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X-RAY MONITORING OF η CARINAE: VARIATIONS ON A THEME

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ABSTRACT

We present monitoring observations by the *Rossi X-Ray Timing Explorer* of the 2–10 keV X-ray emission from the supermassive star η Carinae from 1996 through late 2003. These data cover more than one of the stellar variability cycles in temporal detail and include especially detailed monitoring through two X-ray minima. We compare the current X-ray minimum, which began on 2003 June 29, with the previous X-ray minimum, which began on 1997 December 15, and refine the X-ray period to 2024 days. We examine the variations in the X-ray spectrum with phase and with time, and also refine our understanding of the X-ray "peaks," which have a quasi period of 84 days, with significant variation. Cycle-to-cycle differences are seen in the level of X-ray intensity and in the detailed variations of the X-ray flux on the rise to maximum just prior to the X-ray minimum. Despite these differences, the similarities between the decline to minimum, the duration of the minimum, and correlated variations of the X-ray flux and other measures throughout the electromagnetic spectrum leave little doubt that the X-ray variation is strictly periodic and produced by orbital motion as the wind from η Carinae collides with the wind of an otherwise unseen companion.

Key words: binaries: general — stars: early-type — stars: individual (η Carinae) — X-rays: stars

Online material: machine-readable table

1. INTRODUCTION

The supermassive star η Carinae (Davidson & Humphreys 1997) is a key object in our understanding of the formation and evolution of extremely massive stars. A key piece of observational evidence concerning the nature of this object was the identification of periodic variations in the near-IR (Damineli 1996; Whitelock et al. 1994) that are stable over many decades, along with correlated variability in X-ray (Corcoran et al. 1995) and radio (Duncan et al. 1995) bands. This variability has an especially dramatic effect in the 2–10 keV X-ray band, where the spatially unresolved X-ray emission drops by about a factor of 100 for ~3 months, as monitoring observations with the *Rossi X-Ray Timing Explorer* (*RXTE*) during the X-ray minimum of 1997–1998 showed (Ishibashi et al. 1999). The variable X-ray emission is believed to arise in a shocked region where the wind from η Carinae collides with the wind from an otherwise unseen (or not yet seen) companion star. This colliding wind binary model has been shown to reproduce the gross variations of the X-ray light curve (Pittard et al. 1998; Ishibashi et al. 1999; Corcoran et al. 2001a; Pittard & Corcoran 2002). Even though the X-ray luminosity is an extremely small fraction of the bolometric luminosity ($L_X/L_{bol} \sim 10^{-7}$), the observed X-ray variations are extremely important in disentangling this system, since the source of the X-ray emission is spatially compact and the hard X-ray emission is little effected by circumstellar absorption or reemission from the Homunculus nebula. The emission in no other wavelength region can be so qualified.

Published models of the X-ray variation show significant discrepancies between the expected and observed variation (Pittard et al. 1998; Ishibashi et al. 1997; Corcoran et al. 2001a; Pittard & Corcoran 2002), which may indicate the importance of the orbital motion of the stars on the wind structure, or perhaps indicates the enhancement of mass loss from η Carinae due to some interaction with the companion near periastron, or uncertainties in the orbital orientation, or some combination of these effects. In addition, short-term variations ("flares" or "spikes"; Ishibashi et al. 1997, 1999; Corcoran et al. 1997) have been observed whose origin is not clear. Secular changes in the underlying wind properties of either η Carinae or the companion star (which may reflect changes in the physical conditions of either or both stars) may be reflected in cycle-to-cycle variations in the X-ray emission. Thus, continued monitoring of the X-ray emission from η Carinae is vital.

In this paper we present the results of our continued (and continuing) monitoring of the η Carinae system with *RXTE*. We present new data obtained since our previous publication (Ishibashi et al. 1999; Corcoran et al. 2001a), and emphasize a comparison of the X-ray brightness from the last X-ray minimum in mid-2003 with the behavior near the first minimum observed with *RXTE* in late 1997.

2. THE *RXTE* OBSERVATIONS

The *RXTE* observations are typically between 1000 and 2000 s in duration and are usually obtained a few times per month. During the year before the most recent X-ray minimum (which occurred in mid-2003), daily X-ray observations were obtained. This is a higher observing frequency than was obtained prior to the 1997–1998 minimum, in which we obtained approximately weekly observations prior to the minimum, with daily observations only after the beginning of the X-ray minimum. Obtaining daily observations prior to the X-ray minimum was important, since we saw very rapid changes in brightness during this time frame. These brightness variations were temporally resolved with daily observations, but underresolved in the approximately weekly observations obtained in 1997.

We use data obtained by the *RXTE* Proportional Counter Array (PCA) and consider only data obtained in layer 1 of the proportional counter units (PCUs), since layer 1 provides the

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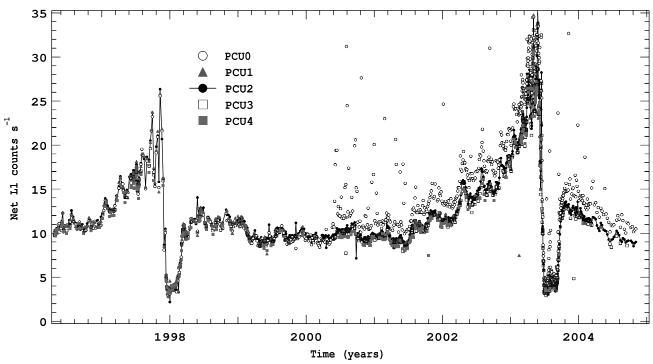

FIG. 1.—Observed layer 1 rates for PCU0–4, corrected for instrumental background. The discrepancies between the PCU0 rates and the rates from the other PCUs are due to the loss of the PCU0 propane layer in 2000 May.

highest signal-to-noise ratio for a relatively soft ($E < 10$ keV) source like η Carinae. Because of the loss of the PCU0 propane layer on 2000 May 12, there is additional noise in the apparent X-ray rate in this PCU; in addition, without the propane layer *RXTE* electron-screening criteria are undefined, resulting in additional noise in the reduced PCU0 layer 1 data. Both effects cause a large scatter in the gross PCU0 layer 1 rates, making PCU0 observations after 2000 May 12 difficult to interpret. In the following analysis we ignore PCU0 observations after this date.

Data extraction and instrumental background correction are as described in Ishibashi et al. (1999). One improvement is that we use corrected PCU2 faint-background models to calculate the net rates. These new background files were necessary to correct for changes in the background models that resulted in an oversubtraction of instrumental background for observations obtained late in the *RXTE* gain epochs.[2] For each observation, data in 16 s bins were extracted from layer 1 for right and left anode chains for each PCU. Instrumental background event files for each observation were constructed using appropriate instrumental model backgrounds, and instrumental background light curves were extracted from the model background event files again using 16 s time bins. We calculated net count rates for each data bin by subtracting the background data from the observed gross data. Since casual inspection of the 16 s light curves showed no significant variations within any observation, to increase the signal-to-noise ratio we calculated average net rates and errors for each observation. This provides the average PCU count rate of η Carinae (and sources nearby that fall within the $\sim 45'$ field of view of each PCU) for each observation.

Most of the early data were obtained using three proportional counter units (PCUs). There were a total of 976 *RXTE* observations of η Carinae between 1996 February 9 and 2004 November 2, an average of one observation every 3.3 days. Nearly all PCUs were switched off for at least some of the observations. PCU1 was switched off 613 times; PCU3 was switched off 450 times; PCU4 was switched off 737 times. The best coverage was obtained by PCU0 and PCU2, which have observed η Carinae nearly every time *RXTE* pointed at the star; PCU2 was switched off only once, on 2000 October 6, while PCU0 was switched off six times, on 1998 March 21, March 22, March 23, 2000 May 15, October 6, and 2003 November 21. The PCU2 data provide the most reliable coverage of η Carinae's X-ray variability of the five PCUs. The observed PCU rates, corrected for estimated instrumental background, are shown in Figure 1.

3. THE X-RAY LIGHT CURVE

3.1. *Calibration*

We converted the average, instrument background–corrected count rates to fluxes by comparing the *RXTE* count rates with 2–10 keV X-ray fluxes for η Carinae directly measured by contemporaneous observations with imaging X-ray spectrometers. In addition to using observations with the *ASCA* X-ray observatory, as was done in Corcoran et al. (2001a), here we also include spatially resolved data from the *BeppoSAX*, *Chandra*, and *XMM-Newton* observatories as well, to cover a wider range in X-ray flux. Table 1 shows the measured fluxes from the imaging satellites and the corresponding *RXTE* rates. The *ASCA* fluxes are taken from Corcoran et al. (2000), while the *BeppoSAX* fluxes are from Viotti et al. (2002). Detailed descriptions of the derivation of the *Chandra* and *XMM-Newton* fluxes will be given elsewhere. The fluxes are corrected for instrumental and sky background, but there is no correction for foreground absorption. The flux count rate relation and our linear fits are shown in Figure 2. The conversion from *RXTE* net count rates to flux for each of the five PCUs are

$$\text{PCU0: flux (2–10 keV)} = 7.11\times10^{-12}\ (\text{Net Rate} - 2.34),$$
$$\text{PCU1: flux (2–10 keV)} = 7.92\times10^{-12}\ (\text{Net Rate} - 2.44),$$
$$\text{PCU2: flux (2–10 keV)} = 8.38\times10^{-12}\ (\text{Net Rate} - 3.03),$$
$$\text{PCU3: flux (2–10 keV)} = 8.73\times10^{-12}\ (\text{Net Rate} - 2.79),$$
$$\text{PCU4: flux (2–10 keV)} = 8.85\times10^{-12}\ (\text{Net Rate} - 2.94),$$

in units of ergs s^{-1} cm^{-2}.

The tabulated fluxes for all the *RXTE* observations through 2004 November 2 are given in Table 2. Fluxes calculated with the above scalings are shown in Figure 3 for all PCUs. Table 2 also gives the "PCA" layer 1 2–10 keV fluxes derived by averaging fluxes from all operating PCUs (although PCU0 measurements after 2000 May 1 were excluded to avoid high-background observations after the loss of the propane layer). We excluded from Table 2 an observation on 2000 September 24 taken when the PCU2 observation was anomalously low and the only other available datum was a noisy one from PCU0.

3.2. *The X-Ray Ephemeris*

Inspection of the 1997–1998 and 2003 PCA light curve shows that the X-ray minimum begins at a flux level of about 6×10^{-12} ergs s^{-1} cm^{-2}. This flux level was achieved on JD 2,450,799.792 and again on JD 2,452,819.667, an interval of 2019.875 days. Thus, the interval between the start of X-ray minima is 2019.8 ± 0.62 days, where the uncertainty on this interval is estimated from the time between consecutive observations at the start of the minima.

We tried to refine the period between X-ray minima via epoch folding, by looking for the minimum of the statistic $g = \sum_{\phi=0.95}^{1.10} (f_\phi - f_{\phi-1})^2$, where f_ϕ is the PCA flux at a given phase, $f_{\phi-1}$ is the PCA flux at the same phase in the previous cycle, and phases ϕ are calculated with test periods in the range 2000–2050 days. We linearly interpolated the observations in the range $-0.05 < \phi < 0.10$ to the more frequent sampling of the observations in the later phase range. The minimum of g was reached for a period of 2024 days. This is significantly larger than the period derived above from simple inspection of the start of the minimum. This longer period gives a better match to the decline to minimum and to the egress from minimum, and we adopt this

[2] See http://heasarc.gsfc.nasa.gov/docs/xte/pca_news.html.

TABLE 1

RXTE FLUX CALIBRATION DATA

					RXTE PCU NET RATES[a]				
OBSERVATORY	DATE	OBSERVATION ID	FLUX[b]	*RXTE* DATE	PCU2	PCU0	PCU2	PCU3	PCU4
ASCA	1996 Jul 29	24035000	7.19E−11	1996 Jul 31	11.77 ± 0.19	11.51 ± 0.19	11.60 ± 0.19	11.36 ± 0.18	...
ASCA	1997 Jul 3	11504000	1.15E−10	1997 Jul 3	16.98 ± 0.27	16.94 ± 0.26	17.13 ± 0.26	...	...
ASCA	1997 Jul 19	11504010	9.75E−11	1997 Jul 20	15.68 ± 0.20	15.49 ± 0.20	15.56 ± 0.20	...	...
ASCA	1997 Feb 24	26033000	3.84E−12	1997 Feb 24	3.40 ± 0.22	3.53 ± 0.22	3.80 ± 0.22	3.39 ± 0.21	3.26 ± 0.22
ASCA	1998 Jul 16	26034000	7.12E−11	1998 Jul 14	10.98 ± 0.19	10.58 ± 0.18	10.93 ± 0.19	10.74 ± 0.18	10.42 ± 0.18
ASCA	1999 Feb 8	27023000	8.51E−11	1999 Feb 7	10.96 ± 0.20	10.80 ± 0.19	10.65 ± 0.19	...	...
ASCA	1999 Jun 14	27024000	5.68E−11	1999 Jun 15	10.87 ± 0.22	10.06 ± 0.21	...	...	...
BeppoSAX	1996 Feb 29	...	7.33E−11	1996 Feb 27	11.85 ± 0.22	10.97 ± 0.22	11.28 ± 0.22	...	...
BeppoSAX	1998 Mar 18	...	6.12E−11	1998 Mar 18	10.48 ± 0.22	10.37 ± 0.21	10.62 ± 0.22	...	...
Chandra	2000 Jan 19	200057	5.95E−11	2000 Nov 19	9.36 ± 0.15	10.51 ± 0.19	...	9.03 ± 0.14	...
Chandra	2002 Oct 16	200219	1.17E−10	2002 Oct 15	15.77 ± 0.18	18.24 ± 0.22	...	15.26 ± 0.18	...
Chandra	2003 May 3	200215	2.56E−10	2003 May 3	34.53 ± 0.22	39.92 ± 0.26	34.75 ± 0.22	33.12 ± 0.22	...
Chandra	2003 Jun 16	200218	1.45E−10	2003 Jun 16	22.15 ± 0.21	25.47 ± 0.25	...	21.09 ± 0.20	20.64 ± 0.21
Chandra	2003 Jul 20	200216	2.25E−12	2003 Jul 21	3.84 ± 0.16	4.98 ± 0.21	...	3.75 ± 0.16	3.61 ± 0.16
Chandra	2003 Sep 26	200217	6.26E−11	2003 Sep 26	11.28 ± 0.18	12.44 ± 0.22	11.52 ± 0.18	...	...
XMM-Newton[c]	2003 Jan 25–29	01457401–01457405	1.52E−10	2003 Jan 25	20.95 ± 0.17	24.09 ± 0.20	...	20.15 ± 0.17	19.73 ± 0.17
XMM-Newton	2003 Jun 8	160160101	1.29E−10	2003 Jun 8	18.02 ± 0.20	21.83 ± 0.24	...	17.28 ± 0.19	17.05 ± 0.19
XMM-Newton	2003 Jun 13	160160901	1.97E−10	2003 Jun 13	23.95 ± 0.27	27.08 ± 0.33	...	22.55 ± 0.26	...
XMM-Newton	2003 Jul 22	01457801	3.65E−12	2003 Jul 21	5.03 ± 0.81	4.09 ± 0.98	4.95 ± 0.83	4.90 ± 0.77	...
XMM-Newton	2003 Aug 2	01605601	8.47E−12	2003 Aug 2	4.12 ± 0.16	5.86 ± 0.21	...	3.89 ± 0.15	...
XMM-Newton	2003 Aug 9	01605602	9.47E−12	2003 Aug 9	4.72 ± 0.15	5.67 ± 0.19	...	...	...
XMM-Newton	2003 Aug 18	01605603	1.13E−11	2003 Aug 18	4.51 ± 0.26	4.98 ± 0.33	...	4.11 ± 0.25	...

NOTES.—*ASCA* fluxes from Corcoran et al. (2001b); *BeppoSAX* fluxes from Viotti et al. (2002); *Chandra* flux from observation on 2000 November 19 from Corcoran et al. (2001a); 2003 *Chandra* and *XMM-Newton* fluxes from M. F. Corcoran et al. (2005, in preparation) and K. Hamaguchi et al. (2005, in preparation), respectively.

[a] Rates are corrected for estimated instrumental background.

[b] In the 2–10 keV band; fluxes have not been corrected for absorption.

[c] Combination of five observations.

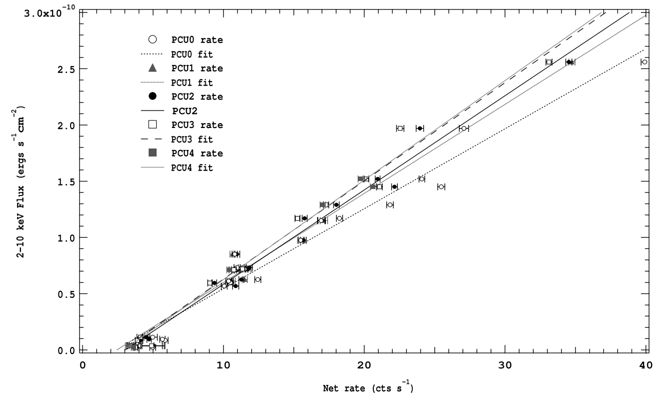

FIG. 2.—Linear fits to the instrumental background–corrected PCU rates and fluxes directly measured from contemporaneous imaging X-ray spectrography.

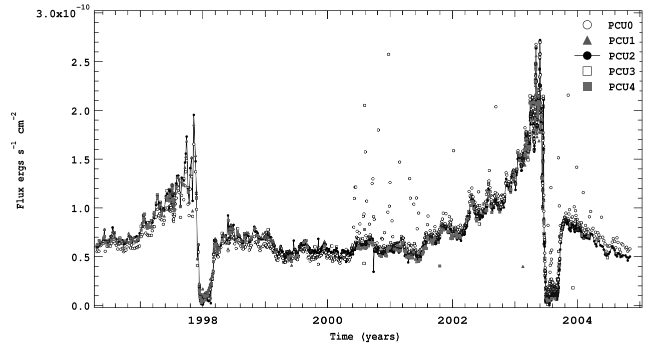

FIG. 3.—Scaled layer 1 fluxes for PCU0–4, corrected for instrumental and estimated sky background.

as the true X-ray cycle period. Times of X-ray minima are given by

$$\mathrm{JD(X\text{-}ray\ minimum)} = 2{,}450{,}799.792 + (2024 \pm 2)E, \quad (1)$$

where E is the cycle count. Figure 4 shows the 2–10 keV layer 1 PCA light curve versus time, with the PCA light curve repeated using the above period. Figure 5 emphasizes the variations around the X-ray minima. The quoted uncertainty is estimated by matching the decline to minimum and the rise from minimum in the two minima observed by *RXTE*. Part of the uncertainty arises because of the large variation in the X-ray flux just prior to the start of the 2003 X-ray minimum.

We estimated the duration of the X-ray minimum from the FWHM, taken to be the width of the minimum at the point where the flux is midway between the minimum flux level and the peak level seen just after the end of the eclipse. With this definition, the duration of the 1997–1998 minimum is 81.2 days, while the duration of the 2003 minimum is 89.0 days. As can be seen in Figure 5, the width of the eclipse in the two cycles are in good agreement for most of the minimum. The longer duration of the 2003 minimum is mainly due to the higher flux of the peak after the 2003 minimum and the fact that the peak occurred 113 days after the start of the X-ray minimum, compared with the peak after the 1998 minimum, which occurred only 86 days after the minimum began.

4. COLOR VARIATIONS

Each PCU provides coarse measurements of the X-ray spectrum during each observation. A typical PCU2 layer 1 spectrum is shown in Figure 6. For each observation, we extracted net spectra (corrected for instrumental background) in the PCA band (roughly 2–60 keV) and created photon redistribution matrices for the spectra to take into account variations in the relation between PCU channels and photon energy for different PCA gains. We restricted ourselves to PCU2 observations, since these form the most homogeneous data set. We linearized each spectrum to a common energy scale and extracted instrument background–corrected light curves in a soft band (2–5 keV) and a hard band (7–10 keV). The soft band is sensitive to changes in the absorbing column, while the hard band is sensitive to the emission measure of the hottest gas. Figure 7 compares the variation in the soft and hard bands. There are significant differences in the variability seen in the soft versus the hard band: the recovery from the X-ray minimum is significantly slower in the soft band than in the hard band and the soft band is brighter than the hard band for most of the cycle, except for times around the X-ray minima.

We also constructed a hardness ratio curve (Fig. 8), where hardness ratio is defined as $\mathrm{hr} = (\mathrm{hard} - \mathrm{soft})/(\mathrm{hard} + \mathrm{soft})$ and the hard and soft bands are defined above. Figure 9 compares the variation in hardness around the X-ray minima. Unlike the variation in flux around the X-ray minimum, the hardness ratio shows a rather symmetric variation before and after the minimum. The maximum in hardness ratio before and after the minima are nearly the same in the two cycles, and the day-to-day changes in hardness around the minimum are very similar in the two minima.

Figure 10 compares the hardness ratio changes around the X-ray minima to the variation in X-ray flux seen by the PCA. There is a significant increase in spectral hardness after the end of the X-ray minimum. There is also an apparent correlation between some of the strong X-ray flux "spikes" seen just prior

TABLE 2

ROSSI X-RAY TIMING EXPLORER SCALED FLUXES

Date	JD −2,400,000	*RXTE* PCU Fluxes[a] PCU0	PCU1	PCU2	PCU3	PCU4	PCA Flux[a]
1996020915......................	50123.125	6.10	6.75	6.95	6.93	6.73	6.70 ± 0.35
1996021610......................	50129.917	6.18	6.69	6.60	6.88	6.34	6.54 ± 0.28
1996022113......................	50135.042	6.11	6.82	6.95	7.15	6.95	6.80 ± 0.40
1996022920......................	50143.333	6.04	6.56	6.66	6.92	7.06	6.65 ± 0.40
1996030520......................	50148.333	6.12	6.70	6.65	7.25	6.86	6.71 ± 0.41

NOTES.—Table 2 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

[a] In the 2–10 keV band, 10^{-11} ergs s^{-1} cm^{-2}; fluxes have not been corrected for absorption.

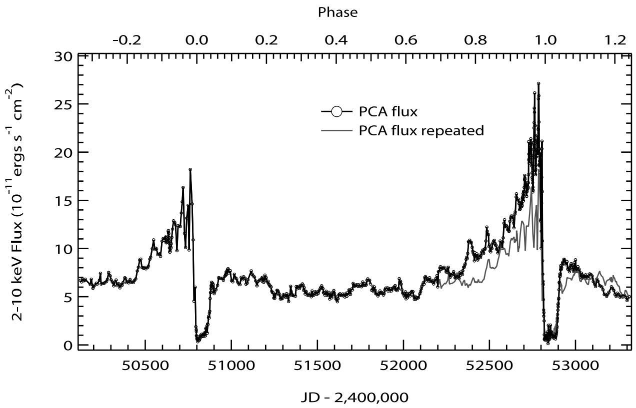

FIG. 4.—Scaled layer 1 PCA fluxes, corrected for instrumental and estimated sky background. The flux is repeated assuming a period of 2024 days.

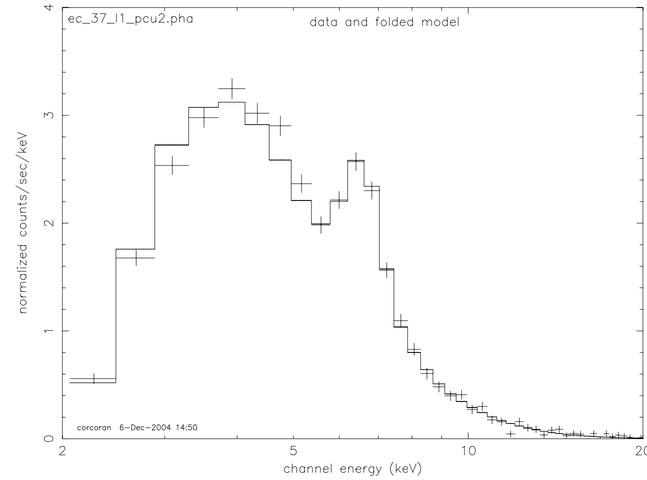

FIG. 6.—Typical PCU2 layer 1 spectrum of η Carinae, obtained on 2002 July 7. The histogram shows a three-component thermal model fit.

to the X-ray minimum and spikes in the hardness ratio curve. The minimum in spectral hardness during the X-ray flux minimum is mainly produced by contamination of the X-ray spectrum by other sources of emission within the field of view of the PCA and should not be interpreted as a real softening of the X-ray spectrum of η Carinae. Interestingly, however, the hardness of the source appears to increase during the middle of the X-ray minimum. This behavior should be interpreted with caution, since the *RXTE* spectrum of η Carinae is dominated by uncertainties in the instrument and sky backgrounds during the X-ray minimum; however, the mideclipse hardening was seen during both X-ray minima, suggesting that this may be a real effect associated with η Carinae.

5. TRANSIENT BEHAVIOR

As noted by Ishibashi et al. (1997) and Corcoran et al. (1997), and as can be seen in Figure 4, the X-ray emission from η Carinae exhibits transient increases in brightness. These peaks vary in intensity, duration, and in the interval between adjacent peaks. We have identified peaks by eye in Figure 11, and have calculated the interpeak intervals for all identified peaks. These intervals (defined as the interval from one flare to the previous one) are shown as filled circles. The average peak-to-peak interval is 56.6 days. There appears to be significant variation of the interpeak interval with phase. The interpeak interval grows shorter just prior to the X-ray minima, an effect seen in both 1997 and 2003. There may be a lengthening of the interpeak interval midway between the minima, although admittedly these peak timings are difficult to measure reliably because the peaks are so weak. The amplitude of the peaks relative to the interpeak brightness also changes with cycle phase. The peak amplitudes are very high just prior to the X-ray minima and very low in the times between minima.

Ishibashi et al. (1999) showed that some peaks occur rather regularly, with a quasi period of 84.8 days. We plotted times of expected X-ray peaks according to this period on Figure 11 as plus signs. There is fairly good correlation between these times and observed X-ray peaks, although not all peaks occur at these calculated times. In addition, the correlation becomes poorer for times after those analyzed by Ishibashi et al. (1999); in particular, the correlation is rather poor for the strong peaks just prior to the 2003 X-ray minimum, as shown in Figure 12, and for the weaker peaks following the X-ray minimum. For comparison, we recalculated peak times using a period of 84.333 days, which is commensurate with the 2024 day period of the X-ray minima. Expected peak times calculated with this 84.333 day period are marked by vertical lines in Figures 11 and 12. These calculated peak times correlate well with observed peak times in the early part of the light curve, and also give a somewhat better match to the peaks seen near the later X-ray minimum.

6. CYCLE-TO-CYCLE COMPARISON

As can be seen in Figures 4 and 5, there are significant differences between the 2–10 keV fluxes at the same phases in consecutive cycles. η Carinae was significantly brighter in the

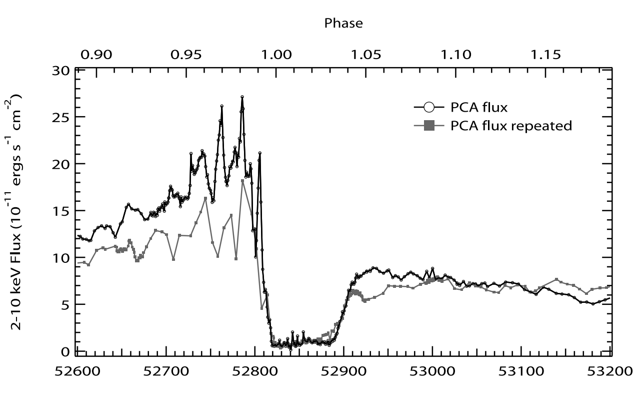

FIG. 5.—Same as Fig. 4, emphasizing the variation around the X-ray minima. Again, a period of 2024 days is used.

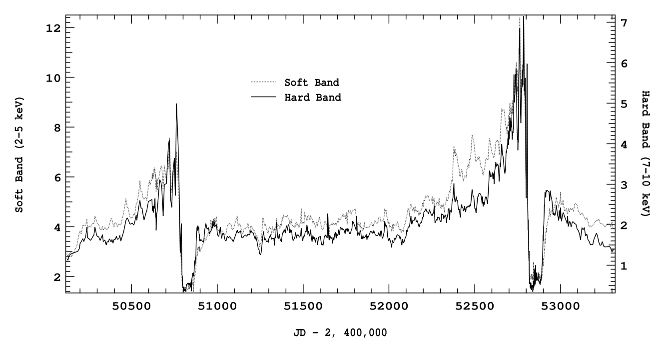

FIG. 7.—Comparison of the PCU2 layer 1 2–5 keV count rate light curve with the light curve in the 7–10 keV band. Both light curves are corrected for estimates of instrumental background.

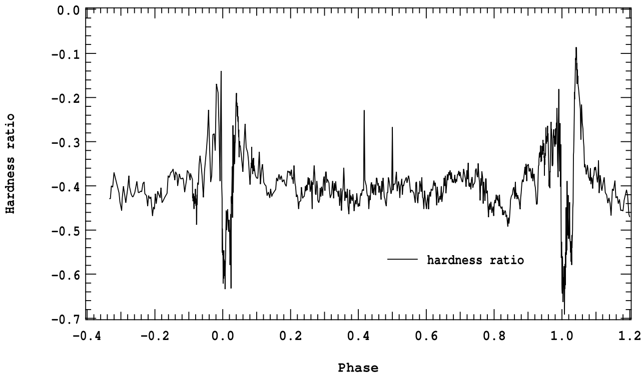

FIG. 8.—Hardness ratio variation; hr = (high − low)/(low + high), where high is the net count rate in the 7–10 keV band and low is the net count rate in the 2–5 keV band.

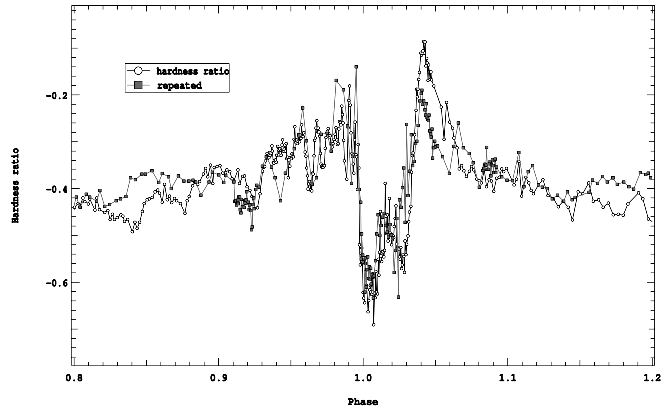

FIG. 9.—Hardness ratio variation, emphasizing the variation around the X-ray minima; hr = (high − low)/(low + high), where high is the net count rate in the 7–10 keV band and low is the net count rate in the 2–5 keV band.

phase interval $0.7 < \phi < 1.0$ compared to the corresponding interval in the previous cycle. During the most recent cycle, η Carinae continued brighter in X-rays after the minimum up to $\Delta\phi = 0.1$ However, starting at about $\phi = 1.09$ its 2–10 keV flux became once again comparable to its flux at the same phase in the previous cycle. The brightness has continued to drop,[3] so that, starting on 2004 April 21 and up to the time of this writing, η Carinae is currently fainter than it was at the same phase in the previous cycle.

The difference between the hardness ratio variation in the two cycles seems somewhat less than the variation of the X-ray flux. In particular, the change in hardness ratio prior to the X-ray minima is nearly the same in cycle 0 and cycle 1. However, while the hardness ratio prior to the 2003 minimum is remarkably similar to that prior to the 1998 minimum, there are significant differences in hardness ratio after the minimum.

In both cycles there is good evidence of spectral hardening around the times of X-ray intensity peaks. In addition, during each cycle the interpeak interval seems to decline on approach to the X-ray minimum, reaching a value of about 12 days just before the X-ray minimum begins.

7. DISCUSSION

Despite some detailed differences from cycle-to-cycle, the overall behavior of the X-ray emission seems remarkably consistent between the 1998 and 2003 minima. Particularly striking is the rapid decline from the X-ray maximum to X-ray minimum seen during both minima, and the consistent shape and duration of each minima. The repeatability of the X-ray minima, along with correlated changes in other wave bands (Steiner & Damineli 2004; Whitelock et al. 2004; Smith et al. 2004; Martin & Koppelman 2004; van Genderen & Sterken 2004; Fernandez Lajus et al. 2003), leaves little doubt that the phenomenon is strictly periodic and is produced by a gravitational clock, i.e., orbital motion in a binary system where the X-ray emission is from shocked gas produced by the collision of the wind of η Carinae with that of the companion. With this acknowledgement we need to understand the detailed behavior of the system exhibited by the X-ray radiometry in order to fully understand how the winds interact and ultimately determine the physical conditions of both stars as a function of time. While the stellar behavior can only be fully understood in the context of the multiwavelength data, we can still draw some conclusions solely from the X-ray data.

The differences in X-ray brightness between the 1998 and 2003 events is probably produced by an enhancement of the local density at the shock boundary. This implies that the wind density (or densities) at a given distance from the star varies with time. Such an enhancement in density suggests an enhancement in wind mass-loss rate from one or both stars. An increase in the mass-loss rate from η Carinae would push the shock front into the denser part of the companion's wind, resulting in increased emission measure, while an increase in the companion's wind would provide a direct increase in the density of the shock and its emission measure. Given the brightening of η Carinae seen in the optical and IR (Davidson et al. 1999; Sterken et al. 1999; van Genderen et al. 1999; Whitelock et al. 1994) it may be reasonable to attribute any variation in the X-ray brightness to variations in η Carinae itself, so that perhaps the variation in the X-ray brightness indicates changes in the mass-loss rate of η Carinae, perhaps driven by variations in the star's photospheric luminosity. The optical and IR light curves show continuing cycle-to-cycle increases, in contrast to our η Carinae observations, which showed an increase in brightness prior to the X-ray minimum in 2003 but a decline in X-ray brightness thereafter. However, the brightness of η Carinae at optical and IR wavelengths is complicated by the absorption and reradiation of photospheric emission by local dust, and it may be that a continuing decrease in the local dust (due to expansion of the Homunculus nebula, which surrounds η Carinae, or perhaps due to real destruction of the dust) contributes substantially to the observed long-term brightening of the optical and IR emission. As mentioned previously, dust plays little role in understanding the X-ray emission, at least at sufficiently high energies.

One of the most unusual results of these *RXTE* observations is the behavior of the spectral shape with time. It is important to note that the X-ray emission hardens considerably approaching the minimum, and declines dramatically after the minimum. This indicates that the source is highly absorbed, even after the X-ray flux recovers. This is in agreement with an observation of unusually large absorption seen in the X-ray spectrum by *BeppoSAX* (Viotti et al. 2002). The *RXTE* hardness curve suggests that the enhanced absorption lasts for about 58 days after the X-ray brightness recovers from the minimum, indicative of a buildup of material between the observer and the X-ray source. This could be due to some sort of phase-dependent mass-loss

[3] See http://lheawww.gsfc.nasa.gov/users/corcoran/eta_car/etacar_rxte_lightcurve/ for the most recent *RXTE* data.

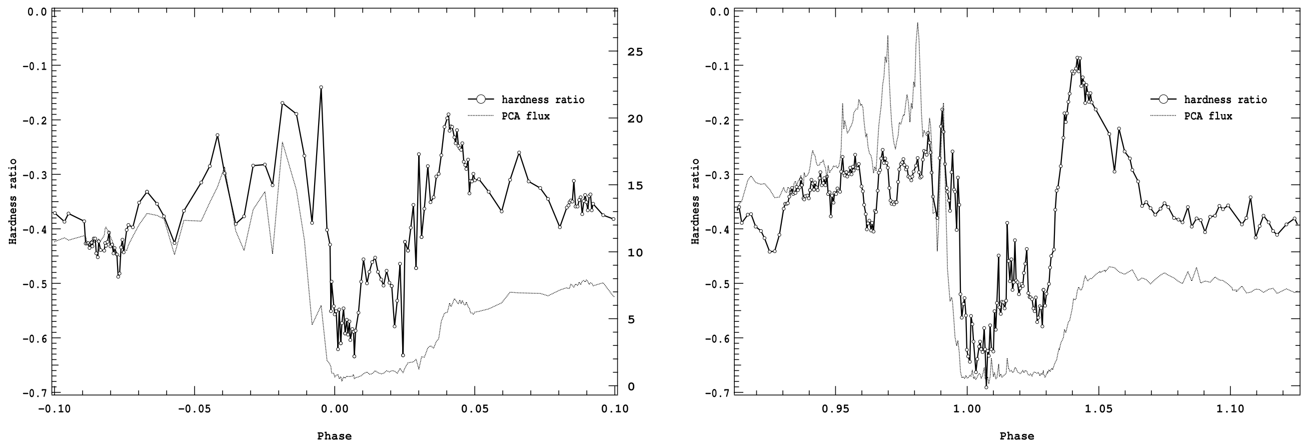

FIG. 10.—Hardness ratio variation compared to the flux variation. *Left*: The 1998 minimum. *Right*: The 2003 minimum. In each case, X-ray peaks are associated with X-ray spectral hardening.

enhancement (as suggested by Corcoran et al. 2001a), or is perhaps due to a disturbance in the wind produced by the passage of the companion star around η Carinae, or some combination of these effects.

While the nature of the short-term X-ray intensity peaks is still not understood, we have some new clues from the new *RXTE* data since the last minimum. Some of the peaks seem to recur periodically, or quasi-periodically, but the period given by Ishibashi et al. (1999) is slightly too long to match the peaks near the 2003 minimum. We find a better correspondence using a period of 84.333 days, which, interestingly enough, is commensurate with the orbital period of the system of 2024 days. It is also interesting that using this period, the start of the X-ray minima corresponds to a predicted intensity maximum. Another characteristic is that the intensity peaks also correspond fairly well to peaks in hardness ratio. This means that the intensity peaks are not caused by decreases in intervening absorption, but rather represent real increases in the amount of X-ray–emitting material. These variations probably suggest a highly structured wind around η Carinae, although detailed modeling of the nature of these variations is beyond the scope of this paper.

8. CONCLUSIONS

We present here X-ray observations of η Carinae from the *RXTE* observatory during the interval 1996 February 8 to 2004 November 2, inclusive. These observations have shown:

1. The X-ray minimum that occurred on JD 2,450,799.792 (1997 December 16) recurred on JD 2,452,819.667 (2003 June 29). A period of 2024 days fits the start and end of the minima, and we believe this represents the orbital period of a companion star around η Carinae.
2. These observations show significant changes in X-ray brightness: a secular brightening prior to the 2003 minimum, and a secular fading about 2 months after the end of the minimum.
3. Significant variations is spectral hardness were seen, suggesting a buildup of absorbing material prior to the X-ray minimum and a decline in absorption after the minimum. The interval of increased hardness lasts much longer than the X-ray minimum.
4. A period of 84.333 days seems to describe the times of X-ray intensity peaks better than the longer period of Ishibashi et al. (1999), at least for times near the X-ray minimum in 2003. This period is commensurate with the orbital period. The X-ray peaks are associated with a hardening of the spectrum and thus are not due to a decrease in absorption between the observer and the X-ray–emitting region.

Continued monitoring of the 2–10 keV flux will help clarify these conclusions and help resolve the current mystery of the secular variations in the X-ray flux of η Carinae that *RXTE* revealed. Unfortunately, current plans make it unlikely that *RXTE* will be able to monitor the flux of η Carinae through the

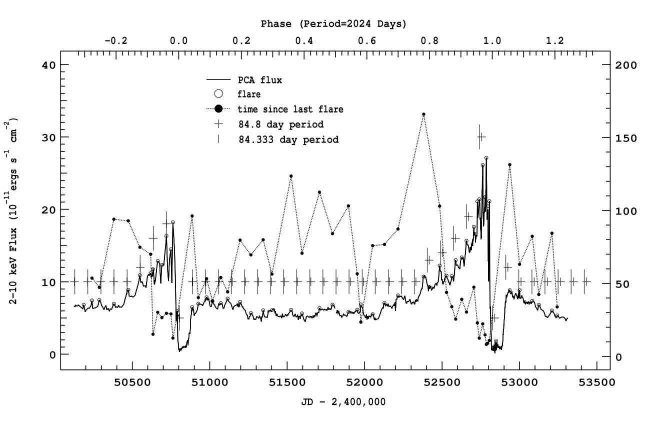

FIG. 11.—PCA light curve with identified X-ray peaks marked by open circles. The filled circles show the times between flares. The peak times according to the period of Ishibashi et al. (1999) are marked by plus signs. Expected peak times calculated with a period of 84.333 days are marked by vertical lines.

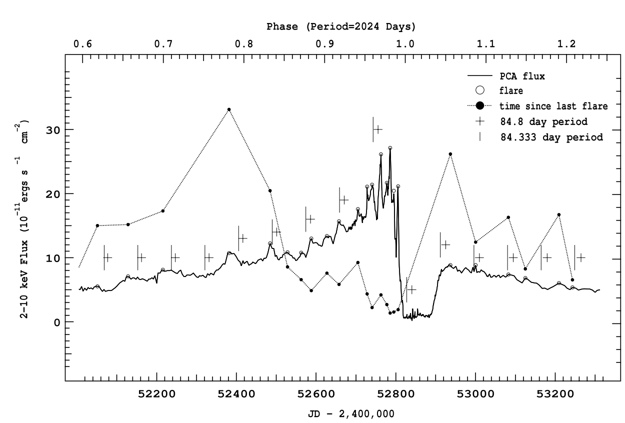

FIG. 12.—Same as Fig. 11, emphasizing the 2003 X-ray minimum.

2009 minimum. We hope to continue monitoring η Carinae with *RXTE* as long as the observatory is available.

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