X-RAY OBSERVATIONS OF THE BLACK HOLE TRANSIENT 4U 1630–47
DURING 2 YEARS OF X-RAY ACTIVITY

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ABSTRACT

The black hole candidate (BHC) X-ray transient 4U 1630–47 continuously produced strong X-ray emission for more than 2 years during its 2002–2004 outburst, which is one of the brightest and longest outbursts ever seen from this source. We use more than 300 observations made with the Rossi X-Ray Timing Explorer (RXTE) to study the source throughout the outburst, along with hard X-ray images from the International Gamma-Ray Astrophysics Laboratory (INTEGRAL), which are critical for interpreting the RXTE data in this crowded field. The source exhibits extreme behaviors, which can be interpreted as an indication that the system luminosity approaches the Eddington limit. For 15 observations, fitting the spectral continuum with a disk-blackbody plus power-law model results in measured inner disk temperatures between 2.7 and 3.8 keV, and such temperatures are only rivalled by the brightest BHC systems, such as GRS 1915+105 and XTE J1550−564. If the high temperatures are caused by the dominance of electron scattering opacity in the inner regions of the accretion disk, it is theoretically required that the source luminosity be considerably higher than 20% of the Eddington limit. We detect a variety of high-amplitude variability, including hard 10−100 s flares, which peak at levels as much as 2−3 times higher than nonflare levels. This flaring occurs at the highest disk luminosities in a regime in which the source deviates from the Ldisk ∝ T 4 in relationship that is seen at lower luminosities, possibly suggesting that we are seeing transitions between a Shakura & Sunyaev disk and a “slim” disk, which is predicted to occur at very high mass accretion rates. The X-ray properties in 2002−2004 are significantly different from those seen during the 1998 outburst, which is the only outburst with detected radio jet emission. Our results support the “jet line” concept recently advanced by Fender and coworkers. Our study allows for a test of the quantitative McClintock & Remillard spectral state definitions, and we find that these definitions alone do not provide a complete description of the outburst. Finally, for several of the observations, the high-energy emission is dominated by the nearby sources IGR J16320−4751 and IGR J16358−4726, and we provide information on when these sources were bright and on the nature of their energy spectra.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (4U 1630−47, IGR J16320−4751, IGR J16358−4726) — X-rays: stars

Online material: color figures

1 INTRODUCTION

The X-ray (∼1−10 keV) luminosities from Galactic black hole candidate (BHC) transients range from values below 10 39 ergs s −1 when the sources are in quiescence (Garcia et al. 2001) to values that can approach or exceed 10 39 ergs s −1 for some sources (Done et al. 2004). During outbursts, luminosities above ∼10 39 ergs s −1 are usually seen for at least several months (Chen et al. 1997), and significant changes in the X-ray properties occur over time. We do not have a detailed understanding of all the physical changes that lead to changes in the X-ray emission properties, but the physics involves the structure of the accretion disk around the black hole, as well as the connection between the accretion disk and the steady or impulsive jets that can be launched from these systems. The changes in the X-ray emission properties are partially caused by changes in the mass accretion rate onto the black hole; however, it has been demonstrated that other physical parameters must also be important for determining those properties (Homan et al. 2001; Tomsick 2004b).

The emission properties of accreting black holes are often classified in terms of “spectral states.” Recently, efforts have been made to make the state definitions more quantitative and to connect these definitions directly to the continuum spectral components (McClintock & Remillard 2003). The spectra can often be described as the combination of a soft, thermal component along with a hard component that can fall off more or less steeply with energy. The thermal component is almost certainly blackbody emission from an accretion disk, as in Shakura & Sunyaev (1973), but the mechanism for producing the hard component is less clear. Accreting black holes can be highly variable, sometimes with quasi-periodic oscillations (QPOs); spectral and timing properties are both incorporated in the following spectral state definitions from McClintock & Remillard (2003).

In the thermal-dominant (TD) state, the thermal component accounts for >75% of the total 2−20 keV flux. In this state, no or weak QPOs are seen with rms levels below 1%, and the 0.1−10 Hz continuum rms is ≤6%. In the steep power-law (SPL) state, the hard component is a power law with Γ > 2.4, where Γ is the power-law photon index. A source is said to be in the SPL state if QPOs are present and the hard component contributes >20% of the 2−20 keV flux or if, regardless of the timing properties, the hard component contributes >50% of the 2−20 keV flux. Finally, in the hard state, the hard component is much less steep, at 1.5 < Γ < 2.1, the hard component contributes more than 80% of the 2−20 keV flux, the 0.1–10 Hz continuum rms is between 10% and 30%, and the presence of radio emission...
signals the presence of a compact jet (Fender 2001). As discussed in McClintock & Remillard (2003), systems also exhibit intermediate states, with properties that are usually some combination of the three main states (TD, SPL, and hard).

The X-ray activity from the BHC transient 4U 1630−47 over more than 2 years during 2002–2004, along with good high-energy coverage of the source by the Rossi X-Ray Timing Explorer (RXTE) and the International Gamma-Ray Astrophysics Laboratory (INTEGRAL), provides an opportunity to study the long-term evolution of the source as it enters different spectral states and exhibits different emission properties. Among BHC transients 4U 1630−47 is one of the most active, and it has produced strong hard X-ray emission during its 17 detected outbursts (Trudolyubov et al. 2001; Tomsick & Kaaret 2000; Oosterbroek et al. 1998; Kuulkers et al. 1997; Parmar et al. 1997). The source has a quasi-periodic ∼600–700 day outburst recurrence time (Kuulkers et al. 1997), which is unusually short for systems of this type, probably indicating a higher time-averaged mass accretion rate from its companion (Chen et al. 1997). Highly polarized radio emission was detected from 4U 1630−47 during its 1998 outburst (Hjellming et al. 1999), indicating the presence of jets, and the source is often compared to microquasars such as GRS 1915+105 and GRO J1655−40. The compact object mass has not been measured for 4U 1630−47, but McClintock & Remillard (2003) classify it as a very likely ''category A'' BHC. Also, the binary orbital period is not known, and our lack of knowledge is due to the difficulty in performing optical and infrared studies of the source due to its high column density (but see Augusteijn et al. [2001] for the likely identification of the source’s infrared counterpart).

The current outburst from 4U 1630−47, which began in 2002 September (Wijnands et al. 2002), is one of the brightest and longest recorded outbursts from this system. A new high-amplitude flaring behavior has been reported at different times during this outburst (Homan & Wijnands 2002; Tomsick et al. 2004b; Tomsick 2004a). In addition to the high level of recent activity from 4U 1630−47 and the recent work on defining spectral states, our study comes at a time when INTEGRAL is providing high-quality hard X-ray images. Images of the 4U 1630−47 field, which we present in this work and in Tomsick et al. 2004b, are extremely useful for avoiding source confusion. In the following, we present X-ray spectral and timing studies of 4U 1630−47.

2. OBSERVATIONS

RXTE regularly monitored 4U 1630−47 in outburst with pointed observations between 2002 September 12 (MJD 52,529) and 2005 January 4 (MJD 53,375). Here we study the evolution of the X-ray properties throughout the outburst by analyzing data from the 318 RXTE observations that occurred during this time. With the exception of five 22–36 day observing gaps caused mainly by Sun angle constraints, pointed observations occurred, on average, approximately every other day for 2.3 years. The observations were made under seven different proposals (see Table 1 for the proposal IDs): In three cases (P70113, P80117, and P90128) we observed 4U 1630−47 in conjunction with our INTEGRAL program; and in the other four cases (P70417,

### Table 1

| Proposal ID  | Number of Observations | Range of Exposure Times (s) | Mean Exposure Time (s) |
|-------------|------------------------|----------------------------|------------------------|
| P70417      | 53                     | 96–7504                    | 1745                   |
| P70113      | 55                     | 288–11,216                 | 2756                   |
| P80117      | 53                     | 96–7376                    | 1849                   |
| P80417      | 1                      | 1072–1072                  | 1072                   |
| P80420      | 55                     | 320–2320                   | 1144                   |
| P90128      | 54                     | 256–3392                   | 1635                   |
| P90410      | 47                     | 464–3264                   | 1775                   |

![Fig. 1](image-url) — X-ray light curves and hardness vs. time for 4U 1630−47 from 2002 September to 2005 January. (a) RXTE ASM 1.5–12 keV rates (daily averages). (b) 3–20 keV PCA light curve for the 318 pointed observations. (c) 20–100 keV HEXTLE light curve. (d) 9–20/3–9 keV hardness ratio using the PCA count rates. The vertical dashed line marks the time of the INTEGRAL observation. In (b) "fl" marks the examples of the flaring behavior shown in Fig. 4. Also, the PCA count rates for the final four observations (see [b]) are consistent with little or no contribution to the emission from 4U 1630−47.
the observations were made under a public Target of Opportunity program, and we analyzed data from the public archive. The Proportional Counter Array (PCA) and High-Energy X-Ray Timing Experiment (HEXTE) light curves shown in Figure 1 indicate the times of the RXTE observations. After the launch of the European Space Agency (ESA) satellite INTEGRAL (Winkler et al. 2003) in 2002 October, we triggered our Target of Opportunity to observe 4U 1630−47 when the source became observable during outburst in early 2003. We obtained a 293 ks exposure between UT 2003 February 1.2 and UT 2003 February 5.3, and the time of this observation is marked in Figure 1. We previously used the data from this observation for studies of the obscured X-ray source IGR J16320−4751 (AX J1631.9−4752), which is a hard and persistent (though highly variable) source that is close to 4U 1630−47 (Tomsick et al. 2003; Rodriguez et al. 2003; Foschini et al. 2004), and we used these data to report detections of two other new INTEGRAL sources (Tomsick et al. 2004a). In addition, the 20–40 keV images from this observation can be found in Tomsick et al. (2004b) along with information about the sources in the INTEGRAL field of view (FOV), including an initial look at the hard X-ray and gamma-ray properties of 4U 1630−47. Although we do not present a full analysis of the INTEGRAL data here, the hard X-ray INTEGRAL images are important for interpreting the RXTE data. 3. DATA ANALYSIS We extracted energy spectra and light curves from the RXTE data using scripts developed at the University of California, San Diego, and the University of Tübingen that incorporate the standard software for RXTE data reduction (FTOOLS). We processed the data using the most recent RXTE calibration files, which were released on 2003 July 7, and performed extractions using FTOOLS versions 5.3 and 5.3.1. The RXTE routines are identical for these two versions of FTOOLS. We performed time filtering for the 330 observations using data from times during which the following criteria are satisfied: the RXTE pointing is within 0.5 of the nominal pointing position, the nominal pointing position is more than 100/14 above the limb of the Earth, a South Atlantic Anomaly (SAA) passage has not occurred within the previous 30 minutes, Proportional Counter Unit (PCU) 2 is turned on, and the PCU 2 electron ratio is less than 0.25. We chose PCU 2 because, in normal RXTE operation, this unit is programmed to have a very high duty cycle to allow for the most precise observation-to-observation comparisons. Our filtering led to zero exposure time for only 12 out of 330 observations (3.6%), leaving us with 318 observations for further study. As shown in Table 1, we typically obtained 1–3 ks of exposure time per observation, but exposure times vary greatly, from 96 s up to 11 ks. For all 318 observations, the mean exposure time is 1.8 ks. We extracted the following information for each observation: the 3–20 keV PCU 2 count rate, the 3–9 keV PCU 2 count rate, the 9–20 keV PCU 2 count rate, the 20–100 keV HEXTE-A count rate, the 3–200 keV PCA+HEXTE energy spectrum, and the 3–20 keV PCA light curve with 16 s time bins. We took the PCA information from the standard 2 data, which includes 129 channel energy spectra taken with 16 s time resolution. We used the sky-VLE model to estimate and subtract off the background.
For HEXTE, we used event list data, and we used the normal HEXTE rocking mode to estimate and subtract off the background. As described below in § 7, we also selected five observations for more detailed study, and for these, we used the higher time resolution PCA data to produce power spectra. For four of the observations, we used a PCA mode with 64 energy channels and $2^{-15}$ s ($= 122 \mu s$) time resolution. In the fifth case, we combined the data from two PCA modes: a mode with $2^{-11}$ s (7.8 ms) time resolution, covering the lower energy portion of the spectrum; and a second mode with higher time resolution, containing an event list for the higher energy photons. We used data from all the active PCUs when producing the power spectra.

**INTEGRAL** hard X-ray images from the observation described above show that 4U 1630–47 lies in a region of the Galaxy that has a high density of hard X-ray sources, including a source, IGR J16320–4751, that is 0.58 from 4U 1630–47. The 20–40 keV IBIS (Imager On-board the INTEGRAL Satellite) image, produced using the Off-line Scientific Analysis (OSA version 4.2) software (Goldwurm et al. 2003), is shown in Figure 2. When we realized that there is another hard X-ray source within the RXTE FOV for the nominal 4U 1630–47 pointing position, we requested a change in the pointing position to avoid IGR J16320–4751. From MJD 52,691 to 52,722, we used the pointing position labeled offset 1 in Figure 2. However, the presence of IGR J16393–4643 (Combi et al. 2004) and a third X-ray transient, IGR J16358–4726 (Patel et al. 2004), prompted another change in pointing position to offset 2, and we used this pointing position from MJD 52,722 to 52,781. The PCA and HEXTE collimators have a triangular response with a FWHM FOV of 10° and a full-width at zero-intensity (FWZI) FOV of 2°.

### 4. FLUX AND HARDNESS EVOLUTION DURING THE OUTBURST

Figure 1a shows the RXTE All-Sky Monitor (ASM) 1.5–12 keV light curve for 4U 1630–47 with the source in outburst from 2002 September to the end of 2004. In addition to being the longest outburst during the RXTE lifetime, at its peak its ASM flux is $\approx 800$ mcrab (1 crab = 74 ASM counts s$^{-1}$), which is $\approx 50\%$ brighter than any previous outburst observed by the ASM. Below we divide the outburst into the various spectral states the source entered, but in general the ASM light curve shows two very bright and highly variable periods: the first occurred for $\approx 120$ days between MJD 52,530 and 52,650, and the second occurred for $\approx 200$ days in 2003 between MJD 52,750 and 52,950. The source was also bright for much of 2004, but it did not become as bright as the previous two periods of very high activity. Twice in 2003 and once in early 2004 the source flux was low enough to be only marginally detected by the ASM. The source became undetectable again in late 2004, and it appears that the source has remained in quiescence into 2005.

Figure 1b shows the count rates measured in the 3–20 keV band by the PCA during the pointed RXTE observations. For the observations made at the offset pointing positions, the count rates are corrected using the PCA collimator response. The RXTE monitoring program began soon after the source was detected by the ASM. While the source flux was at the ASM sensitivity limit at times, the PCA, with its better sensitivity, shows continuous activity until 2004 November 16 (MJD 53,326). After this date there was a 36 day gap in coverage, and we obtained four more PCA measurements after this gap. For these observations, the PCA rates are consistent with Galactic ridge emission and flux from IGR J16320–4751, with little or no emission from 4U 1630–47. They are not included in the spectral and timing analysis in the next two sections (leaving 314 observations). Figure 1c shows the HEXTE-A 20–100 keV count rate, and Figure 1d shows the source hardness, defined as the ratio of the 9–20 keV PCA rate to the 3–9 keV PCA rate.

### 5. ENERGY SPECTRA

For the 314 observations, we used the XSPEC version 11.3.1t software to perform $\chi^2$-minimization spectral fits to the PCA+HEXTE 3–200 keV energy spectra. For the PCA spectra, we included systematic errors at a level of 0.6% for 3–8 keV and at a level of 0.3% for 8–25 keV, and these numbers are derived by fitting energy spectra of the Crab nebula as described in Tomsick et al. (2001). For many of the observations, the standard two component model—disk-blackbody (Makishima et al. 1986) plus power law with interstellar absorption—provides acceptable fits, but for 31 observations, we obtain $\chi^2 > 2.0$ for 63 degrees of freedom (doF), and for the 314 observations, the mean $\chi^2$ is 1.51. By examining the residuals for several of the spectra with statistically poor fits, we found two main reasons for the poor fits. First, in many cases, large residuals (positive and negative) are present around the iron K$\alpha$ complex. Second, negative residuals are sometimes seen at high energies, above 50 keV, indicating the presence of a cutoff in the spectrum. The presence of iron features and high-energy cutoffs is not surprising, as they have been seen previously for 4U 1630–47 as well as for other black hole sources (Tomsick & Kaaret 2000; Zdziarski et al. 1996).

Thus, we refit all the energy spectra after adding a narrow iron K$\alpha$ emission line and a smeared iron edge (Ebisawa et al. 1994) in a similar manner to that described in Tomsick & Kaaret (2000). We restricted the line energies to between 6.4 and 7.1 keV, spanning the possible iron K$\alpha$ transition for nonredshifted lines. Similarly, we restricted the edge energy to between 7.1 and 9.3 keV. Sample fits to several spectra show that the width of the smeared edge is not well constrained in most cases, and we fixed the width to 10 keV (Ebisawa et al. 1994; Tomsick & Kaaret 2000). We also added a high-energy cutoff allowing the model to exponentially turn over above an energy $E_{\text{cut}}$ with an $e$-folding energy of $E_{\text{fold}}$. Finally, although the column density ($N_H$) has been fixed to values close to $10^{23}$ cm$^{-2}$ in some previous studies (e.g., Tomsick & Kaaret 2000), the results for this RXTE data set indicate significant changes during the outburst. Thus, we have left $N_H$ as a free parameter, except that we have restricted the column density to be greater than $6 \times 10^{22}$ cm$^{-2}$, which is the lowest value that has been measured for 4U 1630–47 by a soft X-ray instrument (Parmar et al. 1997). This value may represent the interstellar value along the line of sight.

These additions to the spectral model produce significant improvements in the quality of the fits. For the 314 spectra, the mean $\chi^2$ is 1.15 for 57 doF, and only 13 have $\chi^2 > 2.0$. We examined the spectral residuals as well as the 16 s light curves for the cases in which the worst fits are obtained. In most of these cases, the light curves show a high degree of variability, suggesting that spectral variability during the observation degrades the quality of the fits. However, in several cases, the level of variability is not particularly high, and in four of these observations significant positive residuals are present at high energies, above $\approx 40$ keV. Although it is possible that these residuals indicate a high-energy excess from 4U 1630–47, the observations for which the excess is present occurred at the nominal pointing position for 4U 1630–47, so that the RXTE FOV includes the persistent hard X-ray source IGR J16320–4751 (see Fig. 3). Using
the McClintock & Remillard (2003) state definitions to divide the bar size from observation-to-observation (see Table 2). The crosses indicate observations that we believe are contaminated by the power-law; open diamonds: intermediate state; circles: thermal-dominant; squares: Remillard (2003). The symbols correspond to states as follows: triangles: steep power-law flux to the total flux (PLR). When the entire outburst occurred between MJD 52,560 and 52,596, and as the spectra for these four observations are likely contaminated, we do not consider them in the following analysis.

Figure 3 shows the PCA rates and spectral parameters versus time. The spectral parameters shown include the temperature of the disk-blackbody component ($kT_{in}$), the normalization of this component ($N_{diskbb} = (R_{in}/d_{10})^{2} \cos i$, where $R_{in}$ is the inner radius of the accretion disk in kilometers, $d_{10}$ is the source distance in units of 10 kpc, and $i$ is the disk inclination), the power-law photon index ($\Gamma$), and the ratio of the unabsorbed 2–20 keV power-law flux to the total flux (PLR). When the entire outburst is considered, the range of $kT_{in}$ values is 0.49–3.81 keV, while the range is 0.63–4.13 for $\Gamma$. We use the spectral parameters and the McClintock & Remillard (2003) state definitions to divide the observations into different spectral states, and the classifications are indicated in Figure 3. The steep power-law (SPL) observations have $\Gamma > 2.4$ and $\text{PLR} > 0.5$. Those in the thermal-dominant (TD) state have $\text{PLR} < 0.25$. The source was only in the hard state with $1.5 < \Gamma < 2.1$ and $\text{PLR} > 0.80$ for two observations near MJD 53,069. The remainder of the observations do not fit into any of the spectral states as defined by McClintock & Remillard (2003), and we say that the source was in one or more intermediate states (ISs) during these observations. It should be noted that we have divided the observations into spectral states using only spectral and not timing information. While timing information is important to the study of spectral states and is part of the full McClintock & Remillard (2003) definitions, our results for a sample of the power spectra (see § 7) show that the timing properties are in line with the McClintock & Remillard (2003) criteria for the various states. If we had included timing information in dividing up the spectral states, it is possible that some TD observations with higher noise levels would be reclassified as IS and that if some of the IS or TD observations have QPOs, they might be reclassified as SPL. However, such reclassifications would not change the results or conclusions of this work.

There are seven observations with distinctly different spectra. For these observations, the power law is very hard, with values of $\Gamma$ between 0.6 and 1.7, and it is sharply cut off, with $\epsilon$-folding energies between 10 and 50 keV. While such a spectrum would represent the discovery of a new black hole state, we strongly suspect that these observations are contaminated by emission from the hard X-ray transient IGR J16358–4726. Although IGR J16358–4726 was not detected during our 2003 February INTEGRAL observation (see Fig. 2), four of the observations for which we see the very hard X-ray spectrum occurred during the time period from MJD 52,701 to 52,722, when the source was known to be active (Revnivtsev 2003; Revnivtsev et al. 2003; Patel et al. 2004). During this time period, we used the offset 1 pointing position, so the FOV included IGR J16358–4726 but not IGR J16320–4751. In addition, the hard spectrum is not detected for any of the observations for which we used the offset 2 pointing position, which does not include IGR J16358–4726 in the FOV. In Appendix B, we include details about the hard spectra, as they provide useful information on IGR J16358–4726. Other than in Appendix B, we do not consider these observations further.

6. HIGH-AMPLITUDE VARIABILITY

An inspection of the 3–20 keV 16 s PCA light curves for all 314 observations indicates that in addition to the observation-to-observation variability that is clearly seen in Figures 1 and 3, many of the light curves show high-amplitude variability during the observations. To quantify the level of variability, we calculated the peak-to-peak amplitude for each observation, $A_{pp}$, defined simply as the maximum PCA count rate minus the minimum rate divided by the mean rate for the observation. The errors on $A_{pp}$ depend on the uncertainties in the count rates for the individual maximum and minimum 16 s time bins as well as the error in the mean rate. For the 314 observations, the mean value of $A_{pp}$ is 0.26 and the standard deviation is 0.20. While the majority of the observations have some form of significant variability, we focus on the observations with high-amplitude variability, defined as the observations during which $A_{pp}$ minus the 2 $\sigma$ error on $A_{pp}$ is greater than 0.3. With this definition, there are 72 observations with high-amplitude variability.

A more careful examination of the 72 light curves with high-amplitude variability indicates that there are at least four types of high-amplitude variability, and examples of the most common type are shown in Figure 4, while the other three types are

![Figure 3](https://example.com/figure3.png)
shown in Figure 5. The light curves shown in Figure 4 can be interpreted as a series of 10–100 s flares; however, in some of the light curves the flares occur so often that it is difficult to distinguish the individual flares. We refer to this as “flaring” behavior below, and we chose the examples to illustrate that flaring occurs over a wide range of times during the outburst, as shown in Figures 1 and 3. While all of the examples shown in Figure 4 are from IS observations, flaring also sometimes occurs during observations classified as TD and SPL. Figure 4 also shows the 9–20/3–9 keV hardness as a function of time. For the observations shown in Figure 5. The light curves shown in Figure 4 can be interpreted as a series of 10–100 s flares; however, in some of the light curves the flares occur so often that it is difficult to distinguish the individual flares. 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shown in panels (a), (b), and (c), the hardness is tightly correlated with the total 3–20 keV rate (i.e., these are hard flares). However, this correlation is not seen for the panel (d) observation.

Even more extreme variability, with $A_{pp} > 1.0$, is seen in the two light curves shown in Figures 5a and 5b. These light curves exhibit deep dips that are clearly different from the other types of variability observed. The dip shown in Figure 5a is very similar to the dip observed from 4U 1630–47 during its 1996 outburst (Tomsick et al. 1998; Kuulkers et al. 1998). Spectral analysis of the 1996 dip indicates that it is likely caused by...
absorption, perhaps from accretion disk material, but the fact that the dip is not spectrally hard indicates partial covering of the X-ray source (Tomsick et al. 1998; Kuulkers et al. 1998). Similarly, the dip shown in Figure 5a shows, at most, only a moderate level of hardening.

A third type of variability is illustrated in Figure 5c and can be described as short, 10–20 s dips, and similar dips have been reported during the 1998 outburst from 4U 1630–47 (Tomsick & Kaaret 2000; Dieters et al. 2000). The hardness ratio indicates that the spectrum becomes softer during the dips. During this outburst, we only see these short, soft dips during the three observations from MJD 52,794.289, 52,795.340, and 52,801.445, and a total of seven or eight short dips are seen in the 19 ks of exposure time accumulated for these three observations, which are all classified as SPL.

The final type of high-amplitude variability is shown in Figure 5d and consists of a single, very hard flare that occurred at the end of the observation performed on MJD 53,087.832, at which time the source was in the TD state. The flare did not occur close to the time of any SAA passage, and we checked that the PCA electron ratio was not high during the time of the flare, indicating that the flare did not have any instrumental or environmental cause. In addition, we checked for solar flares using the X-ray data from the Solar X-Ray Imager (SXI) on the Geostationary Operational Environmental Satellites (GOES-12), but the Sun did not flare during the RXTE observation. Finally, we extracted a 16 s HEXTE light curve, and we see that HEXTE also detected the hard flare. Thus, we conclude that origin of the flare was an astronomical source in the RXTE FOV. It is likely that the flare came from 4U 1630–47, but we cannot rule out the possibility that it came from one of the other sources in the FOV, such as IGR J16358−4726 or IGR J16320−4751.

7. EXAMPLES OF ENERGY AND POWER SPECTRA

We selected representative observations for more detailed spectral and timing analysis. The selected observations include one observation from each of the spectral states (SPL, TD, and hard) and two observations from the IS state: one that exhibits the flaring behavior described above and one that does not. The energy spectra from these observations are shown in Figure 6, and the parameters from the spectral fits are given in Table 2. From the SPL state to the hard state, the spectra are ordered according to decreasing $kT_{\text{in}}$ and 3–200 keV flux, as shown in Table 2. While $kT_{\text{in}}$ is correlated with the flux, the disk-blackbody normalization is anticorrelated with the flux. The changes for $\Gamma$ and PLR do not have a simple relationship with the total flux. The PLR is the highest at the highest flux and the lowest flux, but the thermal, disk-blackbody component contributes a higher fraction of the flux at intermediate flux levels. Table 2 also provides the measured values for the column density ($N(H)$). The values, with

![Figure 6](image-url)
90% confidence error bars, indicate that the column density drops significantly with flux.

The 0.005–64 Hz rms-normalized power spectra for the same five observations are shown in Figure 7. In fitting the power spectra, we considered various combinations of three different components, which we also previously used to fit the 4U 1630–47 spectra from the 1998 outburst (Tomsick & Kaaret 2000): a power-law function (PL); a band-limited noise component (BL), which we modeled as a zero-centered Lorentzian; and a QPO, which we modeled using a Lorentzian. For the SPL state, the power-law function (PL); a band-limited noise component (BL), which we modeled as a zero-centered Lorentzian; and a QPO, which we modeled using a Lorentzian. For the SPL state, the power-law function (PL); a band-limited noise component (BL), which we modeled as a zero-centered Lorentzian; and a QPO, which we modeled using a Lorentzian. For the SPL state, the

![Graph showing power spectra for five observations](image)

**Figure 7.** RXTE power spectra for each of the five observations shown in Fig. 6, illustrating examples of the following states or behaviors: SPL, flaring, TD, IS, and hard. The solid lines represent model fits, and the parameters for these models are given in Table 3.

The 0.005–10 Hz continuum is well described by the PL model. In addition, a QPO is present at 12.15 ± 0.15 Hz with a quality factor of \( Q = 4.4 ± 0.7 \) and a fractional rms of 1.30% ± 0.07% (see Table 3). Above this QPO, the power drops much more rapidly than the extrapolation of the PL. For the IS observation with flaring, nearly the entire 0.005–64 Hz range is well described by the PL. There are no QPOs in this case, but there is excess power below ~0.02 Hz due to the flaring. The TD state power spectrum has approximately a power-law shape from 0.005 to 10 Hz. There appears to be a narrow dip in the power at 10 Hz, and the power drops off more rapidly than the extrapolation of the power law above 20 Hz. In the IS state, there is evidence for BL and PL components, although the statistics are rather poor for this state due to a lower count rate and a lower rms noise level. There is no evidence for the presence of QPOs in the IS state. Finally, in the hard state, the continuum is well described by only the BL component, and a QPO is present at 5.13 ± 0.01 Hz with \( Q = 21 ± 5 \) and a fractional rms level of 5.4% ± 0.3%. The other hard state observation exhibited a very similar power spectrum but with the QPO at 4.03 ± 0.01 Hz.

The power spectra for the observations we previously identified as being in the TD, SPL, and hard states based on their spectral properties are consistent with the typical power spectra expected for these states as described by McClintock & Remillard (2003). TD power spectra typically have 0.1–10 Hz rms values ≤6% with weak or no QPOs and a power-law shape, and these properties are consistent with our example TD power spectrum. For SPL power spectra, the continuum often (but not always) has a power-law shape, and low-frequency (1–15 Hz) QPOs are usually present. Our example SPL power spectrum exhibits similar properties. Based on the fact that the QPO in our SPL example is relatively broad, it would be classified as type A or B (depending on its phase lag properties) using the QPO classifications given in Remillard et al. (2002), and the combination of a power-law continuum and type A or B QPOs is typical (Casella et al. 2004).

The power spectra for the two observations identified as being in the hard state have relatively strong band-limited noise, which is a characteristic of hard state power spectra. The 0.1–10 Hz rms values for these two observations are 9.6% ± 0.4% and 9.0% ± 0.6%, lying just below the 10%–30% range that is typical for the hard state. While this could indicate that the source was close to but not quite in the hard state, it is important to note that these are the only two observations for which we found strong band-limited noise. We produced power spectra for the five IS observations closest in time to the two hard state observations. We fitted them with a power-law model and obtained reduced-\( \chi^2 \) values between 0.4 and 2.1 for 17 dof. The

**TABLE 3**

| Observation ID | Spectral State | Model | Continuum rms (0.1–10 Hz) (%) | \( \nu_{QPO} \) (Hz) | \( Q \) | QPO rms (%) |
|----------------|----------------|-------|-------------------------------|-------------------|--------|-----------|
| 70417-01-09-00 | SPL            | PL+QPO| 1.8 ± 0.2                     | 12.15 ± 0.15      | 4.4 ± 0.7| 1.30 ± 0.07|
| 70113-01-43-00 | Flaring        | PL    | 6.1 ± 0.5                     | ⋯                 | ⋯      | ⋯         |
| 70417-01-06-00 | TD             | PL    | 5.8 ± 0.7                     | ⋯                 | ⋯      | ⋯         |
| 70113-02-04-00 | IS             | PL+BL | 3.5 ± 1.3                     | ⋯                 | ⋯      | ⋯         |
| 80117-01-21-01 | Hard           | BL+QPO| 9.6 ± 0.4                     | 5.13 ± 0.01       | 21 ± 5 | 5.4 ± 0.3 |

a SPL, TD, IS, and hard state label the spectral state of the observation. The observation labeled “flaring” is an IS observation that exhibits the flaring behavior.

b Components used in modeling the power spectra, where PL = power law, BL = band limited, and QPO = quasi-periodic oscillation.

c The quality factor of the QPO, defined as \( \nu_{QPO} \) divided by the QPO’s FWHM.

d The peak-to-peak amplitude of the noise (see the text for a precise definition.)
power-law fits give 0.1–10 Hz rms values between 1% and 4%, indicating that the noise level is much lower for these observations than for the two observations identified as hard state observations. Thus, these two observations distinguish themselves from the other observations on the basis of their spectral and timing properties, which appears to indicate that the source did briefly enter the hard state.

The properties of the QPOs seen for the two hard state power spectra are also different from the QPO seen in the SPL. In addition to being at lower frequency, 4–5 Hz, the hard state QPOs are much narrower, and they would be classified as type C QPOs. The combination of type C QPOs and band-limited noise is typical (Casella et al. 2004). It is also notable that the hard state power spectra are very similar to those seen at the end of the 1998 outburst from 4U 1630–47 (Tomsick & Kaaret 2000). As the source declined in 1998, the QPO was first detected at 3.4 Hz and then gradually dropped to 0.2 Hz. Thus, the 4–5 Hz QPO we see in the 2002–2004 outburst likely indicates that a similar phenomenon began to occur but was stopped, perhaps by an increase in the mass accretion rate.

8. DISCUSSION

Good X-ray coverage of 4U 1630–47 during the 2002–2004 outburst has allowed us to study its source properties throughout the outburst in detail, and here we discuss these properties in the context of previous outbursts from 4U 1630–47, as well as in the context of accreting black holes in general. The 2002–2004 outburst is by far the longest and brightest that has occurred during the RXTE era, and in § 8.1 we make comparisons to historical outbursts. In our study, we have found several extreme and unusual source properties, and in § 8.2 we discuss our measurements of the soft component, including the extremely high inner disk temperatures that occur for some of the steep power-law state observations. In § 8.3 we extend the analysis described above to constrain the nature of the high-amplitude flaring. In § 8.4 we compare the X-ray and radio properties of the 2002–2004 outburst to those of the 1998 outburst and discuss radio–X-ray connections. Finally, our study has provided a test of the quantitative McClintock & Remillard (2003) state definitions, and in § 8.5 we discuss some of the pros and cons of these definitions.

8.1. Comparison of the 2002–2004 Outburst to Previous Outbursts

Prior to the 2002–2004 outburst from 4U 1630–47, four outbursts from this source had been observed by the RXTE ASM during the RXTE era (1996–present). The mean duration of these four outbursts as measured by the RXTE ASM is 140 days, and the mean peak ASM count rate is 28 counts s⁻¹ (0.38 crab). From the ASM light curve (Fig. 1a), the duration of the 2002–2004 outburst is 825 days, and the peak ASM rate is 62 counts s⁻¹ (0.84 crab), making it longer by a factor of nearly 6 and brighter by a factor of 2.2 than the mean values for the first four outbursts.

While the current outburst is unusual compared to the 4U 1630–47 outbursts of the past decade, it is not unprecedented in duration or in brightness when compared to the entire group of outbursts going back to 1969. Although there are many cases in which poor X-ray coverage makes it difficult to tell whether outbursts were extended or not, the clearest example of an extended outburst occurred when the Ginga All-Sky Monitor detected the source for 2.4 years between 1988 October and 1991 March (Kuulkers et al. 1997). The Ginga light curve shows that the 1988–1991 outburst had many similarities to the current outburst, including flares in which the flux reached ~0.6 crab, as well as multiple time periods of low flux during the outburst. For the 1988–1991 outburst, the low-flux periods are separated by ~220 days (Kuulkers et al. 1997). The ASM light curve for the 2002–2004 outburst has local minima at MJD 52,685, 53,000, 53,075, and 53,250, indicating separations of 315, 75, and 175 days; thus, they are the same order of magnitude as the 220 day separations, but they are clearly different.

With a peak flux of 0.84 crab (1.5–12 keV), the 2002–2004 outburst is somewhat brighter than the 0.6 crab (1–20 keV) flares detected during the 1988–1991 outburst. However, at a 3–6 keV flux of 1.4 crab (Chen et al. 1997), the 1977 outburst, which lasted for about 0.3 yr, was brighter than the current outburst. In summary, while the 2002–2004 outburst is one of the longest and brightest outbursts ever detected from 4U 1630–47, it is not unprecedented in either category. On the other hand, no previous outburst was both brighter and longer than the current outburst, so it is very likely that the total mass accreted is higher for the 2002–2004 outburst than for any previous outburst.

The high level of recent activity from 4U 1630–47 strengthens the argument made by Chen et al. (1997) that the mass accretion rate from the binary companion (M₆) is unusually high for this source. Furthermore, Chen et al. (1997) point out that this implies a very long binary orbital period (Porb > 12 days) for 4U 1630–47 based on the calculations of van Paradis (1996), which show that for a given Porb an X-ray binary will only be transient if M₆ is smaller than a critical value.

8.2. The Soft Component: Disk Temperatures and Luminosities

In BHC energy spectra the presence of a strong soft component is a clear indication that we are seeing thermal emission from an optically thick accretion disk. The basic physical properties that determine the shape of the soft component include the mass accretion rate, the mass of the black hole, the inner radius of the disk, and the binary inclination. If we could assume a standard Shakura & Sunyaev (1973) accretion disk, at least some of these parameters might be directly measurable by modeling the shape of the soft component; however, in practice, other physical processes can be important and can complicate the interpretation of any derived parameters.

For 4U 1630–47, we detect the soft component over a wide range of luminosities and mass accretion rates. While we have modeled the soft component using the disk-blackbody (diskbb) model, the limitations of this model must be understood when interpreting the parameters. For example, the shape of the soft component can be drastically changed if the disk opacity is dominated by electron scattering rather than free-free absorption (Shimura & Takahara 1995). It has been shown that this effect can cause measurements of inner disk radii to be underestimated by a factor of 5 or more (Merloni et al. 2000). In addition, at high mass accretion rates, additional cooling mechanisms may cause a change from the thin Shakura & Sunyaev (1973) disk solution to a geometrically thicker "slim" disk (Abramowicz et al. 1988). This can lead to significantly more material, and thus emission, at small radii and can also produce a much flatter radial temperature profile (T ∝ R⁻α), with a change in p from 0.75 to ~0.5 (Watarai et al. 2000). As a final example of the limitations of the diskbb model, it has been shown that assumptions about the boundary conditions at the inner radius of the disk can be important. The nonzero torque boundary condition assumed (basically for computational convenience) in the diskbb model can lead to an overestimation of the inner disk radius by a factor of more than 2 (Zimmerman et al. 2005).

Using observations of BHC systems XTE J1550–564, GRO J1655–40, and LMC X-3 and observations from previous
outbursts of 4U 1630–47, Kubota and coworkers show how effects of electron scattering and changes in the radial temperature profile can manifest themselves (Kubota & Makishima 2004; Kubota et al. 2001; Abe et al. 2004). Following these studies, we plot in Figure 8 the disk temperature ($kT_{in}$) versus the bolometric disk luminosity ($L_{disk}$) as derived from the 4U 1630–47 diskbb parameters. In deriving the luminosity, we assume a source distance of 10 kpc and a binary inclination of 60°, but these are highly uncertain. In Figure 8, we plot a solid line representing the slope of the $L_{disk} \propto T_{in}^4$ relationship that is expected for a standard Shakura & Sunyaev (1973) accretion disk with a constant inner radius ($R_{in}$). A large number of mostly TD and IS points at disk luminosities between $3 \times 10^{37}$ and $3 \times 10^{38}$ ergs s$^{-1}$ lie close to the line of constant $R_{in}$, and for these observations, we may be seeing a standard disk with a relatively stable inner radius. However, many of the points also deviate from this line, and we identify three regions of deviation that likely have distinct explanations. First, several IS and hard state observations at the lower luminosities ($\leq 10^{38}$ ergs s$^{-1}$) show disk temperatures well below values that would be consistent with the line of constant $R_{in}$. These are cases for which the overall source luminosity and presumably also the mass accretion rate are low, and these are likely cases in which the inner disk radius increases or at least in which the inner part of the disk is radiatively inefficient.

A second region of deviation includes TD, IS, and some of the SPL observations and occurs at the highest disk luminosities. This flattening of the $L_{disk}-kT_{in}$ relationship may be similar to what has been seen for XTE J1550–564 at high $L_{disk}$ (Kubota & Makishima 2004). For XTE J1550–564, Kubota & Makishima (2004) showed that the relationship flattened to a slope close to $L_{disk} \propto T_{in}^2$, which, based on the work of Watarai et al. (2000), could be an indication of a transition to a slim disk. In 4U 1630–47, it is clear from Figure 8 that the source leaves the solid line above $\sim 2 \times 10^{38}$ ergs s$^{-1}$, and it appears that it may begin to follow the $T_{in}^2$ relationship (Fig. 8, dotted line) for at least some luminosity range. However, the source appears to deviate from the $T_{in}^2$ relationship at the very highest values of $L_{disk}$, and it is possible that the source recovers the $T_{in}^4$ relationship (Fig. 8, dashed line). Although the exact evolution is not completely clear, it is interesting that the observations at the highest values of $L_{disk}$ that deviate from the solid line are also the observations for which the high-amplitude flaring occurred (see Fig. 8b). For transitions between the standard disk and the slim disk, theory predicts a limit cycle with a region of instability in between the two solutions. Thus, the flaring may be a consequence of the limit cycle, and this is a possibility we explore further below.

A third region of deviation from the line of constant $R_{in}$ contains mostly SPL observations for which $kT_{in}$ is extremely high, including 15 observations with $kT_{in}$ between 2.7 and 3.8 keV. Along with extremely high temperatures, the spectra exhibit very low values of $N_{diskbb}$, in the range of 1.2–12.3, implying values of $R_{in}$ that are unphysical. As an example, for a source distance of 10 kpc and a binary inclination of 60° (as assumed above), this range of normalizations indicates inner radii between 1.5 and 5.0 km; the former being an order of magnitude lower than the gravitational radius of a 10 M$_{\odot}$ black hole. Rather than extremely small inner disk radii, these high temperatures and luminosities are much more likely to be caused by spectral hardening due to the dominance of electron scattering in the inner region of the accretion disk.

Although the explanation for the high SPL state values of $kT_{in}$ is very likely electron scattering, it is notable that the extremely high temperatures are seen for such a large number of observations. During its 1998 outburst, 4U 1630–47 entered the SPL state, and fits to RXTE spectra gave $kT_{in} = 1.6–1.7$ keV and $N_{diskbb} = 46$ (Tomsick & Kaaret 2000; McClintock & Remillard 2003), which are considerably less extreme when compared to the 2002–2004 values. Very high values of $kT_{in}$ have been seen for other accreting BHs, although they are not common. For the 10 SPL spectra of accreting black holes studied by McClintock & Remillard (2003), only XTE J1550–564 and GRO J1655–40 have $kT_{in} > 2.0$ keV. In 1998, the XTE J1550–564 spectrum showed $kT_{in} = 3.3$ keV and $N_{diskbb} = 7.8$ (Sobczak et al. 2000; McClintock & Remillard 2003), which are within the range of values we see for 4U 1630–47; however, for XTE J1550–564, this spectral shape was only seen for a single RXTE observation, which occurred during a remarkable 6 crab flare during which powerful superluminal jets were ejected (Hannikainen et al. 2001). For GRO J1655–40, another superluminal jet source, McClintock & Remillard (2003) give a SPL example where the disk-blackbody temperature is 2.2 keV, and this source showed temperatures of $\sim$2 keV for a few other observations (Sobczak et al. 1999). However, for the other eight McClintock & Remillard (2003) SPL systems, $kT_{in}$ is in the range 0.5–1.7 keV. Although not discussed in McClintock & Remillard (2003), very high disk-blackbody temperatures have also been seen for GRS 1915+105. For six of the 1996–1997 observations made when the GRS 1915+105 luminosity was very high, Munoz et al. (1999) report values of $kT_{in}$ in the range 2.6–4.8 keV. Based on the McClintock & Remillard (2003) definitions...
and the parameters reported in Muno et al. (1999), GRS 1915+105 was in the SPL state during these observations, but it should be noted that the properties of GRS 1915+105 make it difficult to classify its behaviors into the canonical spectral states (Reig et al. 2003).

Concerning 4U 1630–47, we can conclude that the extremely high disk-blackbody temperatures that we measure during the 2002–2004 outburst are rare and may be a new phenomenon for this source. When compared to other BHC sources, the 4U 1630–47 temperatures are only matched by XTE J1550–564 and GRS 1915+105. For 4U 1630–47 and XTE J1550–564, the high temperatures are only measured during observations for which the sources are at their very brightest, and for GRS 1915+105, the high temperatures occur when the source is at or close to its brightest level (Muno et al. 1999; Done et al. 2004). It is possible that these high temperatures are an indication of the highest accretion rates that are possible from these systems. As described above, the cause of these high temperatures may be electron scattering in the inner disk. This causes the observed temperature, $kT_{\text{in}}$, to be higher than the effective temperature, $kT_{\text{eff}}$, by a factor of $f$. For the highest values of $kT_{\text{in}}$ that occur for 4U 1630–47 and GRS 1915+105 ($\sim 4$ keV), $f$ would need to be $\sim 3$ to obtain the temperatures expected for a Shakura & Sunyaev (1973) disk around a $10M_\odot$ black hole. Although this is higher than the value of $f = 1.7$ theoretically expected for luminosities around 10% of the Eddington luminosity (Shimura & Takahara 1995), these authors also find that much higher values of $f$ can occur for luminosities approaching the Eddington limit.

8.3. Flaring Behavior

Flaring from accreting BHC systems is seen on a wide range of timescales and may have various physical origins, including (but not limited to) accretion of clumps of matter or magnetically powered particle acceleration. While black hole variability is common, the flaring we see for 4U 1630–47, with amplitudes as high as $A_{\text{pp}} = 1.0$ on timescales of 10–100 s, is extreme. The 4U 1630–47 amplitudes are comparable to the wild variability seen for GRS 1915+105 (e.g., Belloni et al. 2000); however, the 4U 1630–47 light curves do not show the distinctive repeating patterns seen for GRS 1915+105. Recently, high-amplitude variability at relatively long timescales has been seen for the black hole systems XTE J1859+226 (Casella et al. 2004) and H1743–322 (Miller et al. 2004; Homan et al. 2005). Although the flares in these systems are not as extreme as we see in 4U 1630–47, they may be related.

To determine if the flaring is unique to the 2002–2004 outburst from 4U 1630–47, we inspected the 16 s light curves for the nearly 300 pointed RXTE observations made during the four previous outbursts. Similar flaring only occurred for three of the observations, and these observations were made during the 2000–2001 outburst over the time period 2000 November 16–18. Figure 9 shows the 16 s light curve and hardness ratio versus time for the November 18 observation, and it is notable that the PCA count rates and hardness levels are similar to those seen during the 2002–2004 flaring observations. For the November 18 observation, we extracted a PCA plus HEXTE energy spectrum and fitted the spectrum as described above for the 2002–2004 observations. The spectral parameters are remarkably similar to those seen for the 2002–2004 flaring observations. The measured inner disk temperature is $kT_{\text{in}} = 1.450_{-0.010}^{+0.007}$ keV and $L_{\text{disk}} = 3.2 \times 10^{38}$ ergs s$^{-1}$, putting it in the same region as the other flaring observations in Figure 8. Also, $\Gamma = 2.59_{-0.03}^{+0.04}$ and $PLR = 0.43$, so the observation would be classified as IS.

For the observations with light curves shown in Figure 4b (70113-01-43-00) and Figure 4c (80117-01-13-02), we performed spectral fits to study the spectral evolution as a function of PCA count rate. In both cases, we divided the 16 s time-resolution data into different PCA count rate ranges. We separated the full range from minimum rate to maximum rate into four subranges of equal size and produced four PCA spectra. We did not use HEXTE for this analysis because the HEXTE rocking would complicate the analysis. We fitted the four spectra simultaneously, leaving the parameters for the iron features free, but requiring that they be the same for all four spectra. We did not include a high-energy cutoff, as a cutoff was not required for either observation. Originally, for both observations we allowed the column density to be different for all four spectra. For 70113-01-43-00, when we forced $N_{\text{HI}}$ to be the same for all four spectra, the quality of the fit changed from $\chi^2/\nu = 187.8/174$ to 189.4/177. For 80117-01-13-02, the change was from $\chi^2/\nu = 208.8/174$ to 209.7/177, indicating that the spectra are consistent with a constant $N_{\text{HI}}$ for both observations. Figure 10 shows the evolution of the spectral parameters with count rate. For both observations, clear trends are seen with $kT_{\text{in}}$ increasing and $\Gamma$ hardening with count rate. The results indicate that both the soft and hard components are affected. In light of the above standard/slim disk discussion above, perhaps the most important result is the clear and strong increase in $kT_{\text{in}}$. The temperature increase is expected if the disk solution changes from a standard disk at low count rates to a slim disk at high count rates. This, along with the fact that the flaring may be a consequence of the zone of instability between the standard and slim disk solutions, make this explanation attractive. However, from the spectral evidence alone we cannot rule out that the disk temperature increases because of an increase in the mass accretion rate.

Although the spectral analysis indicates that changes in the accretion disk are important in producing the flaring, one might also ask whether the flaring behavior could have any physical connection to outflows or jets in the system. For example, in the case of the BHC H1743–322, from which spectacular hard flares were also recently detected, the flaring was accompanied by the
outburst (including times of other flaring episodes and when the source was in the SPL state), but no radio detections were reported.

8.4. A Connection between X-Ray Properties and Radio Jet Emission

The absence of radio emission during the 2002–2004 outburst is also interesting when comparing the X-ray properties during this outburst to those seen during the 1998 outburst, which is the only time radio emission has been detected from 4U 1630–47. In Figure 11, for both the 2002–2004 and 1998 outbursts, we show the hardness, defined as the ratio of the 9–20 keV PCA count rate to the 3–9 keV PCA count rate, versus the source intensity (the 3–20 keV PCA count rate). For the 2002–2004 outburst, we divide the observations into the different spectral states. All of the 1998 observations are marked with open squares. There are potentially important differences between the X-ray properties for the two outbursts in light of the fact that radio jet emission was only present for the 1998 outburst. Although both outbursts have C-shaped hardness-intensity diagrams, as is relatively typical for BHC systems (Fender et al. 2004; Homan & Belloni 2005), the 1998 outburst is shifted in hardness, indicating that the spectrum was harder in 1998 than in 2002–2004.

Also, as marked in Figure 11, 4U 1630–47 traveled through the hardness-intensity diagram in a counter-clockwise fashion during its 1998 outburst, while in 2002–2004, the source often moved in the clockwise direction. A related fact is that 4U 1630–47 entered a hard and bright state at the beginning of its 1998 outburst, whereas in 2002–2004 there is no evidence that this occurred. Although it is likely that 4U 1630–47 did enter a hard state during the 2002–2004 rise as this is the common pattern in BHC systems, the combination of the ASM and pointed RXTE observations (see Fig. 1) indicate that such a state would
have had to last a very short time and be limited to a time period when the source was dim.

These patterns are especially interesting in light of recent work on connections between black hole X-ray states, a source’s position in the hardness-intensity diagram, and radio jet ejections (Homan & Belloni 2005; Corbel et al. 2004; Fender et al. 2004; Fender & Belloni 2004). A general pattern seen in a number of BHC outbursts is that the systems will evolve from the hard state to an intermediate state and then a radio ejection will occur during the subsequent transition to the SPL state (Corbel et al. 2004). Fender et al. (2004) use the hardness-intensity diagram to quantify this effect, and it should be noted that they follow Homan & Belloni (2005) by using somewhat different terminology, describing the transition from the IS to the SPL states as a transition from the “hard intermediate” state to the “soft intermediate” state. Fender et al. (2004) suggest that each BHC system has a threshold hardness and that major jet ejections are only produced when the source crosses this “jet line” from a high to a low hardness level. If this is the case, Figure 11 suggests that the jet line for 4U 1630–47 may be around a hardness of 0.4. Our results for 4U 1630–47 provide evidence in favor of the jet line concept; however, based on the behavior of 4U 1630–47, it is not entirely clear if the presence of a radio jet in 1998 occurred because the outburst was harder overall or if the source simply entering a bright hard state led to the jet ejection.

8.5. Notes on Spectral States

Our analysis of this data also provides a test of the quantitative spectral state definitions of McClintock & Remillard (2003). In some ways, these definitions are quite successful. For example, it is impressive that the only two observations with spectral parameters meeting the hard state requirements are also the only two we found with power spectra that include a strong band-limited noise component. Also, looking at the hardness-intensity diagram in Figure 11, these two observations lie at the extreme end of the c-shaped pattern. However, in other areas, the definitions appear to be less satisfactory. Although most of the observations labeled as SPL lie at the other end of the c-shaped pattern in the hardness-intensity diagram, the SPL observations have a extremely wide variety of properties. For example, for about half of the SPL observations \( kT\text{in} \) lies in the 2.7–3.8 keV range, while the other half have temperatures <1.8 keV. We argue above that there are important physical differences between these two groups. Also, it is notable that over half of the observations made during the 2002–2004 outburst are put in the IS, meaning that a large fraction of the observations have X-ray properties that do not meet the requirements for any of the McClintock & Remillard (2003) states. Overall, while the McClintock & Remillard (2003) criteria appear to be useful for classifying the observations at the extremes of BHC behavior, it should be recognized that they, by themselves, do not provide a complete description of a BHC outburst due to significant variations in properties within states and the large fraction of IS observations.

9. SUMMARY AND CONCLUSIONS

Outstanding RXTE coverage of 4U 1630–47 during its 2002–2004 outburst has allowed us to study the detailed evolution of its X-ray spectral and timing properties over a period of more than 2 years. Historically, this outburst is among the longest and brightest seen in 36 years of observing 4U 1630–47, and it is very likely that it is the largest ever observed in terms of total mass transfer.

The X-ray properties during this outburst were also extreme, including 15 observations with very high disk-blackbody inner disk temperatures between 2.7 and 3.8 keV. The inner disk radii inferred from these fits are unphysically small, and it is likely that the high temperatures and small radii are caused by electron scattering. This explanation requires a spectral hardening factor of \( f \sim 3 \), implying a source luminosity that is considerably higher than 20% of the Eddington limit (Shimura & Takahara 1995), which is not unreasonable, as we measure 3–200 keV luminosities of \( 5 \times 10^{38} \) erg s\(^{-1}\) (\( d/10 \) kpc\(^2\)).

At the highest disk luminosities, we detect a deviation from the \( L_{\text{disk}} \propto T_{\text{in}}^{4} \) relationship (line of constant \( R_{\text{in}} \)) seen at lower luminosities as well as high-amplitude flaring. The deviation may be a sign of a transition from a standard disk to a slim disk as suggested by Kubota and coworkers. The flaring behavior of 4U 1630–47 may be consistent with this interpretation, as a zone of instability is expected between the two disk solutions. Also, our spectral analysis of flaring observations, showing that \( kT_{\text{in}} \) is correlated with PCA count rate is consistent with a change from a standard disk to a slim disk.

Although sensitive radio observations occurred during the 2002–2004 outburst, no strong radio emission that would indicate the presence of radio jets was detected. This is interesting in light of the fact that the X-ray properties were very different during the 1998 outburst when radio jet emission was detected. Compared to the 2002–2004 outburst, the 1998 outburst hardness-intensity diagram was shifted to a higher hardness level, and in 1998 the source entered into a bright and hard state, while it did not in 2002–2004. These findings support the connections between radio jets and spectral states found by Corbel et al. (2004) and the jet line idea recently proposed by Fender et al. (2004).

Finally, our analysis of a large number of RXTE observations has provided a good test of the quantitative McClintock & Remillard (2003) spectral state definitions. While the hard state appears to be well defined, the spectral and timing properties of the observations selected as SPL are highly nonuniform. Also, it is notable that over half of the observations are put in the IS because they do not meet the requirements of any of the McClintock & Remillard (2003) definitions. The results show that 4U 1630–47 exhibits many properties not encompassed by the McClintock & Remillard (2003) definitions that are likely to be physically important.

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APPENDIX A

As described in § 5 above, there are four RXTE observations for which we see strong positive residuals at high energies (\( \geq 30 \) keV) after fitting the PCA plus HEXTE spectra with our standard spectral model. These occur for observations made at the nominal pointing position, and during these observations IGR J16320–4751 was in the FOV, 0.58 from 4U 1630–47 and the center of the FOV. Due to the high level of activity from IGR J16320–4751, its known hard spectrum, and its known strong variability (see
From the Foschini et al. (2004) analysis of the ISGRI spectrum, the peak 20–60 keV flux during this observation is 2; C0 count rate varied significantly between 8 and 26 counts s (typically 500 s) observations. During this sequence of observations (Observation IDs 40112-01-01-00 to 40112-01-36-00) the PCA quiescence in an effort to observe 4U 1630 made of 4U 1630 times.

These observations (observation ID 70417-01-07-02 taken on MJD 52,539.094) to measurements of IGR J16320–4751 taken at other levels than this has been reported from IGR J16320–4751 (Rodriguez et al. 2003), making it probable that the source gets bright enough emission is dominated by a source other than 4U 1630 energy residuals. In summary, this analysis provides strong evidence that IGR J16320–4751 is the cause of the high-energy residuals. Foschini et al. 2004 and references therein), we suspect that this source may be producing much of the high-energy emission that we see in the four observations with strong positive residuals. As a test, we compare the flux of the high-energy emission seen in one of these observations (observation ID 70417-01-07-02 taken on MJD 52,539.094) to measurements of IGR J16320–4751 taken at other times.

Our 2003 February INTEGRAL observation provides the cleanest measurement of the high-energy flux from IGR J16320–4751. From the Foschini et al. (2004) analysis of the ISGRI spectrum, the peak 20–60 keV flux during this observation is \(2 \times 10^{-10} \text{ergs cm}^{-2} \text{s}^{-1}\), and the energy spectrum is consistent with a power law with \(\Gamma\) between 2.6 and 3.1. In Figure 12, we plot the RXTE spectrum for observation ID 70417-01-07-02 and the 20–60 keV flux measured by INTEGRAL \(\sim 135\) days later. We reduced the INTEGRAL flux appropriately to account for the RXTE collimator response at the location of IGR J16320–4751. Although the measured INTEGRAL flux at the time of the INTEGRAL observation is a factor of \(\sim 2–3\) too low to explain the strong residuals, long-term variability at higher levels than this has been reported from IGR J16320–4751 (Rodriguez et al. 2003), making it probable that the source gets bright enough to explain the strong residuals at times.

Further evidence that IGR J16320–4751 is sometimes bright enough to explain the strong residuals comes from RXTE observations made of 4U 1630–47 between 1999 December 25 and 2000 January 14. These observations were made when 4U 1630–47 was in quiescence in an effort to observe 4U 1630–47 as it turned on; however, it did not turn on during this sequence of 36 very short (typically 500 s) observations. During this sequence of observations (Observation IDs 40112-01-01-00 to 40112-01-36-00) the PCA count rate varied significantly between 8 and 26 counts s \(^{-1}\) PCU\(^{-1}\). Although some of the detected emission is probably Galactic ridge emission, the high level of variability indicates that a compact source is producing much of the flux, and IGR J16320–4751 is the most likely candidate. In Figure 12, we show the PCA spectrum from the observation with the highest count rate, which was made on 2000 January 11 (Observation ID 40112-01-31-00). We note that no collimator response correction is necessary because the pointing position is approximately the same for this observation and for 70417-01-07-02. Another technical note is that although we attempted to also use HEXTE, with such short observations in a crowded field, this was not straightforward. Figure 12 indicates that the source was very hard \(\Gamma \sim 1.3\), and the extension of this spectrum is more than bright enough to explain the high-energy residuals, even if the spectrum breaks above 20 keV. In summary, this analysis provides strong evidence that IGR J16320–4751 is the cause of the high-energy residuals.

APPENDIX B

In addition to the four observations discussed in Appendix A, there are seven other observations for which it is likely that the high-energy emission is dominated by a source other than 4U 1630–47. The spectral parameters for these seven observations are shown in Figure 3, and these are the extremely hard observations with \(\Gamma\) in the 0.6–1.7 range. As discussed in § 5 above, four of the seven observations (70113-01-20-00, 70113-01-21-00, 70113-01-25-00, and 70113-01-28-00) occurred during a time period when IGR J16358–4726 was active according to reports from INTEGRAL, Chandra, and other RXTE observations (Revnivtsev 2003; Revnivtsev et al. 2003; Patel et al. 2004). As was the case for IGR J16320–4751, INTEGRAL provides the cleanest measurement of the high-energy flux due to its imaging capabilities, and Revnivtsev et al. (2003) report a 15–40 keV flux of 50 mcrab (\(\sim 2 \times 10^{-9} \text{ergs cm}^{-2} \text{s}^{-1}\)) and a 40–100 keV flux of 20 mcrab (\(\sim 3 \times 10^{-10} \text{ergs cm}^{-2} \text{s}^{-1}\)) on MJD 52,727.4. Our observation 70113-01-25-00 occurred on the
same day (MJD 52,727.633), and after correcting the RXTE collimator response for the position of IGR J16358–4726, which is 0.61 from the center of the offset 1 FOV, we measure 15–40 and 40–100 keV fluxes of $7.5 \times 10^{-10}$ and $2.5 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$, respectively. The 15–40 keV flux is a factor of 2.7 lower than the INTEGRAL measurement, and the 40–100 keV is nearly the same in the two cases. Although the 15–40 keV flux measured by RXTE is somewhat low, the difference is consistent with a report by Revnivtsev et al. (2003) that the flux varies by a factor of ~2 on a timescale of hours. More importantly, the flux comparison confirms our suspicion that the 4U 1630–47 spectrum is contaminated by the flux from IGR J16358–4726 at high energies.

Although it is clear that we are seeing emission from IGR J16358–4726 in four of the seven observations with low values of $\Gamma$, it is less clear whether the high-energy emission for the other three observations (80420-01-15-00 made on MJD 53,002.863; 80117-01-24-00 made on MJD 53,076.664; 90410-01-01-01 made on MJD 53,114.410) is also dominated by IGR J16358–4726, because no INTEGRAL detections of IGR J16358–4726 were reported and also because IGR J16320–4751 was in the RXTE FOV for these three observations. In Figure 13, we compare the PCA plus HEXTE spectrum from 90410-01-01-01 to that of 70113-01-25-00, where we know the emission spectrum of the region, and we argue in the text that it is very likely that the high-energy flux comes from IGR J16358–4726. The RXTE spectrum (thick histogram) comes from much later (observation ID 90410-01-01-01 taken on MJD 53,114.410), but the two spectra are very similar, suggesting that they may be from the same source. [See the electronic edition of the Journal for a color version of this figure.]

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