OBSERVATIONS OF GIANT OUTBURSTS FROM CYGNUS X-1

S. Golenetskii, R. Aptekar, D. Frederiks, E. Mazets, and V. Palshin
Ioffe Physico-Technical Institute, St. Petersburg 194021, Russia; golen@pop.ioffe.rssi.ru
K. Hurley
University of California, Berkeley, Space Sciences Laboratory, Berkeley, CA 94720-7450
T. Cline
NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771
AND
B. Stern
Institute for Nuclear Research, Moscow 117312, Russia
Received 2002 December 21; accepted 2003 June 27

ABSTRACT

We present interplanetary network localization, spectral, and time history information for seven episodes of exceptionally intense gamma-ray emission from Cyg X-1. The outbursts occurred between 1995 and 2003, with durations up to ~28,000 s. The observed 15–300 keV peak fluxes and fluences reached $3 \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$ and $8 \times 10^{-4}$ ergs cm$^{-2}$, respectively. By combining the triangulations of these outbursts we derive an ~1700 square arcminute (3 $\sigma$) error ellipse that contains Cyg X-1 and no other known high-energy sources. The outbursts reported here occurred both when Cyg X-1 was in the hard state as well as in the soft one and at various orbital phases. The spectral data indicate that these outbursts display the same parameters as those of the underlying hard and soft states, suggesting that they represent another manifestation of these states.

Subject headings: black hole physics — gamma rays: observations — stars: individual (Cygnus X-1)

1. INTRODUCTION

The X-ray source Cyg X-1 was discovered by Bowyer et al. (1965), and its optical counterpart, a spectroscopic binary at a distance of ~2 kpc with a 5.6 day period (HDE 226868), was identified by Webster & Murdin (1972) and Bolton (1972). The primary is a supergiant, (HDE 226868), was identified by Webster & Murdin (1972) and Bolton (1972). The primary is a supergiant, (HDE 226868), was identified by Webster & Murdin (1972) and Bolton (1972). The primary is a supergiant, was identified by Webster & Murdin (1972) and K. Hurley (1995, private communication). The outbursts reported here occurred both when Cyg X-1 was in the hard state as well as in the soft one and at various orbital phases. The spectral data indicate that these outbursts display the same parameters as those of the underlying hard and soft states, suggesting that they represent another manifestation of these states.

2. OBSERVATIONS

The outbursts reported here were discovered in the time history data of the gamma-ray burst (GRB) detectors aboard the Wind, Ulysses, and Compton Gamma-Ray Observatory (CGRO) spacecraft (Konus, GRB, and the Burst and Transient Source Experiment [BATSE] experiments, respectively). In general, the data used were for the nontriggered modes, with low temporal and spectral resolution (0.25–2.9 s and three channels, respectively). Although, in some cases, the emission was intense enough to trigger BATSE, the data obtained in the triggered modes had too small a duration to cover the entire outburst, and the lower
time resolution continuous data have been used for most of our analysis. Table 1 gives the dates, times, and durations of the seven events, as well as the spacecraft that observed them, and the spectral state and orbital phase of Cyg X-1. To determine the source of the outbursts, we have employed the usual method of Interplanetary Network (IPN) triangulation for a repeating source (e.g., Hurley et al. 1999). In all cases, the IPN consisted of only two widely separated spacecraft (Ulysses and either CGRO or Wind), so a single annulus of location was obtained for each flare. The seven annuli were statistically combined to produce the 1, 2, and 3 $\sigma$ error ellipses shown in Figure 1. The only known hard X-ray source in this region is Cyg X-1, which lies at the $\sim95\%$ confidence level.

Although Ulysses observed all seven of the outbursts in Table 1, it was in a mode in which no energy spectra were accumulated. Konus-Wind observed six of the seven outbursts (one outburst, 990421B, occurred during a period when the data were contaminated by solar particles), and we have used the data from it exclusively for time-resolved spectral analysis. The time and energy resolutions vary depending on the mode of operation. For five outbursts we have data in three energy channels (nominally 10–50, 50–200, and 200–750 keV, or G1, G2, and G3, respectively), which span the entire event. In the sixth case (950325) a cosmic gamma-ray burst fortuitously triggered Konus during the outburst, allowing it to record multichannel energy spectra for a total of 360 s, starting 120 s after the GRB trigger, when the 15 s long GRB had ceased emitting. In addition, for this event, there are also three-channel data. Because the most detailed data are available for it, we discuss this outburst first.

The 950325 outburst is presented in detail in Figure 2. In the top three panels, the time histories in the G1, G2, and G3 windows are shown, and in the bottom panels, the hardness ratios G2/G1 and G3/G2 are shown. The letters A–D indicate the intervals where energy spectra have been analyzed. (The results of this and other analyses are summarized in Table 2.) In particular, B marks the 360 s interval where multichannel spectra were accumulated. The gap following B is the interval where the data were transferred to the onboard tape recorder. The hardness ratios display a weak but obvious spectral variability. From them, it is reasonable to assume that the multichannel energy spectra measured in interval B, during the fading stage of the flare, also characterize the spectrum of the preceding intense phase. The multichannel spectrum is presented in Figure 3 in $\nu F_{\nu}$ units. (The spectral deconvolution procedure has been described by Terekhov et al. 1998.)

![Figure 1](http://xte.mit.edu/ASM_lc.html)

Fig. 1.—Shows 1, 2, and 3 $\sigma$ error ellipses for the seven Cyg X-1 outbursts. Their areas are 328, 887, and 1700 square arcminutes. The best-fit position is at $\alpha$(J2000.0) = 19h58m09s, $\delta$(J2000.0) = 35°08'20", with a $\chi^2$ of 7.24 for 5 dof (seven annuli minus two fitting parameters). Cyg X-1 lies 0:35 away, at the $\sim95\%$ confidence level. A search through the SIMBAD database has not identified any other X-ray sources within the 3 $\sigma$ error ellipse.

![Figure 2](http://xte.mit.edu/ASM_lc.html)

TABLE 1

| Date         | Onset UT (approx.) | Duration (approx.) | Spacecraft | Underlying Spectral State | Orbital Phase $^d$ |
|--------------|--------------------|--------------------|------------|----------------------------|-------------------|
| 1995 Jan 10  | 18,600             | 27,500             | Ulysses $^a$, Konus $^a,b$, BATSE $^c$ | Hard $^d$         | 0.37              |
| 1995 Mar 25  | 14,400             | 28,000             | Ulysses $^a$, Konus $^a,b$, BATSE $^c$ | Hard $^d$         | 0.57              |
| 1999 Apr 21A | 54,510             | 4870               | Ulysses, Konus, BATSE $^a$            | Hard $^b$         | 0.38              |
| 1999 Apr 21B | 63,100             | 1360               | Ulysses, BATSE $^a$                   | Hard $^b$         | 0.40              |
| 2002 Feb 24  | 54,600             | 10,000             | Ulysses $^a$, Konus $^b$              | Soft $^b$         | 0.10              |
| 2002 Mar 31  | 35,925             | 910                | Ulysses, Konus                        | Soft $^b$         | 0.31              |
| 2003 Feb 12  | 65,000             | 5800               | Ulysses, Konus                        | Hard $^b$         | 0.16              |

$^a$ Golenetskii et al. 2002a, 2002b.
$^b$ Mazets et al. 1995.
$^c$ Schmidt 2002.
$^d$ Stern et al. 2001.
$^e$ Terekhov et al. 1998.) The solid line gives $F_{\nu} = \left(2.1 \pm 0.9 \times 10^{-10}\right) \exp \left(-E/E_0\right) \mathrm{keV} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, with $E_0 = 0.88 \pm 0.23 \mathrm{keV}$.
$^f$ The state was derived using the online data of RXTE.
letters at the top of the Konus plots indicate the intervals over which three-channel energy spectra were accumulated to improve statistics. Fits were done with the function $A(E/1 \text{ keV})^{-\alpha} \exp(-E/E_p)$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$, and the fitting parameters are given in Table 2. The value $E_p$, the peak energy, was obtained from the spectrum expressed in $\nu F_\nu$ units. The fluences and peak fluxes, given in Table 3, were calculated assuming no spectral evolution over the intervals considered.

It should be noted that an omnidirectional sensor detects an outburst from a source as a temporary increase in the count rate over an average background level. Clearly, in this case that level includes any persistent flux from Cyg X-1. Thus, the total flux during an outburst will be the sum of the persistent and flaring fluxes detected by Konus. However, the value of the persistent flux from Cyg X-1 at time intervals adjacent to the outburst is poorly known. Accordingly, the fluences and peak fluxes in Table 3 are to be considered only estimates of the outburst component.

Fig. 2.—Shows the Cyg X-1 outburst on 950325 as observed by Konus-Wind. The time histories are shown in the three energy bands: G1, G2, and G3 with a time resolution of 47.104 s; the hardness ratios G2/G1 and G3/G2 are also shown. A, B, C, and D denote the time intervals where the spectral parameters were estimated. The backgrounds in G1–G3 were slightly unstable due to an apparent Forbush decrease that began on March 23 and lasted through March 25, according to the Konus data. Thus, the apparent weak onset of the event prior to interval A cannot be definitely attributed to Cyg X-1. The narrow spike at 25,841 s in the beginning of interval B is the GRB that triggered a series of multichannel spectral measurements, covering the entire interval B. The gap after B was caused by the transmission of high-resolution data to the onboard tape recorder. Background levels are indicated by the dashed lines.

Fig. 3.—Shows the Konus $\nu F_\nu$ spectrum of the outburst on 950325. The spectrum was accumulated during the decay stage of the flare over 360 s of interval B with moderate statistics. The solid curve is the result of the spectral fit; $\chi^2 = 22.6$ for 18 dof. The spectral shape is consistent with that of the hard state of Cyg X-1.

Fig. 4.—Shows Konus 15–300 keV photon fluxes (background-subtracted) and hardness ratios for the outburst on 950110. Spectral fits were done for intervals A, B, C, and A + B + C. The photon fluxes in photons cm$^{-2}$ s$^{-1}$ were calculated by deconvolving the count-rate data. The time resolution is 47.104 s.
3. DISCUSSION

Long-term observations of Cyg X-1 in X-rays and soft gamma-rays from HEAO 3 (Ling et al. 1987), BATSE (Ling et al. 1997), Mir-Kvant (Borkus et al. 1995), and BeppoSAX (Frontera et al. 2001) have shown that the source spends most of the time in the hard state. According to BATSE data for 1991–1999 (McConnell et al. 2002), the hard flux in the 20–100 keV energy range varied between 0.2 and 0.36 photons cm$^{-2}$ s$^{-1}$, roughly the average value corresponding to the $\gamma_2$ level in the 45–140 keV band identified by Ling et al. (1987). In 1999 April, several outbursts lasting up to

FIG. 6.—Shows Ulysses 25–150 keV count rates for the outburst on 990421B. The time resolution is 15 s. Note that the onset is several hundred seconds prior to the onset at BATSE (Stern et al. 2001) due to Earth occultation. No Ulysses spectral data are available for this outburst. Due to the proximity in time to the previous outburst, the two could be considered manifestations of a single episode, although the Konus and Ulysses count rates remained at their background levels between them. In contrast to the outbursts on 950110, 950325, 990421A, and 020224, this time history exhibits a slow rise and a fast decay. The background level is indicated by the dashed line.

FIG. 5.—Shows Konus 15–300 keV photon fluxes (background-subtracted) and hardness ratios for the outburst on 990421A. The time resolution is 11.77 s. Spectral fits were done for intervals A, B, C, D, and A + B + C + D.

| Date             | Time Interval$^a$ | A   | $\alpha$ | $E_0$ (keV) | $E_p$ (keV) |
|------------------|-------------------|-----|----------|-------------|-------------|
| 1995 Jan 10      | A                 | 0.92 ± 0.08 | 1.24 ± 0.05 | 111 ± 10   | 85 ± 3   |
|                  | B                 | 0.93 ± 0.12 | 1.45 ± 0.07 | 133 ± 22   | 73 ± 4   |
|                  | C                 | 1.07 ± 0.15 | 1.81 ± 0.08 | 452 ± 218  | 84 ± 17  |
|                  | A + B + C         | 0.83 ± 0.06 | 1.50 ± 0.04 | 162 ± 16   | 82 ± 3   |
| 1995 Mar 25      | A                 | 0.97 ± 0.09 | 1.26 ± 0.05 | 112 ± 11   | 82 ± 3   |
|                  | B$^b$             | 0.88 ± 0.23 | 1.24 ± 0.15 | 112 ± 30   | 85 ± 9   |
|                  | B$^c$             | 1.25 ± 0.30 | 1.36 ± 0.14 | 137 ± 41   | 87 ± 11  |
|                  | C                 | 0.61 ± 0.12 | 1.48 ± 0.11 | 156 ± 44   | 81 ± 9   |
|                  | D                 | 0.94 ± 0.47 | 1.80 ± 0.26 | 163 ± 128  | 33 ± 19  |
|                  | A + C + D         | 0.67 ± 0.07 | 1.44 ± 0.06 | 133 ± 17   | 75 ± 4   |
| 1999 Apr 21A     | A                 | 1.35 ± 0.92 | 1.20 ± 0.39 | 87 ± 48    | 69 ± 5   |
|                  | B                 | 4.83 ± 0.94 | 1.83 ± 0.12 | 434 ± 281  | 74 ± 20  |
|                  | C                 | 9.88 ± 0.74 | 1.63 ± 0.05 | 303 ± 54   | 113 ± 8  |
|                  | D                 | 3.08 ± 0.53 | 1.33 ± 0.10 | 111 ± 19   | 75 ± 3   |
| 2002 Feb 24      | A                 | 2.28 ± 1.29 | 1.10 ± 0.34 | 63 ± 21    | 57 ± 3   |
|                  | B                 | 0.48 ± 0.40 | 0.89 ± 0.52 | 64 ± 32    | 71 ± 2   |
|                  | C                 | 2.73 ± 0.47 | 1.44 ± 0.11 | 121 ± 23   | 68 ± 2   |
|                  | A + B + C         | 2.38 ± 0.44 | 1.29 ± 0.11 | 88 ± 13    | 62 ± 1   |
| 2002 Mar 31      | A                 | 57 ± 5     | 2.50 ± 0.08 |             |           |
|                  | B                 | 155 ± 9    | 2.60 ± 0.05 |             |           |
|                  | A + B             | 107 ± 5    | 2.55 ± 0.04 |             |           |
| 2003 Feb 12      | A                 | 0.93 ± 0.47 | 1.31 ± 0.30 | 90 ± 37    | 61 ± 2   |

$^a$ See Figs. 2, 4, 5, 7–9.
$^b$ Multichannel spectrum.
$^c$ Three-channel spectrum.
1000 s were found in the BATSE data (Stern et al. 2001). The peak fluxes in the 50–300 keV range, 0.3–1.1 photons cm\(^{-2}\) s\(^{-1}\), were significantly higher than the average value of \(\sim 0.1\) photons cm\(^{-2}\) s\(^{-1}\). Transitions to the soft state lasting for several months were observed only a few times. According to the data of the all-sky monitor (ASM) on board the Rossi X-Ray Timing Explorer (RXTE/ASM; McConnell et al. 2002), the soft X-ray (2–10 keV) count rates increase from \(\sim 20\) to \(\sim 80\) counts s\(^{-1}\) after transitions to the soft state. From the BATSE and RXTE light curves we have ascertained that outbursts 950110, 950325, 990421A and B, and 030212 occurred while Cyg X-1 was in the hard state, whereas outbursts 020224 and 020331 arose from the soft state.

Broadband spectral observations of Cyg X-1 from numerous spacecraft and combinations of spacecraft have been used to comprehensively study the spectral shapes at various times in order to deduce the emission mechanism and the geometry of the regions emitting and reprocessing radiation (Mir-Kvant: Borkus et al. 1995; CGRO: Ling et al. 1997; Ginga and CGRO: Gierlinski et al. 1997; RXTE: Dove et al. 1998; ASCA, RXTE, and CGRO: Gierlinski et al. 1999; BeppoSAX: Frontera et al. 2001; and CGRO and BeppoSAX: McConnell et al. 2002). The accuracy of our data is insufficient for such a thorough analysis of source models. Rather, we have focused on obtaining the essential information on a new feature of Cyg X-1 activity from limited observational data using the simplest model spectra, namely, a power law \(AE^{-\alpha}\) or a power law with an exponential cutoff \(AE^{-\alpha}\exp(-E/E_0)\). Apart from the lack of high-resolution spectral data, the most serious difficulties in our data processing are connected with slow changes in the background level, especially in the low-energy ranges. Background count rates in the G1 window and, to a lesser extent in G2, are strongly affected by the activity of cosmic X-ray sources and vary, even when the Sun is quiet, by \(\pm 1\%\), averaged over hours and days. For this reason, for example, we do not attempt spectral fits for the long weak onsets of outbursts 950110 and 950325.

The intense stage of each outburst was subdivided into several time intervals in some concordance with the temporal behavior of the hardness ratio, as shown in Figures 2 and 4, 5, 6, 7, 8, and 9. Spectral parameters for all of these intervals were determined using the following procedure. The counts accumulated in energy band \(G_i\) (\(i = 1, 2, 3\)) can be
represented as an integral over an energy-loss spectrum,

\[
N_G = \int_{E_0} \left[ M \cdot f(A, E_0, \alpha) \right] \langle E \rangle dE
\]

using a model photon spectral function \( f \) and the detector response matrix \( M \). The resulting system of three equations with unknowns \( A, \alpha, \) and \( E_0 \) was solved by the Marquardt-Levenberg method, and the uncertainties in the parameters were calculated from the covariance matrix. In the case of the exponentially attenuated power law, parameters \( \alpha \) and \( E_0 \) are strongly correlated. The peak energy \( E_p \) is a more robust characteristic for a \( \nu F_\nu \) spectrum. Estimates of the errors in the spectral parameters were checked by numerical simulations, i.e., by introducing Poissonian-distributed deviations to the count rates \( G_1, G_2, \) and \( G_3 \), applying the procedure described above, and analyzing the distributions of the spectral parameters. The results of the simulations are in very good agreement with estimates from the covariance matrix.

All of these data are collected in Table 2, which includes an additional interval \( B^* \) for 950325. This interval, where \( G_1, G_2, \) and \( G_3 \) data were available, partially overlaps interval \( B \). From this it is evident that the parameters obtained by both methods agree well to within their uncertainties. The 15–300 keV fluences and peak fluxes for all the outbursts are consistent with the values for the 15–300 keV peak fluxes and peak fluxes in Table 2 for the first four outbursts and the seventh one. Many authors have interpreted them as thermal Comptonization with an optical depth \( \tau_T \approx 1 \) and an electron temperature \( \sim 50–100 \) keV (for recent studies see Maccarone & Coppi 2002).

### Table 3

**Fluences and Peak Fluxes from Konus-Wind**

| Date            | Time Interval (s UT) | 15–300 keV Fluence (ergs cm\(^{-2}\)) | 15–300 keV Peak Flux (photons cm\(^{-2}\) s\(^{-1}\)) | Peak Luminosity at 2 kpc (ergs s\(^{-1}\)) |
|-----------------|----------------------|---------------------------------------|---------------------------------------------------|------------------------------------------|
| 95 Jan 10       | 21,712–46,215        | 4.5 \times 10\(^{-4}\)               | 2.4                                               | 9.1 \times 10\(^{37}\)                 |
| 95 Mar 25       | 22,331–42,635        | 2.8 \times 10\(^{-4}\)               | 1.3                                               | 4.6 \times 10\(^{37}\)                 |
| 99 Apr 21A      | 54,514–56,613        | 1.8 \times 10\(^{-4}\)               | 3.8                                               | 1.4 \times 10\(^{38}\)                 |
| 02 Feb 24       | 54,609–64,583        | 8.0 \times 10\(^{-4}\)               | 3.7                                               | 1.3 \times 10\(^{38}\)                 |
| 02 Mar 31       | 35,926–36,835        | 4.7 \times 10\(^{-4}\)               | 2.4                                               | 6.2 \times 10\(^{37}\)                 |
| 03 Feb 12       | 64,982–70,775        | 1.8 \times 10\(^{-4}\)               | 1.6                                               | 5.3 \times 10\(^{37}\)                 |

The soft and hard states of Cyg X-1 and other galactic black hole candidates have comparable bolometric luminosities but different energy spectra (e.g., Ling et al. 1997; Zdziarski et al. 2002). The hard X-ray spectra of these sources are typically characterized by a power law with an exponential cutoff with a photon index \( \alpha \sim -1.6 \) and a cutoff energy \( E_0 \sim 150 \) keV (Philsps et al. 1996; Gierlinski et al. 1997; Dove et al. 1998), which are consistent with those in Table 2 for the first four outbursts and the seventh one. The parameters \( \alpha \) and \( E_0 \) of the peak luminosity in these outbursts approaches one-tenth of the Eddington luminosity for an object with \( M/M_\odot \sim 10 \).

The model for transitions between the soft and hard states discussed in a number of recent works is based on the idea of accretion disk transformations. In the soft state the accretion proceeds via a standard optically thick accretion disk (Shakura & Sunyaev 1973) emitting a blackbody soft X-ray peak and a nonthermal tail resulting from coronal activity in the disk. In the hard state the inner part of the disk is thought to form a hot, geometrically thick corona (see, e.g., Barrio, Done, & Nayakshin 2003; Poutanen, Krolik, & Ryde 1997 and references therein) with a moderate \( \tau_T \approx 1 \) optical depth. The outer region of the disk, beyond a few tens to 100 gravitational radii, still remains optically thick, emitting a cooler \((0.1–0.2 \) keV) and weaker blackbody component. The physical grounds for such a transformation could be a transition of the inner part of the disk into a regime balancing between advection-dominated accretion flow and standard disk modes (Esin et al. 1998). However, such a regime requires a fine-tuning that would clearly be violated during giant outbursts (Stern et al. 2001).

An alternative to disk accretion for the case of the hard state could be accretion of the companion wind with a near-critical angular momentum (Illarionov & Sunyaev 1975). Then, instead of a standard optically thick disk, a small-scale disk with \( \tau_T \sim 1 \) can appear. This scenario can naturally describe the hard-state spectrum (Beloborodov & Illarionov 2001) in terms of thermal Comptonization in the small disk within a few gravitational radii. No difficulties with the large observed variabilities arise in this model.

The absence of a clear correlation between luminosity and hardness is noteworthy. Actually, the presence of a luminosity-hardness correlation or anticorrelation depends on many details, including the geometry of the emission.

### Table 2

| Date            | Time Interval (s UT) | 15–300 keV Fluence (ergs cm\(^{-2}\)) | 15–300 keV Peak Flux (ergs cm\(^{-2}\) s\(^{-1}\)) | Peak Luminosity at 2 kpc (ergs s\(^{-1}\)) |
|-----------------|----------------------|---------------------------------------|---------------------------------------------------|------------------------------------------|
| 95 Jan 10       | 21,712–46,215        | 4.5 \times 10\(^{-4}\)               | 2.4                                               | 9.1 \times 10\(^{37}\)                 |
| 95 Mar 25       | 22,331–42,635        | 2.8 \times 10\(^{-4}\)               | 1.3                                               | 4.6 \times 10\(^{37}\)                 |
| 99 Apr 21A      | 54,514–56,613        | 1.8 \times 10\(^{-4}\)               | 3.8                                               | 1.4 \times 10\(^{38}\)                 |
| 02 Feb 24       | 54,609–64,583        | 8.0 \times 10\(^{-4}\)               | 3.7                                               | 1.3 \times 10\(^{38}\)                 |
| 02 Mar 31       | 35,926–36,835        | 4.7 \times 10\(^{-4}\)               | 2.4                                               | 6.2 \times 10\(^{37}\)                 |
| 03 Feb 12       | 64,982–70,775        | 1.8 \times 10\(^{-4}\)               | 1.6                                               | 5.3 \times 10\(^{37}\)                 |

The main conclusions that can be drawn from these data are the following.

1. An exponential cutoff is essential when fitting outbursts arising from the hard state. The parameters \( \alpha \) and \( E_0 \) for these outbursts are consistent with the values for the hard state of Cyg X-1 reported in the literature.

2. The spectra of the 2002 soft-state outbursts are softer in our energy range. The photon spectra of 020331 are well-fitted by a single-slope power law with \( \alpha \sim 2.6 \), which is certainly softer than any spectrum observed in the hard state. The spectrum of 020224 have an intermediate shape and display a low \( E_0 \) with large uncertainties in \( \alpha \).

3. The hardness ratio \( G_2/G_1 \) varies slightly during outbursts, but it does not display any clear correlation with the luminosity. The only exception is observed in 990421B, where the hardness decreases substantially at the peak (see Stern et al. 2001).

4. In general, it seems that giant outbursts maintain the spectral parameters, and hence emission mechanism, of the current underlying spectral state of Cyg X-1, even though the 15–300 keV peak fluxes are up to 10 times higher than the persistent emission fluxes. The corresponding fraction of the peak luminosity in these outbursts approaches one-tenth of the Eddington luminosity for an object with \( M/M_\odot \sim 10 \).
region, the soft radiation, and pair production. If the Comptonizing plasma is pair-dominated, then the temperature is a weak function of the luminosity; pair production provides a thermostatic effect (see, e.g., Malzac, Beloborodov, & Poutanen 2001). The spectrum in this case is softer at higher luminosities (if the geometry is fixed), but the dependence is weak (Stern et al. 1995). A luminosity-hardness anticorrelation is expected, but we do not observe it because of statistics.

What triggers the giant outbursts? The normal time variability of Cyg X-1 has a broad power-density spectrum that probably arises from instabilities in the disk. The outbursts do not appear to display the same variability pattern; moreover, they show similar temporal behaviors in the hard and soft states, which correspond to different states of the disk. Therefore, they are unlikely to originate because of an intrinsic disk effect. The most straightforward suggestion, and the one that we adopt as a working hypothesis, is that this could be some rare eruptive phenomenon in the donor wind ejection. The typical dynamical timescale for standard disk accretion in the case of Cyg X-1 is much longer than the duration of the outbursts so that any fluctuations in the donor ejection rate would be dilated by up to a day or more (G. S. Bisnovaty-Kogan 2002, private communication). Direct wind accretion, on the other hand, has a dynamical timescale ~1000 s, but a shorter timescale can arise from instabilities in the accreting flow (A. F. Illarionov 2002, private communication).

Other interpretations are possible. For example, the outbursts could be attributed to the recently discovered jet of Cyg X-1 (Stirling et al. 2001), and their recurrence could be explained by its precession (Romero et al. 2002).

4. CONCLUSION

The outbursts reported here have durations comparable to the period of a low Earth-orbiting spacecraft, making them difficult to detect and follow from experiments on board such spacecraft but relatively easy for experiments that are far from Earth and do not undergo occultation and orbital background variations. Indeed, our observations of 990421A show that it continues well beyond the point at which it was Earth-occulted to BATSE, and our observations of 990421B indicate that it commenced several hundred seconds before it rose on BATSE (Stern et al. 2001). These observations point to a new use for the IPN, namely, tracking long, intense flares from galactic transients. The data from a single experiment that has little or no directional and/or spectral information are easily confused with solar X-ray and particle events, which explains why it has taken so long to determine the origin of some of the outbursts presented here. However, confirmation by a second spacecraft solves this problem and gives an annulus of position that in many cases may be sufficient to determine the origin of the emission. For several outbursts, the BATSE observations alone yield source directions that are only accurate to 17°, leaving the possibility that the source could have been Cyg X-3. However, relatively small error ellipses may be obtained from multiple observations, and our localizations rule this possibility out conclusively.

The histories of Cyg X-1 and GRBs have been curiously intertwined over the decades. In the early days of X-ray astronomy, the use of interplanetary spacecraft was suggested to localize sources with rapid time variations such as Cyg X-1 (Giacconi 1972). Although, to our knowledge, such measurements were never carried out on persistent X-ray sources, today the technique is the basis of the IPN, and the present observations demonstrate the feasibility of this suggestion. Later, Mason, McNamara, & Harrison (1997) pointed out that bursts from Cyg X-1 could appear in the BATSE database; BATSE has indeed triggered many times on this source. Some of the long outbursts presented here have time histories that, if compressed in time, would be virtually impossible to distinguish from those of GRBs, and their spectra are hard. These similarities suggest that accretion onto a black hole, which is believed to power both Cyg X-1 and GRBs, albeit under very different circumstances, may manifest itself in similar ways in very different settings.

Support for the *Ulysses* GRB experiment is provided by JPL contract 958056, and *Konus-Wind* is supported by a Russian Aviation and Space Agency contract and RFRB grant N 03-02-17517. We are grateful to Al Levine and the ASM/RXTE team for quick-look results on Cyg X-1 and to Andrei Illarionov for useful discussions. This research has made use of the SIMBAD database, operated at the Centre de Données Astronomiques de Strasbourg, France.

REFERENCES

Barrio, F. E., Done, C., & Nayakshin, S. 2003, MNRAS, 342, 557
Beloborodov, A. M., & Illarionov, A. F. 2001, MNRAS, 323, 167
Bolton, C. T. 1972, Nature, 235, 271
Borkus, V., et al. 1995, Astron. Lett., 21, 794
Bowyer, S., Byram, E. T., Chubb, T. A., & Friedman, M. 1965, Science, 147, 384
Bre RockSopp, C., Tarasov, A. E., Luty, V. M., & Roche, P. 1999, A&A, 343, 861
Cui, W., Feng, Y-X., & Ertmer, M. 2002, ApJ, 564, L77
Cui, W., Feng, Y-X., & Ertmer, M. 2002, ApJ, 564, L77
Dove, J., Wilms, J., Nowak, M., Vaughn, B., & Begelman, M. 1998, MNRAS, 298, 729
Esin, A., Narayan, R., Cui, W., Grove, J. E., & Zhang, S-N. 1998, ApJ, 505, 854
Frontera, F., et al. 2001, ApJ, 546, 1027
Giacconi, R. 1972, ApJ, 173, L79
Gierlinski, M., & Zdziarski, A. 2003, MNRAS, 343, L84
Gierlinski, M., Zdziarski, A., Poutanen, J., Coppi, S., Ebisawa, K., & Johnson, W. 1999, MNRAS, 309, 496
Gierlinski, M., et al. 1997, MNRAS, 288, 938
Gies, D., & Bolton, C. 1986, ApJ, 304, 371
Golenetskii, S., Aptekar, R., Mazets, E., Frederiks, D., Cline, T., Hurley, K., & Briggs, A. 2002a, IAU Circ., 7840, 1

No. 2, 2003 OBSERVATIONS OF GIANT OUTBURSTS FROM CYG X-1 1119

Ling, J., Mahoney, W., Wheaton, W., & Jacobson, A. 1987, ApJ, 321, L117
Ling, J., et al. 1997, ApJ, 484, 375
Maccarone, T., & Coppi, P. 2002, MNRAS, submitted (astro-ph/0204235)
Malzac, J., Beloborodov, A. M., & Poutanen, J. 2001, MNRAS, 326, 417
Mason, P., McNamara, B. & Harrison, T. 1997, AJ, 114, 238
Mazets, E. 1995, in AIP Conf. Proc., 384, Gamma-Ray Bursts, ed. C. Kouveliotou, M. Briggs, & G. J. Fishman (New York: AIP), 492
McConnell, M., et al. 2002, ApJ, 572, 984
Petterson, J. 1978, ApJ, 224, 625
Philips, B. 1995, in GCN Circ., 1176, leaves the possibility that the source could have been Cyg X-3. However, relatively small error ellipses may be obtained from multiple observations, and our localizations rule this possibility out conclusively.

The histories of Cyg X-1 and GRBs have been curiously intertwined over the decades. In the early days of X-ray astronomy, the use of interplanetary spacecraft was suggested to localize sources with rapid time variations such as Cyg X-1 (Giacconi 1972). Although, to our knowledge, such measurements were never carried out on persistent X-ray sources, today the technique is the basis of the IPN, and the present observations demonstrate the feasibility of this suggestion. Later, Mason, McNamara, & Harrison (1997) pointed out that bursts from Cyg X-1 could appear in the BATSE database; BATSE has indeed triggered many times on this source. Some of the long outbursts presented here have time histories that, if compressed in time, would be virtually impossible to distinguish from those of GRBs, and their spectra are hard. These similarities suggest that accretion onto a black hole, which is believed to power both Cyg X-1 and GRBs, albeit under very different circumstances, may manifest itself in similar ways in very different settings.
Stern, B., Poutanen, J., Svensson, R., Sikora, M., & Begelman, M. 1995, ApJ, 449, L13
Stirling, A., Spencer, R., de la Force, C., Garrett, M., Fender, R., & Ogley, R. 2001, MNRAS, 327, 1273
Terekhov, M., Aptekar, R., Frederiks, D., Golenetskii, S., Il’inskii, V., & Mazets, E. 1998, in AIP Conf. Proc. 428, Gamma-Ray Bursts, ed. C. Meegan, R. Preece, & T. Koshut (New York: AIP), 894
Webster, B. L., & Murdin, P. 1972, Nature, 235, 37
Zdziarski, A., Poutanen, J., Paciesas, W., & Wen, L. 2002, ApJ, 578, 357
Zhang, S., Cui, W., Harmon, A., Paciesas, W., Remillard, R., & van Paradijs, J. 1997, ApJ, 477, L95