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THE CORRELATED INTENSITY AND SPECTRAL EVOLUTION OF CYGNUS X-1 DURING STATE TRANSITIONS

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ABSTRACT

Using data from the All-Sky Monitor (ASM) aboard the *Rossi X-Ray Timing Explorer* (*RXTE*), we found that the 1.5–12 keV X-ray count rate of Cygnus X-1 is, on timescales from 90 s to at least 10 days, strongly correlated with the spectral hardness of the source in the soft state but is weakly anticorrelated with the latter in the hard state. The correlation shows an interesting evolution during the 1996 spectral state transition. The entire episode can be roughly divided into three distinct phases: (1) a 20 day transition phase from the hard state to the soft state, during which the correlation changes from being negative to positive, (2) a 50 day soft state with a steady positive correlation, and (3) a 20 day transition back to the hard state. The pointed *RXTE* observations confirmed the ASM results but revealed new behaviors of the source at energies beyond the ASM passband. We discuss the implications of our findings.

Subject headings: binaries: general — stars: individual (Cygnus X-1) — X-rays: stars

1. INTRODUCTION

Cygnus X-1 is identified with a binary system of 5.6 day orbital period, which contains an O9.7 Iab supergiant and a compact object that is believed to be a black hole (Bolton 1972; Webster & Murdin 1972). Observations indicate that the system usually assumes one of the two states, the hard state and the soft state (Oda 1977; Liang & Nolan 1984; Tanaka & Lewin 1995). Most of the time, Cyg X-1 stays in the hard state, where its soft X-ray (often 2–10 keV) flux is relatively low and the X-ray spectrum is hard. Every few years, the system undergoes a transition from the hard state to the soft state, during which the soft X-ray flux increases, often by a factor of more than 4, and the X-ray spectrum softens. It remains in the soft state for weeks to months before returning to the hard state. There is a strong anticorrelation between the soft and the hard (e.g., >20 keV) X-ray flux. Consequently, the bolometric X-ray luminosity does not vary significantly (Zhang et al. 1997b). The transition between the two states lasts from less than a day to more than a week.

A number of models have been proposed to explain the spectral evolution of Cyg X-1 during the state transitions. For instance, Ichimaru (1977) suggested that the physical condition of the accreted gas near the disk outer boundary could drive the disk into either an optically thick state or an optically thin state, which correspond to the soft and hard state, respectively. Zhang, Cui, & Chen (1997a) argued, based on the effects of black hole rotation, that the state transition of Cyg X-1 may be caused by a temporary reversal of the disk from being retrograde (hard state) to prograde (soft state), which can occur in wind accretion systems (e.g., Matsuda, Inoue, & Sawada 1987; Ruffert 1997). In the magnetic flare model (Di Matteo, Celotti, & Fabian 1999), the soft (hard) state corresponds to a lower (higher) scale height of magnetic flares above the accretion disk. The flares are energized by the reconnection of magnetic flux tubes rising from the accretion disk due to magnetic buoyancy instability. In the soft state, intense flares close to the disk greatly enhance the soft photon field, which results in a soft X-ray spectrum. In the hard state, the flare is triggered high above the disk; the system is "photon starved" and thus results in a hard, Comptonized spectrum. In the framework of advection-dominated accretion flows (ADAFs), Esin et al. (1998) argued that the spectral states of Cyg X-1 are uniquely determined by the mass accretion rate $\dot{m}$. In the hard state, $\dot{m}$ is relatively low, the inner edge of the thin disk is far away from the black hole, and thus the emission from the disk is weak compared to that from the large, optically thin ADAF region. In the soft state, $\dot{m}$ is higher, which causes the ADAF region to shrink and the thin disk to extend closer to the black hole. Therefore, at low energies the emission from the disk dominates over that from the smaller ADAF region. More data are needed to distinguish these models.

In this Letter, we report the results from a quantitative study of the correlation between the X-ray flux and the spectral properties of Cyg X-1, on timescales of 90 s to at least 10 days, in both the hard and soft states as well as during the transition phases.

2. DATA

The primary data set for this investigation comes from the All-Sky Monitor (ASM) on board the *Rossi X-Ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993). The ASM yields the intensities of the sources observed in units of the count rate in three energy bands (1.5–3, 3–5, and 5–12 keV). The 1.5–12 keV Crab Nebula flux is about 75 counts s^{-1}. Typically, a source is observed for a 90 s exposure ∼15 times a day, which provides sufficient coverage for studying phenomena such as the ∼90 day state transition episode of Cyg X-1. A detailed description of the ASM and the light curves can be found in Levine et al. (1996) and Levine (1998).

We used the ASM observations of Cyg X-1 between 1996 March and 2000 April, which cover the entire 90 day 1996 soft state including its transition phases (Cui et al. 1997a; Zhang et al. 1997b) and 4 yr of the hard state. The count rate in the 1.5–12 keV band and two hardness ratios HR1 and HR2 were computed. HR1 is the ratio of the count rate in the 3–5 keV band to that in the 1.5–3 keV band, and HR2 is the ratio in the 5–12 keV band to that in the 3–5 keV band. The hardness ratios provide a rough measure of the X-ray spectral shape of the source.

The higher quality data from the Proportional Counter Array (PCA; Jahoda et al. 1996) aboard *RXTE* (with much poorer

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coverage) were used to verify the ASM results and to study the flux–spectral hardness evolution over a wider energy range. We used 63 PCA observations of Cyg X-1, with exposure times ranging from 700 to 22 ks (but typically 3 ks), obtained from 1996 March 26 to 1998 April 28, 19 of which cover the 1996 spectral state transition. To minimize the known effects of calibration uncertainties at higher energies, we limited the spectral analyses to the energy range 2.5–25 keV. Also, since the number of the proportional counter units (PCUs) that were turned on varied from observation to observation, we used data only from PCU 0, which was active during all of the selected observations, in order to facilitate comparison of different observations.

For each PCA observation, we constructed a light curve with 100 s time bins and an energy spectrum for each time bin using FTOOLS (v. 5.0). Each spectrum was then fit with an empirical model using XSPEC (v. 10.0). For the soft state, the model consists of a broken power-law component, an iron line around 6.4 keV, and a fixed absorption ($n_{\mathrm{H}} = 5.6 \times 10^{21}$ cm $^{-2}$; e.g., Ebisawa et al. 1996; Cui et al. 1997a). For the hard state, we replaced the broken power law with a simple power law for the continuum, except for observations near the state transition or a pronounced soft flare in 1997 June. In the latter cases, the broken power law, sometimes an additional blackbody component, is required for obtaining an adequate fit. Variable absorbing column density is also necessary for some of the observations near superior conjunction of the X-ray source. All fits have reduced $\chi^2 < 1.5$. Note that our main objective here is simply to derive the energy flux of the source and its hardness ratios, as opposed to finding a physical model for the observed spectrum. The flux was calculated in the 2.5–25 keV band, as well as in the 3–5, 5–12, 12–17, and 17–25 keV bands. The energy bands were chosen such that the first two coincide roughly with the two upper ASM bands. Here we defined the hardness ratios as the ratios of energy fluxes between the first two (5–12 keV/3–5 keV) and the last two (17–25 keV/12–17 keV) energy bands.

3. ANALYSIS AND RESULTS

The ASM light curve of Cyg X-1 clearly indicates long-term variability on timescales ranging from 90 s to hundreds of days (Fig. 1; see also Fig. 1 in Wen et al. 1999). The rms variation of the light curve with a 90 s exposure in the 1.5–12 keV band is about 35% in the hard state and 22% in the soft state; both are much larger than the expected uncertainties (7% and 3%, respectively) in the data based on counting statistics and systematic uncertainties.

We quantify the correlation between the source count rate and spectral hardness by means of a nonparametric method first proposed by Spearman (the Spearman ranking method; Press et al. 1992, p. 569). For each data set, the value of each data point is replaced by the value of its rank among all other data points. That is, for N data points, the smallest value would be replaced with value 1 and the largest with N. If some of the data points have identical values, they are assigned the mean of the ranks they would have if they were to be slightly different. The correlation coefficient r_s is defined as

$$r_s = \frac{\sum_i (R_i - \bar{R})(S_i - \bar{S})}{\sqrt{\sum_i (R_i - \bar{R})^2}\sqrt{\sum_i (S_i - \bar{S})^2}}, \qquad (1)$$

where R_i and S_i are the assigned ranks for the data points in each of the two data sets. The significance of a nonzero value was tested by computing

$$t = r_s\sqrt{\frac{N-2}{1-r_s^2}}, \qquad (2)$$

which is distributed approximately as Student's distribution with $N - 2$ degrees of freedom.

The main advantage of the Spearman ranking method is that the significance level of the correlation does not depend on the original probability distribution of the data. Because of this, the significance level of the correlation can be reliably computed even if the number of the data points is small. Despite some loss of information in replacing the original values by ranks, the method is reliable in the sense that when a correlation is demonstrated to be present nonparametrically, it is really there. On the other hand, there exist examples where correlations could be detected parametrically but could not be detected nonparametrically. However, such examples are believed to be very rare in practice (Press et al. 1992, p. 569).

We then computed, using eq. (1), the correlation coefficients between the X-ray count rate and the spectral hardness for the ASM and the PCA data. For the ASM data with its original 90 s time bins, we calculated each correlation coefficient over a "correlation interval" for several values that ranged from 1 to 20 days. To explore the correlation relations for variability of different timescales, the calculations were repeated for time bins up to 10 days for the soft state and up to 100 days for the hard state. In these cases, the correlation intervals were chosen to be 5–20 times the time bin size such that the average number of data points per interval is greater than three. For the PCA data (with 100 s time bins), we calculated one cor-

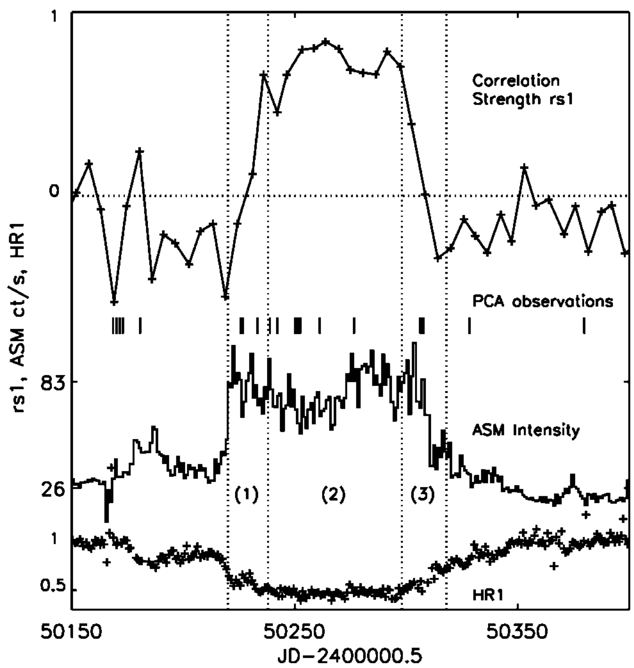

FIG. 1.—Correlation coefficients of the 1.5–12 keV ASM count rate and the hardness ratio HR1 for 90 s time bins and a 5.6 day correlation interval (see text). Also shown are the ASM count rate and hardness ratio HR1 with 1 day time bins. For this time bin, the typical relative uncertainty is 2% for the count rate and 5% for HR1. The PCA observations are indicated with vertical lines.

relation coefficient for each observation because of the limited number of data points. In all our calculations, data segments with less than three data points were excluded.

3.1. *The ASM Results*

The correlation coefficient r_{s1} between the X-ray count rate and the hardness ratio HR1 for a 90 s time bin and 5.6 day correlation intervals is shown in Figure 1. The results for different correlation intervals are similar. For longer intervals, the correlations become statistically more significant as more data points are involved. The correlation interval of Figure 1 is the 5.6 day orbital period of Cyg X-1. This allows us to compare the result to the possible contribution from the orbital modulation of X-rays by the stellar winds (Wen et al. 1999). Both r_{s1} and r_{s2} (count rate vs. HR2) evolve similarly during the state transition.

The ASM count rate and spectral hardness in Figure 1 are positively correlated in the soft state with an average r_{s1} of about 0.7, corresponding to a false alarm possibility less than 10^{-30}. Significant positive correlation was also found for time bins of 0.1, 1, 5, and 10 days. In other words, the positive correlation in the soft state holds for variability on timescales from 90 s up to at least 10 days. In the hard state, the correlation in Figure 1 turns weak and negative with an average r_{s1} of about -0.2. Calculations with time bins of 5.6 (to eliminate the orbital effect), 20, and 100 days also show negative correlation. In both states, the coefficient r_{s2} behaves similarly but with relatively weaker strength; about 0.5 for the soft state and -0.12 for the hard state for 90 s time bins and 5.6 day correlation intervals.

The evolution of the correlation during the state transition is a gradual one, as shown in Figure 1. The entire episode of the 1996 state transition can be roughly divided into three distinct phases: (1) a 15–20 day transition phase from the hard state to the soft state, where r_{s1} goes from negative to positive, (2) a ~50 day soft state with a steady positive r_s, and (3) a 15–25 day transition phase back to the hard state. The start time of phase 1 and end time of phase 3 indicated in Figure 1 were chosen to be the times when the hardness ratios are roughly at the midpoint between the mean levels of the hard and soft states. This yields a ~20 day timescale for phases 1 and 3, similar to what we would get if we were to choose the start (end) time to be when the correlation coefficient just started (ended) its sharp rise (drop). We obtain roughly the same results with smaller time bins (0.1 and 1 day), so the conclusions seem quite robust.

3.2. *The PCA Results*

The evolution of the two PCA hardness ratios with the energy flux is shown in Figure 2. As expected, the energy flux and spectral hardness for $E < 12$ keV (*left panel*) is strongly correlated in the soft state (*large filled circles*) but weakly anticorrelated in the hard state (*small filled circles*). The evolution of the flux-hardness correlation between the two states is apparent during the transition phases 1 and 3 (defined in Fig. 1, *open circles*). These confirm the ASM results.

To investigate possible orbital effects, we separated out the hard-state data at phases 0.2–0.8, where phase 0 is defined as superior conjunction of the X-ray source. The results are shown in the inset of Figure 2. The anticorrelation seems to become less pronounced at low fluxes, indicating the importance of the orbital effects. On the other hand, the overall anticorrelation is still prominent, mostly due to the cluster of data points to the lower right, which come from observations 10–60 days proceeding or following the state transition (labeled "T"). Interestingly, one group of data points is from observations of Cyg X-1 during a 50 day–long soft flare that occurred about 1 yr after the state transition (labeled "F"). It is also worth noting that within the remaining two data groups the correlation is absent (or very weak).

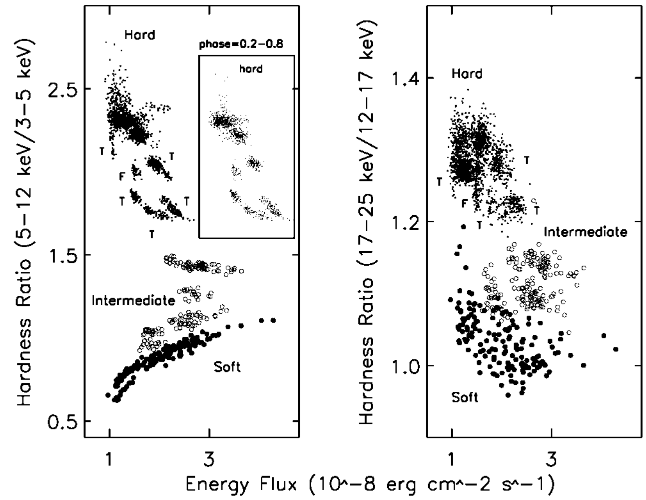

FIG. 2.—Evolution of the two PCA spectral hardness ratios with the 2.5–25 keV incident energy flux (see text). Labels "T" and "F" indicate data near the state transition and during the soft flare, respectively. The inset in the left panel shows the hard-state data at phase 0.2–0.8 (with the X-axis shifted to the right by one tick mark), where phase 0 is superior conjunction of the X-ray source.

Data from the higher PCA energy bands ($E > 12$ keV) show no strong correlations in all states (Fig. 2, *right panel*). There may be a slight anticorrelation in the hard-state data, again mostly due to observations near the state transition and during the soft flare. This is consistent with the fact that, within each state, the general shape of the observed spectrum above ~12 keV seems insensitive to the change of the flux.

4. DISCUSSION

The ASM results show that the transition phases lasted for about 20 days during the 1996 state transition of Cyg X-1, as opposed to $\lesssim 7$ days as indicated by the change in the soft X-ray flux (see Fig. 1). That is, for about 20 days at the beginning and near the end of the state transition episode, the system was in a transitional process even though the soft flux was generally high. A similar conclusion was drawn by Cui et al. (1997a, 1997b) based on the evolution of the power density spectra. We therefore suggest that the spectral states of Cyg X-1 are better defined by the correlation between the soft X-ray flux and the spectral hardness of the source than by the soft flux alone.

The PCA results confirm our findings based on the ASM data. Furthermore, they reveal that the orbital effects could account for the observed negative correlations on timescales of less than 5.6 days, for time periods sufficiently far away from the soft flare or the state transition. This is consistent with the fact that there is a broad absorption-like dip in the orbital light curves obtained from the ASM data, likely caused by absorption and scattering of the X-rays by the stellar wind (e.g., Wen et al. 1999). Our best-fit model ASM orbital light curve and hardness ratios (without noise) would yield r_{s1} to be around -0.6 with a 0.1 day time bin in a 5.6 day correlation interval. The observed correlation strength is weaker ($r_{s1} \sim -0.2$), probably reduced by noise. On the other hand, the observed positive correlation in the soft state is the opposite of what we would expect from the orbital effect. This is consistent with our previous conclusion (Wen et al. 1999) that orbital modulation is much smaller (if present at all) in the soft-state phases.

Both the ASM and the PCA data indicate the existence of the flux-hardness anticorrelation in the hard state on timescales longer than the 5.6 day orbital period. Moreover, the hard-state data near the state transition episode and during the soft flare both contribute to this observed anticorrelation in a similar fashion (Fig. 2). The PCA spectral fitting indicates that these observations also share similar spectral properties, which deviate somewhat from that of typical hard-state data (see § 2). This seems to lend support to the notion that soft flares are "failed" state transitions. Similar soft flares occur randomly on timescales of months to years in the ASM light curve. We therefore conclude that the anticorrelation in the hard state on timescales longer than the orbital period is intrinsic to the source and is probably related to the mechanism that causes the state transition.

Models employing a simple disk-corona geometry predict that, as the mass accretion rate through the disk increases, the soft X-ray flux increases, which provides more seed photons for the inverse Comptonization process and thus cools the hot electrons in the corona. This would be manifested observationally as the "pivoting" of the energy spectrum of the source. Such spectral pivoting is known to occur in Cyg X-1 during a state transition (e.g., Liang & Nolan 1984; Zhang et al. 1997b), and the pivoting energy is in the range of 10–20 keV. This may explain the observed flux-hardness anticorrelation at low energies (below the pivoting energy) for the state transition (and perhaps soft flares). The same might also be true for the general long-term evolution of the source in the hard state, if the pivoting phenomenon is universal (but more pronounced during a state transition).

Interestingly, this may also explain the apparent lack of correlations around 12–25 keV (Fig. 2), since the pivoting energy is right in this energy range. Clearly, the same scenario cannot be applied to the soft state, where the correlation is observed to be (strongly) positive, unless the pivoting energy has moved to a very low energy (below the ASM passband). Such a reduction in the pivoting energy is not apparent in our PCA data and is inconsistent with the lack of correlations in the 12–25 keV band. It is, therefore, likely that different physical processes are involved in the soft state (see A. A. Zdziarski, L. Wen, & W. S. Paciesas 2001, in preparation, for a follow-up investigation of possible models).

Li, Feng, & Chen (1999) discovered similar correlations between the count rate and hardness for Cyg X-1, using the PCA data, but on much shorter timescales (0.01–100 s) and with little coverage in the hard state. In their study, they chose two energy bands, 2–6 and 13–60 keV, from which the hardness ratio was derived. Such a choice of energy bands unfortunately masks the difference in the correlations between the count rate and the spectral shape above and below 12 keV for the soft state. Using the BATSE data (20–200 keV), on the other hand, Crary et al. (1996) did see a lack of correlation between the 45–140 keV energy flux and the photon index within both data groups of high and low flux, which were presumed to correspond to the hard and soft states, respectively. However, they did not have the necessary soft X-ray data to see the count rate–hardness correlation that we found. In this regard, our work bridges critical gaps in those two investigations and provides new insight into the overall spectral behavior of this system.

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