discuss the state transitions in the framework of a two-flow model.

1. INTRODUCTION

Black Hole Candidate (BHC) X-ray transients often show correlated spectral and variability properties during their outbursts. Several distinct states of spectral and variability behavior have been recognized ([123]). Until a few years ago, it was thought that the states of a source and transitions between them were determined and driven by (variations in) the mass accretion rate (\( \dot{m} \)). Recent observations ([4678910]) have challenged this idea; these suggest that in addition to \( \dot{m} \) there is another parameter responsible for the state of a system.

Here we present a study of the state transitions observed with the Rossi High Energy Timing Explorer (RXTE) during the 2001/2002 outburst of the BHC X-ray transient XTE J1650–500.

2. OBSERVATIONS AND RESULTS

2.1. Data analysis

We used 176 pointed RXTE observations for our study of XTE J1650–500, covering the period between 2001 September 6 and 2002 June 21. Especially the beginning of the outburst was extremely well sampled, giving us the opportunity to study the hard→soft transition in great detail. For our spectral analysis, we combined PCA and HEXTE data to obtain 3–150 keV energy spectra. For our timing analysis, we performed Fast Fourier Transforms (FFTs) of the high time resolution data (6–32 keV), resulting in 1/128–1024 Hz power density spectra. All energy spectra were fitted with a combination of a (cut-off) power law, a disk black body, a smeared edge, and a relativistic Fe K emission line from the accretion disk; our power spectra were fitted with a model consisting of several Lorentzians.

2.2. Overall outburst behavior

The 2.5–25 keV PCA light curve and the 4.5–7.9 keV/2.5–4.6 keV hardness ratio are shown in Figure 1. Already before the peak in the count rate the spectrum was softening. This trend continued for the early part of the decay until day 16, when both the count rate and hardness showed erratic changes. After day 33 the smooth softening observed before day 16 continued, which was accompanied by a further decrease in the count rate. On day 75 the spectrum showed a sudden hardening and an increase in the count...
After a 30 day gap in our observations (due to solar constraints) the source had a more or less constant spectral hardness similar to that of the first observation, while the count rate showed long term oscillations on top of a slow decay. The complex relation between count rate and spectral hardness can also be seen in the hardness-intensity diagram (HID; Fig. 2), which shows several distinct branches. Starting in the upper-right corner, the source moved through the HID counter-clockwise. Although it returned to a similar hardness as in the beginning of the outburst, it did so at a count rate that was a factor of 30 lower. Following [5] we defined several groups, based on their position in the HID, the spectral and variability properties of which will be the subject of the next section. An analysis of RXTE/ASM data strongly suggests that during the rise of the outburst the source moved along a path of constant hardness (≈ 0.7) and increasing count rate to the right-hand side of group I/II.

2.3. Correlated spectral and variability properties

Like in other BHC transients, the energy and power spectra evolved in a correlated way during the outburst. In XTE J1650–500 the types of correlated behavior changes from one group to the other. This is clear from Figure 3 in which we show the fractional contribution of the disk component ($f_d$) in the 2–100 keV range [3a], the index ($\Gamma$) of the power-law component [3b] and the strength ($r$) of the 0.01–100 Hz variability [3c]). The three vertical lines mark the transitions between the first four groups, each of which shows distinct behavior - data from after the gap are not shown. At the beginning of the outburst the source showed properties that are typical for the hard state ($f_d < 0.05$, $\Gamma=1.35$, and $r=26\%$ rms). In group I/II these parameters smoothly changed to $f_d \sim 0.4$, $\Gamma=2.1$, and $r=16\%$ rms, which is typical for the very high state. At the time of the transition to group III the 2–100 keV
Figure 3. Evolution of spectral and variability parameters from Sep. 6 to Nov. 24: 2-100 keV unabsorbed disk flux normalized to the total flux (a); photon index of power-law component (b); variability (c). The vertical lines mark the transitions between the first four groups.

flux had decreased from $3.4 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, at the peak of the outburst (third day), to $1.8 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. In group III $f_d$ and $r$ changed erratically, whereas $\Gamma$ was remarkably constant ($\sim 2.25$). Although the properties of group III classify it as very high state, its behavior is quite different from that in group I/II as is evident from Figs. 4 and 5 (more on those later). In group IV the spectrum was dominated by the disk component ($f_d > 0.85$) and variability was very weak ($r < 2\%$ rms), typical for the soft state. Group V/VI was characterized by the sudden decrease in $f_d (<0.3)$ and the return of strong variability ($r \sim 22\%$); $\Gamma$ smoothly decreased to 1.8 – these properties were very similar to observations in group I/II, albeit at a flux that was a factor of $\sim 5-10$ lower. After the $\sim 30$ day gap in our observations (group VII) $\Gamma$ was similar to that in the first observation and variability was strong ($r \sim 35\%$), typical for the hard state. For a discussion of the remarkable $\sim 14$ day oscillations in this phase of the outburst we refer to [13,14].

3. DISCUSSION

During its 2001/2002 outburst XTE J1650–500 showed several types of behavior, which could be classified either as distinct states (groups III and IV, VII) or as transitions between states (groups I/II and V/VI). Only during the transition from the hard to the soft state an extended interval (group III) of nearly constant $\Gamma$ was observed. Interestingly, this is the same part of the outburst in which narrow high frequency QPOs were found by [11]. This is most likely the 'steep power-law' state, as defined by [3]. Figure 4 shows that not only $\Gamma$ saturates in this state, but the QPO frequency as well, although it is not completely clear whether the QPOs in groups I/II and III are of the same type. The behavior of the Iron line flux as a function of power law flux (Fig. 5) also reveals different patterns for groups I/II and III,
suggestive of a change in the properties of the hard component and/or ionizations state of the disk \cite{10}. Additional changes are observed in the high energy cutoff and the coherence and time lag properties. The fact that this state is not observed during the soft→hard transition suggests that this transition does not necessarily display the reverse behavior seen during the hard→soft transition as was suggested by \cite{5}.

The start of the hard→soft transition occurred at an 2–100 keV luminosity that was a factor of ∼10 higher than at the start of the soft→hard transition. This hysteresis effect, which was already recognized as such by \cite{15} in other transients, has been attributed by several authors to the presence of two flows in these X-ray binary systems \cite{9,16,17}: one which responds rapidly to changes in the mass accretion rate (a coronal type flow) and one that responds much slower (a disk flow). The fact that almost the entire rise likely took place in the hard state, suggests that the fast flow couples directly to the medium responsible for the hard flux. Although the hard states in black hole transients are observed over a range of more than $10^4 - 10^6$ in luminosity, they only seem to be stable at the low luminosity end. That they are still observed at high luminosities, for short periods, is likely the result of the slow response of the disk flow. Whether the eventual decrease in the hard component is due to the disappearance of the fast flow, or to another mechanism, possibly involving cooling by the soft disk flux, is not clear. What is clear, though, is that like in many other systems \cite{15}, the hard component in XTE J1650–500 starts to dominate again at luminosities of less than ∼10% of the Eddington luminosity.

REFERENCES

1. Tanaka, Y., Lewin, W., 1995, In: X-ray Binaries, W. Lewin, J. van Paradijs, & E. van den Heuvel (eds.), (Cambridge University Press), p. 126
2. van der Klis, M., 1995, In: X-ray Binaries, W. Lewin, J. van Paradijs, & E. van den Heuvel (eds.), (Cambridge University Press), p. 252
3. McClintock, J. & Remillard, R., 2003, \url{astro-ph/0306215}
4. Rutledge, R. et al., 1999, ApJS, 124, 265
5. Homan, J. et al., 2001, ApJS, 132, 377
6. Wilson, C. & Done, C., 2001, MNRAS, 325, 167
7. Revnivtsev, M. et al., 2000, MNRAS, 312, 151
8. Trudolyubov, S. et al., 2001, MNRAS, 322, 309
9. Maccarone, T. & Coppi, P., 2003, MNRAS, 338, 189
10. Rossi, S. et al., 2003, in prep.
11. Homan, J. et al., 2003, ApJ, 586, 1262
12. Kalemci, E. et al., 2003b, ApJ, 586, 419
13. Tomsick, J. et al, 2003, ApJ, 592, 1100
14. Tomsick, J. et al, submitted to ApJ, \url{astro-ph/0307458}
15. Miyamoto, S. et al., 1995, ApJ, 442
16. van der Klis, M., 2001, 561, 943
17. Smith, D. et al., 2002, ApJ, 569, 362
18. Maccarone, T., 2003, A&A, in press, \url{astro-ph/0308030}