Five Years in the Life of Cygnus X-1:
BATSE Long-Term Monitoring

W. S. Paciesas∗♯, C. R. Robinson♭♯, M. L. McCollough♭♯, S. N. Zhang♭♯, B. A. Harmon♯ and C. A. Wilson♭

∗University of Alabama in Huntsville, AL 35899
♭Universities Space Research Association
♯NASA/Marshall Space Flight Center, Huntsville, AL 35812

Abstract. The hard X-ray emission from Cygnus X-1 has been monitored continually by BATSE since the launch of CGRO in April 1991. We present the hard X-ray intensity and spectral history of the source covering a period of more than five years. Power spectral analysis shows a significant peak at the binary orbital period. The 20–100 keV orbital light curve is roughly sinusoidal with a minimum near superior conjunction of the X-ray source and an rms modulation fraction of approximately 1.7%. No longer-term periodicities are evident in the power spectrum. We compare our results with other observations and discuss the implications for models of the source geometry.

INTRODUCTION

Cyg X-1, the prototypical galactic black hole, is one of the most intensively studied objects in the X-ray sky. Nevertheless, our understanding of its detailed nature has been slow to evolve, due in large part to the strong but rather chaotic variability of its X-ray emission. Long-term monitoring in soft X-rays has been performed by several instruments, including the all sky monitors on Ariel 5 [4], Vela 5B [11], and Ginga [5]. These have identified two main periodic components in Cyg X-1, the 5.6 day binary orbital period and a less well defined period of ∼300 days [11], the cause of which is speculative.

The now well-known soft (“high”) and hard (“low”) emission states were also identified from soft X-ray data. Such states are now known to be common features of black holes, although not all black hole candidate systems have shown both states (e.g., GS 2023+33, LMC X-1).

With CGRO/BATSE we have now accumulated more than 5.5 years of monitoring of Cyg X-1 in hard X-rays. Moreover, since the launch of RXTE we now have wide band long-term monitoring of Cyg X-1. This enabled us to obtain the most comprehensive observations yet of a complete soft state episode [14]. We report
here exclusively on the BATSE long-term monitoring, including a broad overview
of the intensity and spectral variability and our search for periodic or quasi-periodic
components.

**OBSERVATIONS**

Data obtained between 21 Apr 1991 and 24 Sep 1996 (TJD 8367–10350) were
processed using the standard BATSE Earth occultation software. Fluxes in the
energy range 20–100 keV were calculated by fitting standard spectral models to the
16-channel count spectra, either from individual occultation steps or summed over
one day. Two models were used: a single power-law and an optically thin thermal
bremsstrahlung (OTTB). In general, our conclusions do not depend significantly
on the choice of model spectrum.

Figure 1 shows the long-term intensity and spectral history of Cyg X-1 in the
20–100 keV energy range using one-day integrations. The two previously known
soft state episodes are clearly visible around TJDs 9350–9410 and 10220–10300.
During the remaining time, the source intensity in the hard state fluctuated rather
randomly, staying mostly between 0.2 and 0.35 ph cm$^{-2}$ s$^{-1}$. The hard state spec-
tral index remained relatively steady around a value near $-1.85$, although extended
periods with slightly softer spectra occur, e.g., TJD 8950–9030. Flares above the
0.35 ph cm$^{-2}$ s$^{-1}$ level typically last only a few days and show no spectral differ-
entiation, whereas dips below the 0.2 ph cm$^{-2}$ s$^{-1}$ level typically last a week or so,
and may or may not show spectral softening (cf. the intensity dips around TJDs
9510 and 9610).

**FIGURE 1.** Long-term hard X-ray intensity and spectral history of Cyg X-1 from BATSE
observations. The upper panel shows the integrated photon flux in the 20–100 keV band derived
by fitting a power-law model to one-day average count spectra. The lower panel shows the
corresponding photon number spectral index.
Figure 2 shows a plot of the spectral index vs. flux for the same data set. The predominance of the $-1.85$ spectral index over a wide range of intensities is obvious, as is the trend toward softer spectral indices at low intensity. However, the hard state can persist down to intensities as low as $0.15 \text{ ph cm}^{-2} \text{ s}^{-1}$ and spectra as soft as $\alpha \approx -2.2$ can be present at essentially any intensity. Spectra with $\alpha \lesssim -2.2$ are mainly confined to flux levels below $\sim 0.15 \text{ ph cm}^{-2} \text{ s}^{-1}$, which appear to occur only during the low energy “high” states. We do not see well-defined intensity/spectral states corresponding to the three-state classification scheme outlined by Ling et al. [6].

To search for periodic and quasi-periodic signals, we used fluxes deconvolved in a similar manner, but at the resolution of individual occultation steps. We present results using the OTTB model, which produced slightly more robust fits. The unevenly sampled power density spectrum (PDS) (Figure 3) is rather flat at low frequencies, falls off roughly as $1/f$ above $\sim 0.005 \text{ cycle/day}$ (200 day period), and reaches the Poisson noise level at $f \approx 0.4$. To estimate the significance of peaks in the data, we first fit the data with a combination of a constant power $Z_0$ at low frequencies and a power-law $a_0 f^{a_1}$ above a break frequency $f_c$. The resulting parameters were $Z_0 = 148$, $a_0 = 0.333$, $a_1 = -1.117$, and $f_c = 0.00425$. After dividing by the red noise fit, the maximum of the power spectrum is at $f = 0.178606$, consistent with the binary orbit $f = 0.178580$ [2]. Treating this as an a priori interesting frequency, the probability of a chance fluctuation is $1.4 \times 10^{-7}$. If we ignore the a priori argument and scale by the number of independent trial frequencies, the chance probability is $5.4 \times 10^{-5}$. Our data show no evidence for a peak around $f = 0.0033$ (300 day period); however, our sensitivity below $\sim 0.01 \text{ Hz}$ is limited by the red noise.

Figure 4 shows the data folded at the orbital period. The modulation is roughly sinusoidal, with a minimum near phase 0 (supergiant companion nearest the ob-
server). The best-fitting sine function has a minimum at phase 0.025 ± 0.008 and peak-to-peak amplitude 0.0094 ± 0.0004 ph cm⁻² s⁻¹ (statistical errors only), which corresponds to 3.8% of the average intensity. The rms scatter about the mean is ∼ 1.7%.

**DISCUSSION**

Detection of the 5.6 day orbital variation in hard X-rays was first reported by Ling et al. [7], who found a peak-to-peak amplitude of ∼6% in 50–140 keV using ∼120 days of data from the HEAO-3 gamma ray spectrometer. Priedhorsky et al. [12] reported a marginal detection of 10±4% in 17–33 keV from ∼70 days of observations with WATCH/Eureca. Phlips et al. [10], using ∼120 days of CGRO/OSSE data, did not find a significant variation in 60–140 keV, with an upper limit to the rms fraction of 5%. Our result is consistent with the OSSE upper limit, and marginally consistent with the earlier observations.

**FIGURE 4.** Cyg X-1 single occultation step data folded at the 5.6 day binary orbital period. Two cycles are shown for clarity. The best-fitting sine function is superimposed. Error bars represent the statistical error in the mean for each phase bin. Phase 0 corresponds to the time when the supergiant companion is closest to our line of sight.

Since the low energies show obvious absorption dips near phase 0 [4,8,9], it is natural to consider absorption as responsible for the variation we see. The decrease in our data centered roughly around phase 0 cannot be due to absorption by cold matter because the column density required would cause a total eclipse of the soft X-rays, which is not observed. Electron scattering by highly ionized material would require a maximum column density ∼ 6 × 10²⁴ cm⁻². If the material is in a stellar wind, the nearly sinusoidal shape we observe implies that this material is spread over a large portion of the orbit. This is inconsistent with the much lower column density (∼ 3 × 10²³ cm⁻²) estimated for such a wind from 9–12 keV data [12].

An alternative possibility is a variable reflection component from the accretion disk or the companion star. Done et al. [1, also see ref. [3]] showed that the Cyg X-1 spectrum can be fit with a model involving reflection from an ionized accretion disk, similar to models for active galactic nuclei. In these fits, the reflection component represents ∼30% of the flux in the 20–100 keV range, so that our results could be explained by a variation of 5–10% in reflectivity as a function of phase.
SUMMARY

BATSE has observed Cyg X-1 continually for more than 5.5 years. The hard X-ray light curve is dominated by red noise that has a flat power spectrum below a frequency of $\sim 0.004$ cycle/day (periods $\simeq 250$ days) and falls off roughly as $1/f$ at higher frequencies. Periodic variability is detected at the binary orbital period, with an rms modulation of $\sim 1.7\%$ and a minimum flux at the time of superior conjunction of the supergiant companion (phase 0). We find no evidence for the previously reported long-term period of $\sim 300$ days.

The 20–100 keV spectrum of Cyg X-1 appears to have a spectral hardness limit around a power-law index $\alpha \simeq -1.8$. BATSE has observed such a spectrum over a flux range of at least a factor of three, from $\sim 0.15$ to $\gtrsim 0.45$ ph cm$^{-2}$ s$^{-1}$. However, softer spectra can be present at any observed flux level. Below $\sim 0.15$ ph cm$^{-2}$ s$^{-1}$, only soft spectra ($\alpha \lesssim -2.25$) associated with the soft (high) X-ray state have so far been seen.

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