X-RAY SPECTRAL AND TIMING EVOLUTION DURING THE DECAY OF THE 1998 OUTBURST FROM THE RECURRENT X-RAY TRANSIENT 4U 1630–47

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ABSTRACT

We report on the X-ray spectral and timing behavior of the recurrent X-ray transient 4U 1630–47 for 51 Rossi X-Ray Timing Explorer (RXTE) observations made during the decay of its 1998 outburst. The observations began when the source was still relatively bright, and during one of the early observations, a quasi-periodic oscillation (QPO) with a non-Lorentzian profile occurred near 6 Hz. As the source decayed, the X-ray flux dropped exponentially with an e-folding time of 14.4 days. The exponential decay was interrupted by an increase in the X-ray flux, and a secondary maximum occurred 89 days after the onset of the outburst. A transition marked by significant changes in the timing and spectral properties of the source occurred 104 days after the start of the outburst. The transition is similar to soft-to-hard state transitions observed in other black hole candidate X-ray binaries. Most of the changes associated with the transition occurred in less than 2 days. The timing changes include an increase in the continuum noise level from less than 4% rms to greater than 10% rms and the appearance of a QPO at 3.4 Hz with an rms amplitude of 7.3% in the 2–21 keV energy band. At the transition, the energy spectrum also changed with an abrupt drop in the soft component flux in the RXTE bandpass. A change in the power-law photon index from 2.3 to 1.8, also associated with the transition, occurred over a time period of 8 days. After the transition, the source flux continued to decrease, and the QPO frequency decayed gradually from 3.4 Hz to about 0.2 Hz.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (4U 1630–47) — X-rays: bursts — X-rays: stars

1. INTRODUCTION

Although the recurrent X-ray transient and black hole candidate (BHC) 4U 1630–47 has been studied extensively since its first detected outburst in 1969 (Priedhorsky 1986), interest in this source has intensified as a result of observations made during its 1998 outburst. During the 1998 outburst, radio emission was detected for the first time (Hjellming et al. 1999). Although the source was not resolved in the radio, the optically thin radio emission suggests the presence of a radio jet. Also, low-frequency quasi-periodic oscillations (QPOs) were discovered during the 1998 outburst (Dieters et al. 1998a) using the Rossi X-Ray Timing Explorer (RXTE).

Here we report on X-ray observations of 4U 1630–47 made with RXTE (Bradt, Rothschild, & Swank 1993) during the decay of its 1998 outburst. We compare the X-ray light curve to those of other BHC X-ray transients and study the evolution of the spectral and timing properties during the decay. Like many other X-ray transients, the light curve of 4U 1630–47 shows an exponential decay and a secondary maximum (Chen, Shrader, & Livio 1997). During the early part of the decay, when the X-ray flux was high, 4U 1630–47 showed canonical soft-state characteristics (van der Klis 1995; Nowak 1995; Chen & Taam 1996), including an energy spectrum with a strong soft component and a steep power law and relatively low timing variability with a fractional rms (root mean square) amplitude of a few percent. Later in the decay, we observe a transition to a spectrally harder and more variable state, which has similarities to transitions observed for GS 1124–68 (Ebisawa et al. 1994; Miyamoto et al. 1994) and GRO J1655–40 (Mendez et al. 1998) near the ends of their outbursts.

In this paper, we describe the 4U 1630–47 X-ray light curve for the 1998 outburst and the RXTE observations (§ 2). In §§ 3 and 4, we present results of modeling the power and energy spectra, respectively. In § 5, we examine the transition in more detail, and § 6 contains a discussion of the results. Finally, § 7 contains a summary of our findings.

2. OBSERVATIONS AND LIGHT CURVE

We analyzed Proportional Counter Array (PCA) and High-Energy X-Ray Timing Experiment (HEXTE) data from 51 RXTE pointings of 4U 1630–47 during the decay of its 1998 outburst. The observation times, integration times, and background-subtracted 2.5–20 keV PCA count rates are given in Table 1. In Figure 1, we show the 1.5–12 keV PCA fluxes with the All-Sky Monitor (ASM) flux measurements in the same energy band. The ASM light curve was produced from data provided by the ASM/RXTE teams at MIT and at the RXTE Science Operations Facility and Guest Observer Facility at NASA’s Goddard Space Flight Center. The 1998 outburst was first detected by BATSE on Modified Julian Date 50841 (MJD = JD − 2,400,000.5), and 4U 1630–47 was not detected by the ASM until about MJD 50,847 (Hjellming et al. 1999; Kuulkers et al. 1998). Figure 1 shows that the ASM flux increased rapidly after MJD 50,850, peaking at 1.10 × 10⁻⁸ ergs cm⁻² s⁻¹ (1.5–12 keV) on MJD 50,867.
The flux dropped to about $6 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ soon after the peak, and our RXTE observations began during this time. Our observations fill a gap in the ASM light curve near MJD 50,880, showing that a flare occurred during this time. The flux decayed exponentially between MJD 50,883 and MJD 50,902 with an $e$-folding time of 14.4 days. After the exponential decay, the flux increased by about 50% over a time period of about 20 days, and a secondary maximum occurred near MJD 50,936. After the secondary maximum, the flux decay is consistent with an exponential with an $e$-folding time of 14.4 days. After the secondary maximum, the source flux at the transition was between 6 and 7 $\times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$.

Soft $\gamma$-ray bursts were detected from a position near 4U 1630$-$47 on MJD 50,979 (Kouveliotou et al. 1998), 7 days after our last RXTE observation, and the $\gamma$-ray source has been named SGR 1627$-$41. Although the position of SGR 1627$-$41 is not consistent with the position of 4U 1630$-$47 (Hurley et al. 1999), the two sources are close enough so that they were both in the RXTE field of view during our observations, allowing for the possibility of source confusion. As described in detail in the Appendix, RXTE scans and BeppoSAX observations provide information about possible source confusion. Based on the evidence, we conclude that it is very unlikely that SGR 1627$-$41 contributed significantly to the flux detected during our observations of 4U 1630$-$47.

### 3. X-RAY TIMING

For each observation, we produced 0.0156$-$128 Hz power spectra to study the timing properties of the system. For each 64 s interval, we made an rms normalized power spectrum using data in the 2$-$21 keV energy band. To convert from the Leahy normalization (Leahy et al. 1983) to rms, we determined the Poisson noise level using the method described in Zhang et al. (1995) with a dead time of 10 $\mu$s per event. For each observation, the individual 64 s power spectra were averaged, and the average spectrum was fitted using a least-squares technique and several different analytic models. For individual 64 s power spectra, we calculated the error bars using equation (A11) from Leahy et al. (1983).
When combining the power spectra for an entire observation, we used two different methods to calculate the errors. In one method, we calculated the errors by propagating the error bars for individual power spectra. This method does not account for any intrinsic (i.e., nonrandom) changes in the power spectrum over the duration of the observation. We also estimated the error by calculating $\sigma/\sqrt{N}$, where $\sigma$ is the standard deviation of the power measurements from the individual spectra and $N$ is the number of 64 s power spectra being combined. For all observations, the error estimates are approximately the same above $\sim 2$ Hz, indicating that the shape of the power spectrum at higher frequencies does not change significantly during an observation. However, below $\sim 2$ Hz, the calculated errors are significantly larger using the second method, indicating that intrinsic changes in this region of the power spectrum are significant. In the following, we have used the second method to calculate the errors.

To determine the analytic model to use for the continuum noise, we began by fitting the power spectrum for each observation with a power-law model. For some observations, the power-law fits are acceptable ($\chi^2 < 1.0$); however, in most cases, the reduced $\chi^2$ is significantly greater than 1.0 and systematic features appear in the residuals. Strong QPOs dominate the residuals for several observations, and these are discussed in detail below. For the observations without obvious QPOs, the power-law residuals are similar and show a broad excess peaking between 0.5 and 1.0 Hz. To model this broad excess, we focus on the observation 8 power spectrum since the statistics are good for this observation and there are no strong QPOs. Fitting the observation 8 power spectrum with a power law alone gives a poor fit ($\chi^2/v = 680/444$). Previous studies of the power spectra of BHCs show that the continuum noise can be described by a model consisting of two components: a power law and a band-limited noise component (e.g., Cui et al. 1997; Miyamoto et al. 1994). In applying this model to 4U 1630−47, we used a broken power law with the lower power-law index fixed to zero for the band-limited component, and hereafter this model is referred to as the flat-top model. Applying this two-component model to the observation 8 power spectrum gives a significantly improved fit ($\chi^2/v = 486/441$). Figure 2a shows the observation 8 power spectrum fitted with the two-component model.

For each observation, we fitted the power spectrum using the power-law model alone, the flat-top model alone, and the combination of the two components. For several of the observations, the statistics are not good enough to uniquely determine the best continuum model. In these cases, we combined consecutive observations, as indicated in Table 2, to improve the statistics and refitted the power spectra with the same models. For observations 1–10, the fit using the two-component model is significantly better than using either of the individual components, indicating that these power spectra require both components. For observations 11–51, the flat-top model alone provides a significantly better fit than the power-law model alone, and the two-component model does not provide a significantly better fit than the flat-top component alone. We conclude that only the flat-top component is necessary to fit these power spectra. The continuum parameters for all observations are given in Table 2. In cases where the power-law component is not significantly detected, the 90% confidence upper limit on the contribution from a power law with an index of $-1.0$ is given. Figure 2b shows the power spectrum for obser-

### Table 2

| Observation | Flat-Top |          | Power Law |          |
|-------------|----------|----------|-----------|----------|
|             | Rms (%)  | $v_{\text{break}}$ (Hz) | $\alpha$ | Rms (%)  | $\alpha$ | $\chi^2/v$ |
| 1–2$^a$     | 3.24 ± 0.21 | 0.49 ± 0.05 | −0.96 ± 0.04 | 1.37 ± 0.66 | −1.56 ± 0.19 | 471/438 |
| 3$^a$       | 3.55 ± 0.21 | 0.27 ± 0.28 | −1.46 ± 0.15 | 4.36 ± 0.72 | −1.70 ± 0.07 | 552/432 |
| 4$^a$       | 1.83 ± 0.33 | 1.52 ± 0.66 | −0.73 ± 0.11 | 1.10 ± 0.56 | −1.52 ± 0.24 | 495/441 |
| 5$^a$       | 2.04 ± 0.28 | 2.54 ± 0.50 | −1.23 ± 0.28 | 1.98 ± 0.32 | −0.97 ± 0.08 | 418/441 |
| 6$^a$       | 2.71 ± 0.27 | 1.42 ± 0.14 | −1.90 ± 0.33 | 1.60 ± 0.48 | −1.05 ± 0.16 | 453/438 |
| 7$^a$       | 2.49 ± 0.18 | 1.72 ± 0.10 | −2.87 ± 0.54 | 2.47 ± 0.23 | −0.89 ± 0.05 | 405/438 |
| 8$^a$       | 2.48 ± 0.18 | 1.40 ± 0.09 | −2.24 ± 0.38 | 2.38 ± 0.15 | −0.81 ± 0.04 | 470/438 |
| 9–10        | 2.67 ± 0.22 | 1.60 ± 0.14 | −1.69 ± 0.24 | 2.06 ± 0.25 | −0.75 ± 0.07 | 431/441 |
| 11–12       | 3.52 ± 0.16 | 0.56 ± 0.04 | −1.05 ± 0.04 | $<1.0^{a}$ | −1.0$^a$ | 518/443 |
| 13–24       | 3.65 ± 0.12 | 0.76 ± 0.04 | −1.33 ± 0.06 | $<0.7^{a}$ | −1.0$^a$ | 421/443 |
| 24–40       | 3.13 ± 0.27 | 1.57 ± 0.14 | −2.82 ± 0.71 | $<1.0^{a}$ | −1.0$^a$ | 452/443 |
| 41$^{a}$    | 10.2 ± 0.6 | 3.33 ± 0.36 | −1.73 ± 0.24 | $<2.5^{a}$ | −1.0$^{a}$ | 480/440 |
| 42$^{a}$    | 11.3 ± 0.08 | 2.81 ± 0.33 | −1.60 ± 0.21 | $<3.6^{a}$ | −1.0$^{a}$ | 415/440 |
| 43$^{a}$    | 13.6 ± 0.7 | 1.97 ± 0.12 | −1.87 ± 0.16 | $<3.3^{a}$ | −1.0$^{a}$ | 479/440 |
| 44$^{a}$    | 15.9 ± 1.1 | 0.83 ± 0.07 | −1.45 ± 0.10 | $<5.2^{a}$ | −1.0$^{a}$ | 550/440 |
| 45$^{a}$    | 16.1 ± 1.5 | 0.55 ± 0.06 | −1.31 ± 0.08 | $<2.0^{a}$ | −1.0$^{a}$ | 491/440 |
| 46–48$^{a}$ | 17.3 ± 0.8 | 0.48 ± 0.03 | −1.33 ± 0.05 | $<5.4^{a}$ | −1.0$^{a}$ | 453/440 |
| 49$^{a}$    | 14.9 ± 2.2 | 0.26 ± 0.05 | −1.45 ± 0.12 | $<9.0^{a}$ | −1.0$^{a}$ | 550/440 |
| 50–51       | 13.8 ± 1.1 | 0.19 ± 0.02 | −1.28 ± 0.08 | $<8.3^{a}$ | −1.0$^{a}$ | 494/440 |

* The errors correspond to $\Delta \chi^2 = 1.0$ (68% confidence).

* $0.01–10$ Hz rms amplitudes.

* A Lorentzian is included in the model. For observation 3, three Lorentzians are included in the model as described in the text.

* 90% confidence upper limit.

* Power-law index fixed to this value.
These power spectra have been rebinned for presentation.

Table 2.

Figs 2.—Power spectra for (a) observation 8 and (b) observations 11–40. The observation 8 power spectrum is fitted with a model consisting of a power law (dashed line) and a band-limited (or flat-top) noise component (dotted line). The solid line is the sum of the two components. For observations 11–40, only the flat-top component (solid line) is necessary. These power spectra have been rebinned for presentation.

vations 11–40 combined, illustrating that the power-law component is not significant at low frequencies. We note that there is some evidence for excess noise near 45 Hz, but this excess is not statistically significant. For observations 41–51, the rms amplitude for the continuum noise is 10%–17%, which is considerably higher than for observations 1–40. In determining the continuum parameters, we included Lorentzians to model the QPOs as marked in Table 2.

To determine where QPOs are present, we examined the residuals for fits with the continuum model only. For observations 1–2, 3, 6, 7, 8, 41, 42, 43, 44, 45, 46–48, and 49, systematic features in the residuals suggest the presence of QPOs. To determine if these features are statistically significant, we compared the $\chi^2$ for a fit with the continuum model only to a fit with a Lorentzian added to the continuum model. $F$-tests indicate that QPOs significant at greater than 96% confidence occurred for observations 1–3, 41, 42, 43, and 46–48. For observation 1–2, the continuum model provides a relatively poor fit to the data ($\chi^2/v = 561/441$), and the largest residuals occur near 11 Hz. The fit is significantly improved ($\chi^2/v = 471/438$) when a Lorentzian is added to the continuum model. The QPO centroid, FWHM, and rms amplitude are $10.8 \pm 0.2$ Hz, $2.9 \pm 0.6$ Hz, and $2.01\% \pm 0.16\%$, respectively. Although the features for observations 6, 7, and 8 are not as statistically significant, they also have centroids between 10 and 13 Hz and may be related to the observation 1–2 QPO.

For observation 3, the continuum model provides an extremely poor fit ($\chi^2/v = 987/441$), and the largest residuals occur near 6 Hz. Although the fit is significantly improved by the addition of a Lorentzian at 5.7 Hz, the fit is still relatively poor ($\chi^2/v = 685/438$), and systematic features are present in the residuals, which indicate that the 5.7 Hz QPO is not well described by a Lorentzian. As for some other BHCs (Belloni et al. 1997; Revnivtsev, Trudolyubov, & Borozdin 2000), the QPO has a high-frequency shoulder that can be modeled using a second Lorentzian. Modeling the QPO with Lorentzians at 5.4 and 6.2 Hz improves the fit to $\chi^2/v = 608/435$. The fit can be further improved to $\chi^2/v = 552/432$ by the addition of a QPO near 11 Hz. It is possible that the 11 Hz QPO is a harmonic of the lower frequency QPO, but it may also be related to the QPO that occurred during observation 1–2. Table 3 summarizes the QPO parameters for observation 3, and it should be noted that three Lorentzians were included in the model in determining the continuum parameters given in Table 2. Figure 3 shows the observation 3 power spectrum fitted with a model consisting of the continuum plus three Lorentzians to model the QPOs. The Lorentzians at 5.43 $\pm$ 0.02 Hz, 6.19 $\pm$ 0.04 Hz, and 10.79 $\pm$ 0.14 Hz have rms amplitudes of 2.89% $\pm$ 0.18%, 2.85% $\pm$ 0.21%, and 1.85% $\pm$ 0.20%, respectively. To determine if the QPO properties changed during the observation, we divided observation 3 into two

### Table 3

**QPO Parameters for Observation 3**

| Parameter | All of Observation 3 | Time Segment 1 | Time Segment 2 |
|-----------|----------------------|----------------|----------------|
| $v_1$ (Hz) | 5.74 $\pm$ 0.03 | 5.42 $\pm$ 0.02 | 5.43 $\pm$ 0.02 | 5.49 $\pm$ 0.02 | 5.35 $\pm$ 0.03 |
| FWHM$_1$ (Hz) | 1.06 $\pm$ 0.07 | 0.37 $\pm$ 0.06 | 0.41 $\pm$ 0.06 | 0.38 $\pm$ 0.05 | 0.49 $\pm$ 0.10 |
| Rms$_1$ (%) | 4.03 $\pm$ 0.10 | 2.76 $\pm$ 0.19 | 2.89 $\pm$ 0.18 | 2.95 $\pm$ 0.20 | 2.88 $\pm$ 0.25 |
| $v_2$ (Hz) | 6.17 $\pm$ 0.05 | 6.19 $\pm$ 0.04 | 6.17 $\pm$ 0.06 | 6.17 $\pm$ 0.06 | 6.17 $\pm$ 0.06 |
| FWHM$_2$ (Hz) | 0.77 $\pm$ 0.13 | 0.78 $\pm$ 0.12 | 0.71 $\pm$ 0.16 | 0.71 $\pm$ 0.16 | 0.85 $\pm$ 0.17 |
| Rms$_2$ (%) | 2.85 $\pm$ 0.22 | 2.85 $\pm$ 0.21 | 2.60 $\pm$ 0.25 | 2.60 $\pm$ 0.25 | 3.09 $\pm$ 0.27 |
| $v_3$ (Hz) | 10.79 $\pm$ 0.14 | 10.79 $\pm$ 0.14 | 11.00 $\pm$ 0.19 | 11.00 $\pm$ 0.19 | 10.57 $\pm$ 0.18 |
| FWHM$_3$ (Hz) | 1.47 $\pm$ 0.45 | 1.47 $\pm$ 0.45 | 2.00 $\pm$ 0.63 | 2.00 $\pm$ 0.63 | 1.56 $\pm$ 0.53 |
| Rms$_3$ (%) | 1.85 $\pm$ 0.20 | 1.85 $\pm$ 0.20 | 2.11 $\pm$ 0.24 | 2.11 $\pm$ 0.24 | 1.95 $\pm$ 0.26 |
| $\chi^2/v$ | 685/438 | 608/435 | 552/432 | 570/432 | 480/432 |

* The errors correspond to $\Delta \chi^2 = 1.0$ (68% confidence).

* First 576 seconds of Observation 3.

* Last 512 seconds of Observation 3.
time segments with durations of 576 and 512 s, made power spectra for each segment, and fitted the power spectra with a model consisting of the continuum (flat-top plus power-law) plus three Lorentzians. The results for these fits are given in Table 3. There is no evidence for large changes in the QPO properties between the two time segments.

The increase in the continuum noise level that occurred between observations 40 and 41 was accompanied by the appearance of a QPO at $3.390 \pm 0.008$ Hz with an rms amplitude of $7.30\% \pm 0.33\%$. In subsequent observations, the QPO frequency gradually shifted to lower frequency.

Figure 4 shows the power spectra for observations 41, 42, 43, and 46–48. After the 3.4 Hz QPO appeared for observation 41, QPOs occurred at $2.613 \pm 0.012$ Hz, $1.351 \pm 0.012$ Hz, and $0.228 \pm 0.003$ Hz for observations 42, 43, and 46–48, respectively. We note that the observation 43 QPO shows some evidence for a high-frequency shoulder. QPOs with lower statistical significance occurred for observations 44, 45, and 49 with frequencies of $0.430 \pm 0.006$ Hz, $0.365 \pm 0.011$ Hz, and $0.182 \pm 0.005$ Hz. It should be noted that these QPOs are consistent with the gradual shift to lower frequencies. The QPO parameters for observations 41–49 are given in Table 4.

### 4. ENERGY SPECTRA

We produced PCA and HEXTE energy spectra for each observation using the processing methods described in Tomsick et al. (1999). We used the PCA in the 2.5–20 keV energy band and HEXTE in the 20–200 keV energy band. For the PCA, we used standard mode data, consisting of 129 bin spectra with 16 s time resolution, included only the photons from the top anode layers, and estimated the background using the sky-VLE model.

We used the version 2.2.1 response matrices with a resolution parameter of 0.8 and added 1% systematic errors to account for uncertainties in the PCA response. As described in Tomsick et al. (1999), we used Crab spectra to test the response matrices and found that the response matrix calibration is better for

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**TABLE 4**

| Observation | Frequency (Hz) | FWHM (Hz) | Rms (%) |
|-------------|----------------|-----------|---------|
| 41          | $3.390 \pm 0.008$ | $0.14 \pm 0.02$ | $7.30 \pm 0.33$ |
| 42          | $2.613 \pm 0.012$ | $0.17 \pm 0.03$ | $8.46 \pm 0.47$ |
| 43          | $1.351 \pm 0.012$ | $0.22 \pm 0.04$ | $8.68 \pm 0.51$ |
| 44          | $0.430 \pm 0.006$ | $0.07 \pm 0.02$ | $<8.2^b$ |
| 45          | $0.365 \pm 0.011$ | $0.11 \pm 0.04$ | $<9.6^b$ |
| 46–48       | $0.228 \pm 0.003$ | $0.046 \pm 0.010$ | $6.55 \pm 0.51$ |
| 49          | $0.182 \pm 0.005$ | $0.043 \pm 0.012$ | $<10.1^b$ |

* The errors correspond to $\Delta \chi^2 = 1.0$ (68% confidence).

* 90% confidence upper limit.

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2 See M. J. Stark et al. 1999, PCABACKEST, available at http://lheawww.gsfc.nasa.gov/docs/xray/xte/pca.
Proportional Counter Units (PCUs) 1 and 4 than for the other three PCUs; thus, we used only these two PCUs for spectral analysis and allowed for free normalizations between PCUs. PCU 4 was off during three observations (34, 39, and 48), and to avoid instrumental differences, we did not use these observations in our spectral analysis. Previously, we found that the PCA overestimates the source flux by a factor of 1.18 (Tomsick et al. 1999), and in this paper, we reduced the fluxes and spectral component normalizations by a factor of 1.18 so that the PCA flux scale is in agreement with previous instruments.

HEXTE energy spectra were produced using standard mode data, consisting of 64 bin spectra with 16 s time resolution. We used the 1997 March 20 HEXTE response matrices and applied the necessary dead-time correction (Rothschild et al. 1998). For the spectral fits, the normalizations were left free between cluster A and cluster B. It is well known that the HEXTE and PCA normalizations do not agree, so the normalizations were left free between HEXTE and the PCA. The HEXTE background subtraction is performed by rocking on and off source. Each cluster has two background fields, and we checked the HEXTE background subtraction by comparing the count rates for the two fields. In cases where contamination of one of the fields occurred, we used only the data from the noncontaminated background field.

We first fitted the energy spectra using a power law with interstellar absorption, but this model does not provide acceptable fits to any of the spectra. For most of the observations, the residuals suggest the presence of a soft component, which is typical for 4U 1630−47 (Tomsick, Lapshov, & Kaaret 1998; Parmar et al. 1997). A soft component was also detected during BeppoSAX observations of 4U 1630−47, which overlap with our RXTE observations (Oosterbroek et al. 1998). Since Oosterbroek et al. (1998) found that a disk-blackbody model (Makishima et al. 1986) provides a good description of the soft component observed by BeppoSAX, we added a disk-blackbody model to the power-law component and refitted the RXTE spectra. Although the addition of a soft component improves the fits significantly in most cases, the fits are only formally acceptable for a small fraction of the observations, and in the worst case, the reduced $\chi^2$ is 3.1 for 106 degrees of freedom.

A broad iron absorption edge, associated with the Compton reflection component (Lightman & White 1988), is commonly observed in the energy spectra of BHCs (Ebisawa et al. 1994 and references therein; Sobczak et al. 1999). We refitted the 4U 1630−47 spectra with the model given in equation 3 of Ebisawa et al. (1994), which includes a broad absorption edge in addition to the disk-blackbody and power-law components. Following Ebisawa et al. (1994), we fixed the width of the absorption edge to 10 keV and left the edge energy free. For all of the 4U 1630−47 observations, the fits are significantly better with the absorption edge. As an example, for observation 8, the fit improved from $\chi^2/\nu = 179/106$ using the disk-blackbody plus power-law model without the edge to $\chi^2/\nu = 110/104$, indicating that the edge is required at the 99.1% confidence level. In addition to the absorption edge, an iron emission line is expected as a result of fluorescence of the X-ray–illuminated accretion disk material (Matt et al. 1992); thus, we have added an emission line to our model to determine whether the line is present in the spectra. We used a narrow emission line since the width of the emission line could not be constrained, and the energy of the emission line was a free parameter.

We fitted the spectra with the column density free and also with the column density fixed to the mean value for the 51 observations, $9.45 \times 10^{22}$ cm$^{-2}$. For all observations, the quality of the fit is not significantly worse with the column density fixed. Table 5 shows the results for the spectral fits with the column density fixed using a model consisting of a power law, a disk-blackbody component, a narrow emission line, and a broad absorption edge. The free parameters for the power-law component are the photon index (Γ) and the normalization. For the disk-blackbody component, the temperature at the inner edge of the disk ($kT_{in}$) and the normalization are free parameters. Rather than the power-law and disk-blackbody normalizations, the component fluxes are given in Table 5. The emission-line energy ($E_{\text{line}}$) and normalization ($N_{\text{line}}$) and the edge energy ($E_{\text{edge}}$) and optical depth ($\tau_{\text{edge}}$) are free parameters. However, in cases where the best fit value for $E_{\text{edge}}$ is less than 7.1 keV (the value for neutral iron), we fixed $E_{\text{edge}}$ to 7.1 keV. In Table 5, we do not give error estimates for $kT_{in}$ since the uncertainty for this parameter is dominated by systematic error due to uncertainty in the correct value for the column density. By comparing the values found for $kT_{in}$ with the column density fixed to those with the column density free, we estimate that the systematic error is 0.05 keV. For the 51 observations, the largest $\chi^2_{\nu}$ is 1.32 for 102 degrees of freedom and $\chi^2_{\nu} < 1.0$ for 44 of the observations, indicating that the spectra are well described by the model. Figure 5 shows the observation 8 energy spectrum and residuals. The residuals shown in Figure 5 typify the quality obtained for the observations.

![Figure 5](image_url)

**FIG. 5.—**PCA and HEXTE energy spectrum for observation 8 folded with the instrument response and fitted with a model consisting of a disk-blackbody (dashed line), a power law (thin solid line), a narrow emission line (dotted line), and a broad iron absorption edge. The sum of these components is marked with a thick solid line. The column density is fixed to $9.45 \times 10^{22}$ cm$^{-2}$. The bottom panel shows the residuals for the fit.
For each observation, we determined the significance of the emission line by refitting the spectra without the line and using an $F$-test. In cases where the significance of the emission line is less than 90%, we fixed $E_{\text{line}}$ to the best-fit value and determined the 90% confidence upper limit on $N_{\text{line}}$. Although most of the spectra do not require the emission line at a high confidence level, the line is required at greater than 90% confidence for 16 of the 51 observations and at greater than 95% confidence for nine observations. In the cases where the iron line is detected at greater than 90% confidence for 16 of the 51 observations and at greater than 95% confidence for nine observations.
90% confidence, the equivalent width of the iron line is between 45 eV (for observation 7) and 110 eV (for observation 47).

We also determined the significance of the disk-blackbody component using the same method described above for the emission line. With the column density fixed, the disk-blackbody component is required at greater than 97% confidence for every observation; however, with the column density free, the disk-blackbody component is not required for several observations. With the column density free, the disk-blackbody components are significant at only 50% and 65% confidence for observations 3 and 4, respectively, and at between 46% and 70% confidence for observations 41–51. In Table 5, the disk-blackbody fluxes for these observations are marked as upper limits since the component is not detected. For observations 41–51, the best-fit values of $kT_{in}$ are also marked as upper limits since the peak of the disk-blackbody flux falls below the PCA bandpass and we cannot constrain $kT_{in}$ and the column density independently.

The flux levels and line parameters are similar for observations 44–51, so we refitted the combined spectrum for these observations. As shown in Table 5, an emission line at 6.46 ± 0.04 keV is detected at 99.93% confidence. The line energy is consistent with emission from neutral or mildly ionized iron, and the line equivalent width is 91 eV. We also fitted the combined spectrum with a model consisting of a disk-blackbody and a power law, and Figure 6 shows the data-to-model ratio, clearly indicating the presence of the iron line. Since 4U 1630−47 lies along the Galactic ridge ($l = 336.91, b = 0.25$), we have considered the possibility that the 4U 1630−47 spectra are contaminated by Galactic ridge emission. It is unlikely that the ridge emission is the source of the iron line detected in our spectra because the line energy we observe is considerably lower than the values measured by ASCA, Ginga, and Tenma for the Galactic ridge, which are all near 6.7 keV (Kaneda et al. 1997 and references therein). Also, based on the spectrum of the Galactic ridge emission measured by RXTE (Valina & Marshall 1998), the spatially averaged Galactic ridge 2.5–20 keV flux is only 6% of the flux for the combination of observations 44–51, indicating that the level of contamination by the Galactic ridge emission should be low.

5. STATE TRANSITION

Figure 7 shows the evolution of the timing and spectral parameters for observations 33–51. Significant changes in the 4U 1630−47 emission properties occurred between observations 40 and 41, and we interpret this as evidence that a state transition occurred. In Figure 7, the transition is marked with a vertical dashed line at MJD 50,951. At the transition, an increase in source variability occurred with the 0.01–10 Hz rms amplitude of the flat-top component increasing from between 2.1% and 3.9% for observations 33–40 to 10.2% ± 0.6% for observation 41. As shown in Figure 7b1, the rms amplitude continued to increase after the transition, reaching a maximum value of 17.3% ± 0.8% for observation 46–48. In addition to the increase in the continuum noise level, a QPO appeared for observation 41, and the centroid QPO frequency and rms amplitude are shown in Figures 7b2 and 7b3, respectively. The timing changes occurred in less than 2 days and with only a small change in the 1.5–12 keV flux (shown in Fig. 7a).

To determine if a QPO was present before the transition, we made a combined power spectrum for observations 33–40. When the 2–21 keV power spectrum is fitted with a flat-top model, the residuals show no clear evidence for a QPO. The 90% confidence upper limit on the rms amplitude for a QPO in a frequency range 0.1–10 Hz is 2.4%. We performed an additional test by determining the energy range where the observation 41 QPO is strongest. For observation 41, the rms amplitudes are 6.1% ± 0.4% and 8.6% ± 0.4% for the 2–6 keV and 6–21 keV energy bands, respectively, indicating that the strength of the QPO increases with energy. Since the QPO is stronger in the 6–21 keV energy band for observation 41, we produced a 6–21 keV power spectrum for observations 33–40. As before, when a flat-top model is used to fit the power spectrum, the residuals do not show evidence for QPOs, and the 90% confidence upper limit on the rms amplitude for a QPO in a frequency range 0.1–10 Hz is 2.9%.

Although the difference between the observation 40 and 41 energy spectra is not as distinct as for the power spectra, changes occurred. The spectral parameters $\Gamma$ and $kT_{in}$ are shown in Figures 7c1 and 7c2, respectively. The power-law index hardened slightly between observations 40 and 41; however, this change appears to be part of a larger trend, which occurred over a span of 8 days between observations 38 and 43. The inner disk temperature began to decrease near observation 37, and the soft component is not confidently detected after observation 40, which probably indicates that $kT_{in}$ continued to drop after observation 40. The spectral changes are also illustrated in Figures 8a and 8b, which show the energy spectra for observations 40 and 41, respectively. Figure 8c shows the energy spectrum for observations 44–51, indicating that the spectrum continued to harden after the transition.

In summary, during the transition, the noise level increased, the power-law spectral index hardened, and the soft component flux in the RXTE bandpass decreased.
Similar changes are typically observed in BHC systems when soft-to-hard-state transitions occur (van der Klis 1995; Nowak 1995; Chen & Taam 1996), and we conclude that such a transition occurred for 4U 1630—47. We also show that QPOs were not present during the observations leading up to the transition, indicating that their appearance during observation 41 is related to the state transition.

6. DISCUSSION

6.1. Comparisons to Previous 4U 1630—47 Outbursts

Since 4U 1630—47 was discovered in 1969, quasi-periodic outbursts have been observed from this source every 600–690 days (Kuulkers et al. 1997). The light curve for the 1998 4U 1630—47 outburst is the best example of a “fast-rise exponential decay” (or FRED) light curve (Chen et al. 1997) that has been observed for 4U 1630—47. A FRED light curve may have been observed for 4U 1630—47 by the Vela 5B X-ray monitor in 1974.

3 However, the 1999 outburst significantly deviates from this periodicity (McCullough et al. 1999).
transition we report in this paper was observed by Cannizzo, et al. (1996). Although the overall light-curve shapes are different for the two outbursts, it is interesting that the e-folding time for the 1998 outburst, 14.4 days, is close to the 14.9 days e-folding time for the 1996 outburst. This may suggest that the e-folding time is related to a physical property of the system that does not change between outbursts. For example, the e-folding time may be related to the mass of the compact object (Cannizzo, Chen, & Livio 1995) or the radius of the accretion disk (King & Ritter 1998).

A state transition with similarities to the soft-to-hard transition we report in this paper was observed by EXOSAT during the decay of the 1984 outburst from 4U 1630−47. Four EXOSAT observations of 4U 1630−47 were made during outburst decay (Parmar, Stella, & White 1986). During the first two observations in 1984 April and 1984 May, a strong soft component was observed in the energy spectrum. The power law was harder in May than in April and became even harder for two observations made in 1984 July. During the July observations, the soft component was not clearly detected. Assuming a soft-to-hard transition occurred between May and July, the transition took place at a luminosity between $10^{36}$ and $10^{38}$ ergs s$^{-1}$ (1−50 keV), which is consistent with the luminosity where the 1998 soft-to-hard transition occurred, $7 \times 10^{36}$ ergs s$^{-1}$ (2.5−20 keV). The luminosities given here are for an assumed distance of 10 kpc; however, the distance to 4U 1630−47 is not well determined.

6.2. Comparisons to Other Black Hole Candidate X-Ray Transients

Here we compare the properties of 4U 1630−47 displayed during the decay of its 1998 outburst to those observed for other X-ray transients. We have compiled a list of comparison sources using Tanaka & Shibazaki (1996) and Chen, Shrader, & Livio (1997). The comparison group contains the BHC X-ray transients that had strong soft components during outburst and FRED light curves. The comparison sources from the above references are GS 1124−68, GS 2000+251, A0620−00, EXO 1846−031, Cen X-2, 4U 1543−47, and A1524−617. We also include a recent X-ray transient, XTE J1748−288, that has similar properties to this group. For the eight comparison sources, the exponentially decaying portions of their X-ray light curves have e-folding times ranging from 15 to 80 days (Chen et al. 1997; Revnivtsev et al. 2000), and the mean decay time is 39 days. Thus, the 14.4 day e-folding time for 4U 1630−47 is shorter than average, but not unprecedented.

Like 4U 1630−47, secondary maxima occurred in the X-ray light curves of 4U 1543−47, A0620−00, GS 2000+251, and GS 1124−68, and a tertiary maximum occurred for A0620−00 (Kaluzienski et al. 1977). It is likely that the secondary and tertiary maxima are the result of X-ray irradiation of the outer accretion disk or the optical companion (King & Ritter 1998; Chen, Livio, & Gehrels 1993; Augusteijn, Kuulkers, & Shaham 1993). In this picture, the time between the start of the outburst and subsequent maxima depends on the viscous timescale of the disk. For A0620−00, GS 2000+251, and GS 1124−68, secondary maxima are observed 55−75 days after the start of the outburst. These maxima, often referred to as “glitches,” consist of a sudden upward shift in X-ray flux, interrupting the exponential decay. The tertiary maximum observed for A0620−00 about 200 days after the start of the outburst is significantly different and can be described as a broad (35−40 days) bump in the X-ray light curve near the end of the outburst. The 4U 1630−47 secondary maximum is similar to the A0620−00 tertiary maximum since it is a broad (about 25 days) increase in flux near the end of the outburst. However, the secondary maximum peaked about 89 days after the start of the outburst, which is considerably less than for A0620−00.

Four sources in our comparison group exhibited soft-to-hard state transitions during outburst decay: A0620−00 (Kuulkers 1998), GS 2000+251 (Tanaka & Shibazaki 1996), GS 1124−68 (Kitamoto et al. 1992), and XTE J1748−288 (Revnivtsev et al. 2000). The 4U 1630−47 transition occurred 104 days after the start of the outburst, while transitions for the other four sources occurred 100−150 days, 230−240 days, 131−157 days, and about 40 days after the starts of the outbursts for A0620−00, GS 2000+251, GS 1124−68, and XTE J1748−288, respectively. Detailed X-ray spectral and timing information is available after the transition to the hard state for GS 1124−68. Like 4U 1630−47, the GS 1124−68 transition was marked by an increase in the rms noise amplitude; however, in contrast to 4U 1630−47, QPOs were not observed for GS 1124−68 in the hard state (Miyamoto et al. 1994). Also, during the GS 1124−68 transition, the X-ray spectrum hardened with a drop in the inner disk temperature ($kT_in$) and a change in the power-law photon index ($\Gamma$) from 2.2 to 1.6 (Ebisawa et al. 1994). During the 4U 1630−47 transition, the change in the soft component was consistent with a drop in $kT_in$, and $\Gamma$ changed from 2.3 to 1.8. While the Ginga observations of GS 1124−68 were relatively sparse near the transition, our observations of 4U 1630−47 show that soft-to-hard transitions can occur on a timescale of days.

6.3. Hard-State QPOs

Although QPOs were not detected after the GS 1124−68 state transition, QPOs were observed after a similar transition for the microquasar GRO J1655−40 during outburst decay (Mendez et al. 1998). RXTE observations of GRO J1655−40 show that a state transition occurred between 1997 August 3 and 1997 August 14. The transition was marked by an increase in the continuum variability from less than 2% rms to 15.6% rms, a decrease in the characteristic temperature of the soft spectral component ($kT_in$) from 0.79 to 0.46 keV, and the appearance of a QPO at 6.46 Hz with an rms amplitude of 9.8%. A QPO was also detected at 0.77 Hz during an August 18 RXTE observation of GRO J1655−40 when the 2−10 keV flux was about a factor of 4 lower than on August 14; thus, the shift to lower frequencies with decreasing flux is common to GRO J1655−40 and 4U 1630−47. The correlations between spectral and timing properties for the microquasar GRS 1915+105 are similar to those observed for GRO J1655−40 and 4U 1630−47. Markwardt, Swank, & Taam (1999) and Munro, Morgan, & Remillard (1999) found that 1−15 Hz QPOs are observed for GRS 1915+105 more often when the source spectrum is hard. Markwardt et al. (1999) report a correlation between
QPO frequency and disk flux, and Muno et al. (1999) find that the QPO frequency is correlated with $kT_{in}$. Although these results suggest that the QPO is related to the soft component, the fact that the QPO strength increases with energy for 4U 1630$-$47, GRO J1655$-$40, and GRS 1915+105 indicates that the QPO mechanism modulates the hard component flux.

A physical model that has been used to explain the energy spectra of BHC systems involves the presence of an advection-dominated accretion flow (ADAF) (Narayan, Garcia, & McClintock 1997). The model assumes the accretion flow consists of two zones: an optically thin ADAF region between the black hole event horizon and a transition radius, $r_{tr}$, and a geometrically thin, optically thick accretion disk outside $r_{d}$. Esin, McClintock, & Narayan (1997) developed and used this model to explain the spectral changes observed for GS 1124$-$68 during outburst decay, which are similar to the spectral changes observed for 4U 1630$-$47. The different emission states observed during the decay can be reproduced by decreasing the mass accretion rate and increasing $r_d$. This model suggests that the gradual decrease in the QPO frequencies observed for GRO J1655$-$40 and 4U 1630$-$47 may be related to a gradual increase in $r_d$ or a gradual drop in the mass accretion rate (or both).

In studies of the X-ray power spectra of BHC and neutron star X-ray binaries, Wijnands & van der Klis (1999) find a correlation between the frequency of QPOs between 0.2 and 67 Hz and the break frequency of the continuum component (described as a flat-top component in this paper). Such a correlation is interesting since it suggests that there is a physical property of the system that sets both timescales and that the physical property does not depend on the different properties of BHCs and neutron stars. While 4U 1630$-$47 was in its hard state, the break frequency gradually decreased from $3.33 \pm 0.36$ Hz to $0.48 \pm 0.03$ Hz between observations 41 and 46$-$48 as the QPO frequency dropped from 3.4 to 0.23 Hz (see Tables 2 and 4). As for the other sources included in the Wijnands & van der Klis (1999) sample, 4U 1630$-$47 exhibits a correlation between QPO frequency and break frequency. However, for 4U 1630$-$47, the QPO frequency is below or consistent with the break frequency, while in other sources the QPO frequency is above the break frequency.

6.4. Emission Properties during the Flare

Figure 9 shows the 2$-$60 keV PCA light curves for the two observations made during the flare that occurred around MJD 50,880 (observations 3 and 4). For observation 3, short (about 4 s) X-ray dips are observed. We have examined the light curves for all 51 observations and find that X-ray dips are only observed for observation 3. However, 4U 1630$-$47 observations made by another group show that short X-ray dips were observed earlier in the outburst (Dieters et al. 1999). In addition to the dips, Figure 9 shows that the level of variability is much higher for observation 3 than for observation 4. Table 2 details the differences between the power spectra for these two observations. For observation 3, the flat-top and power-law rms amplitudes are 3.55% and 4.36%, respectively, while for observation 4, the flat-top and power-law rms amplitudes are 1.83% and 1.10%, which are even lower than most of the nearby nonflare observations. Also, QPOs are observed for observation 3 but not for observation 4. The timing differences between these two observations are especially remarkable because the energy spectra for observations 3 and 4 are nearly identical (cf. Table 5).

The asymmetry of the low-frequency QPO peak for observation 3 is similar to QPOs observed for GS 1124$-$68 (Belloni et al. 1997) and XTE J1748$-$288 (Revnivtsev et al. 2000). For these two sources and for 4U 1630$-$47, the asymmetric shape of the QPO can be modeled using two Lorentzians, suggesting that the asymmetry may be due to a shift in the QPO centroid during the observation. Revnivtsev et al. (2000) find that some properties of the XTE J1748$-$288 power spectra are consistent with this picture. The 4U 1630$-$47 timing properties during observation 3 are not consistent with a gradual shift in the QPO centroid during the observation since the 5.4 and 6.2 Hz Lorentzians are present in both segments of the observation (cf. Table 3). The stability of the QPO shape may indicate that the asymmetric peak is caused by an intrinsic property of the QPO mechanism. However, for observations of 4U 1630$-$47 containing dips, Dieters et al. (1999) find that the frequencies of some QPOs are lower within the dips than outside the dips. For our observation 3, it is possible that frequency changes during the dips (cf. Fig. 9) cause the QPO profile to be asymmetric.

7. SUMMARY AND CONCLUSIONS

We have analyzed data from 51 RXTE observations of 4U 1630$-$47 during the decay of its 1998 outburst to study the evolution of its spectral and timing properties. During the decay, the X-ray flux dropped exponentially with an e-folding time of about 14.4 days, which is short compared to most other BHC X-ray transients. The e-folding time was nearly the same (14.9 days) for the decay of the 1996 out-
burst, which may indicate that this timescale is set by some property of the system that does not change between outbursts. For the 1998 outburst, the decay was interrupted by a secondary maximum, which is commonly observed for BHC X-ray transients.

Our analysis of the 4U 1630–47 power spectra indicates that 0.2–11 Hz QPOs with rms amplitudes between 2% and 9% occurred during the observations. During one of our early observations, when the source was relatively bright, a QPO occurred near 6 Hz with a profile that cannot be described by a single Lorentzian. Similar asymmetric QPO peaks have been observed previously for GS 1124–68 (Belloni et al. 1997) and XTE J1748–288 (Revnivtsev et al. 2000). For all three sources (4U 1630–47, GS 1124–68, and XTE J1748–288), the QPO is well described by a combination of two Lorentzians.

Near the end of the outburst, an abrupt change in the 4U 1630–47 spectral and timing properties occurred, and we interpret this change as evidence for a soft-to-hard state transition. Our observations indicate that most of the changes in the emission properties, associated with the transition, occurred over a time period less than 2 days. The timing properties changed after the transition with an increase in the continuum noise level and the appearance of a QPO. A 3.4 Hz QPO appeared immediately after the transition, and in subsequent observations, the QPO frequency decreased gradually to about 0.2 Hz. At the transition, the energy spectrum also changed with an abrupt drop in the soft-component flux in the RXTE bandpass, which was probably due to a drop in the inner disk temperature. A change in the power-law photon index from 2.3 to 1.8, also associated with the transition, occurred over a time period of 8 days. Although many of these changes are typical of soft-to-hard state transitions, the QPO behavior and the short timescale for the transition are not part of the canonical picture for state transitions (van der Klis 1995; Nowak 1995; Chen & Taam 1996). Finally, we note that 4U 1630–47 exhibits interesting behavior (e.g., state changes and QPOs) below a flux level of $10^{-9}$ ergs cm$^{-2}$ s$^{-1}$, indicating that observing programs for X-ray transients should be designed to follow these sources to low flux levels.

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APPENDIX

SGR 1627–41

Soft $\gamma$-ray bursts were detected from a position near 4U 1630–47 on MJD 50,979 (Kouveliotou et al. 1998), 7 days after our last RXTE observation. The soft $\gamma$-ray repeater, SGR 1627–41, was observed with RXTE on MJD 50,990, and a 0.15 Hz QPO was detected during the observation (Dieters et al. 1998b). Although the position of SGR 1627–41 is not consistent with the position of 4U 1630–47 (Hurley et al. 1999), the two sources are close enough so that they were both in the RXTE field of view during the observation made on MJD 50,990 and also during our observations, allowing for the possibility of source confusion. We inspected the RXTE 0.125 s light curves for our 4U 1630–47 observations, and there is no evidence for activity (e.g., bursts) from SGR 1627–41. An RXTE scanning observation made on 1998 June 21 (MJD 50,985) and BeppoSAX observations made on 1998 August 7 (MJD 51,032) and 1998 September 16 (MJD 51,072) provide information about possible source confusion. The scanning observation indicates that 4U 1630–47 was much brighter than SGR 1627–41 on June 21. Below, we present an analysis of the data from the scanning observation. 4U 1630–47 was also much brighter than SGR 1627–41 during the BeppoSAX observations. On August 7 and September 16, the 2–10 keV unabsorbed flux for 4U 1630–47 was 30–40 times higher than for SGR 1627–41 (Wood et al. 1999; Dieters et al. 1999). It is likely that 4U 1630–47 also dominated the flux detected during the June 26 RXTE observation and that it is responsible for the 0.15 Hz QPO. Given the low persistent flux detected for SGR 1627–41 by BeppoSAX, $6.7 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ unabsorbed in the 2–10 keV band (Wood et al. 1999), it seems very unlikely that this source could be bright enough to produce the QPOs observed during our observations.

After soft $\gamma$-ray bursts were detected from SGR 1627–41 by BATSE (Burst and Transient Source Experiment) on 1998 June 15 (Kouveliotou et al. 1998), RXTE scanning observations were made to locate a source of persistent X-ray emission related to soft $\gamma$-ray repeater (SGR). When the scans were made, the position of SGR 1627–41 was restricted to the IPN (3rd Interplanetary Network) annulus reported in Hurley et al. (1998a), which is consistent with the position of the supernova remnant G337.0–0.1. RXTE scans were made along the IPN annulus on 1998 June 19 and nearly perpendicular to the IPN annulus on 1998 June 21. Since other SGRs are associated with supernova remnants, the perpendicular scan was centered on G337.0–0.1. In the following months, the IPN position was improved (Hurley et al. 1998b) and a source of persistent X-ray emission related to the SGR was discovered using BeppoSAX (Wood et al. 1999). These observations restrict the SGR 1627–41 position to a 2'' by 16'' region that is consistent with the position of G337.0–0.1, making an association between the two likely (Hurley et al. 1999).

We analyzed the RXTE data from the June 21 scan to determine if the persistent X-ray emission from SGR 1627–41 could have been bright enough to contaminate our RXTE observations of 4U 1630–47. The linear scan passed through the positions of both G337.0–0.1 and 4U 1630–47 for this purpose. Figure 10 shows the background subtracted 2–60 keV PCA count rate versus scan angle. We fitted the light curve using a model consisting of a single point source and a constant count rate offset to account for small uncertainties in the background subtraction. We used the 1996 June 5 PCA collimator response to model the scan light curve produced by a point source. A good fit is achieved ($\chi^2$/v = 91/161), indicating that the light curve is consistent with the presence of one source. Figure 10 shows that the source position is consistent with 4U
1630 − 47 and not G337.0 − 0.1. Also, the source amplitude is about 187 s$^{-1}$ (2–60 keV, five PCUs), which is close to the count rates reported for observations 44–51 in Table 1. The RXTE scan indicates that it is very unlikely that our 4U 1630 − 47 observations are significantly contaminated by emission from SGR 1627 − 41.

REFERENCES

Augusteijn, T., Kuulkers, E., & Shaham, J. 1993, A&A, 279, L13
Belloni, T., et al. 1997, A&A, 322, 857
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Cannizzo, J. K., Chen, W., & Livio, M. 1995, ApJ, 454, 880
Chen, W., Livio, M., & Gehrels, N. 1993, ApJ, 408, L5
Chen, W., Shrader, C. R., & Livio, M. 1997, ApJ, 491, 312
Chen, X., & Taam, R. E. 1998, ApJ, 466, 404
Cui, W., et al. 1997, ApJ, 484, 383
Dieters, S., et al. 1998a, IAU Circ., 6823, 1
Dieters, S., et al. 1998b, IAU Circ., 6962, 1
Ebisawa, K., et al. 1994, PASJ, 46, 375
Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
Hjellming, R. M., et al. 1999, ApJ, 514, 383
Hurley, K., et al. 1998a, IAU Circ., 6948, 1
———. 1998b, IAU Circ., 6966, 1
Kaneda, H., et al. 1997, ApJ, 491, 638
King, A. R., & Ritter, H. 1998, MNRAS, 298, L42
Kitamoto, S., et al. 1992, ApJ, 394, 609
 Kouveliotou, C., et al. 1998, IAU Circ., 6944, 2
 Kuulkers, E. 1998, NewA Rev., 42, 1
 Kuulkers, E., Parmar, A. N., Kitamoto, S., Cominsky, L. R., & Sood, R. K. 1997, MNRAS, 291, 81
 Kuulkers, E., et al. 1998, IAU Circ., 6822, 1
 Leahy, D. A., et al. 1983, ApJ, 266, 160
 Lightman, A. P., & White, T. R. 1988, ApJ, 335, 57
 Makishima, K., et al. 1986, ApJ, 308, 635
 Markwardt, C. B., Swank, J. H., & Taam, R. E. 1999, ApJ, 513, L37
 Matt, G., et al. 1992, A&A, 257, 63
 McCollough, M. L., Harmon, B. A., Dieters, S., & Wijnands, R. 1999, IAU Circ., 7165, 2
 Mendez, M., et al. 1998, ApJ, 499, L187
 Miyamoto, S., et al. 1994, ApJ, 435, 398
 Muno, M. P., Morgan, E. H., & Remillard, R. A. 1999, ApJ, 527, 321
 Narayan, R., Garcia, M. R., & McClintock, J. E. 1997, ApJ, 478, L79
 Nowak, M. A. 1995, PASP, 107, 1207
 Oosterbroek, T., et al. 1998, A&A, 340, 431
 Parmar, A. N., Stella, L., & White, N. E. 1986, ApJ, 304, 664
 Parmar, et al. 1997, A&A, 319, 855
 Priedhorsky, W. C. 1986, Ap&SS, 126, 89
 Revnivtsev, M. G., Trudolyubov, S. P., & Borozdin, K. N. 2000, MNRAS, 312, 151
 Rothschild, R. E., et al. 1998, ApJ, 496, 538
 Sobczak, G. J., et al. 1999, ApJ, 520, 776
 Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607
 Tomisick, J. A., Kaaret, P., Kroeger, R. A., & Remillard, R. A. 1999, ApJ, 512, 892
 Tomisick, J. A., Lapshov, I., & Kaaret, P. 1998, ApJ, 494, 747
 Valina, A., & Marshall, F. E. 1998, ApJ, 505, 134
 van der Klis, M. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 252
 Wijnands, R., & van der Klis, M. 1999, ApJ, 514, 939
 Woods, P. M., et al. 1999, ApJ, 519, L139
 Zhang, W., et al. 1995, ApJ, 449, 930