A SEQUENCE OF DECLINING OUTBURSTS FROM GX 339−4

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ABSTRACT

The flux and spectrum of the black hole candidate GX 339−4 has been monitored by the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory since the observatory became operational in 1991 May. Between the summer of 1991 and the fall of 1996, eight outbursts from GX 339−4 were observed. The history of these outbursts is one of declining fluence or total energy release, as well as a shortening of the time between outbursts. A rough linear correlation exists between the fluence emitted during an outburst and the time elapsed between the end of the previous outburst and the beginning of the current one. The peak flux is also roughly linearly correlated with outburst fluence. The light curves of the earlier, more intense, outbursts (except for the second one) can be modeled by a fast exponential (time constant ∼10 days) followed by a slower exponential (∼100 days) on the rise and a fast exponential decay (∼5 days) on the fall. The later, weaker, outbursts are modeled with a single, rising time constant (∼20 days) and a longer decay on the fall (∼50 days). An exponential model gives a marginally better fit than a power law to the rise/decay profiles. GX 339−4 is a unique source in having more frequent outbursts than other low-mass X-ray binary black hole candidates. These observations can be used to constrain models of the behavior of the accretion disk surrounding the compact object.

Subject headings: binaries: general — black hole physics — stars: individual (GX 339−4) — X-rays: stars

1. INTRODUCTION

Much effort has been made to study the X-ray source GX 339−4 since its original discovery by OSO-7 (Markert et al. 1973). GX 339−4 is usually considered a black hole candidate (BHC) owing to the similarity of its X-ray spectral and timing states to dynamical BHCs, such as Cyg X-1, and to the lack of detection of pulsations or X-ray bursts. However, there is considerable uncertainty about the mass of the compact object, and GX 339−4 is not at this time a dynamical BHC (Callanan et al. 1992). However, it is similar to the two established jet sources GRS 1915+105 and GRO J1655−40, the latter being a dynamical BHC, in exhibiting multiple hard X-ray outbursts. The recent report of a weak radio jet in GX 339−4 (Fender et al. 1997) (the velocity of the jet is essentially unknown) is a hint that these three sources may be fundamentally similar (Zhang et al. 1998). The existence of the radio jet requires confirmation from future observations.

Most X-ray observations of GX 339−4 have focused on determining which of four X-ray spectral states (off, low, high, very high) the source is in and describing the properties of those states (Motch et al. 1985; for a recent review, see Tanaka & Lewin 1995). Here we will present new data from six recent outbursts observed by CGRO-BATSE. Our analysis will also include two earlier outbursts observed by BATSE (Harmon et al. 1994). The eight outbursts observed by BATSE can be roughly divided into two types based on the outburst fluence, light curve, spectral evolution, and recurrence pattern. In these respects, the first four outbursts appear to be different from the last four.

More important than this classification, however, is the observation that the general pattern of these outbursts is one of decreasing total energy release, as subsequent outbursts occur closer together in time, so that outburst fluence in the 20−300 keV band is correlated with the time elapsed since the previous outburst.

2. OBSERVATIONS

Figure 1 shows the BATSE flux history obtained using the Earth occultation technique and an optically thin thermal bremsstrahlung (OTTB) spectral model fit to the observed count rates in the 20−300 keV band. The functional form of the OTTB model used is $A \exp(-E/kT)/E$, where $E$ is the photon energy in kilo-electron volts and the amplitude, $A$, and temperature, $kT$ (in kilo-electron volts), are determined from the fit. The observational techniques are described in Harmon et al. (1994).

Figure 1 shows eight outbursts separated by intervals during which the source was not detected above the $\sim 30$ mcrab threshold for 10 day integrations. We will label these outbursts B1−B8. The first three outbursts have similar light curves and recur at an approximately periodic interval of $\sim 450$ days. However, neither the profiles nor the recurrence intervals of the later outbursts, especially the last four, show evidence of being related to the earlier outbursts. Information on outburst beginning and ending times, peak fluxes and times, and total fluences appears in Table 1.

Three spectral models, OTTB, photon power law (PL), and Sunyaev-Titarchuk comptonization (ST) (Sunyaev & Titarchuk 1980), were fit to the data over 20−300 keV. An OSSE observation near the peak of B1 was consistent with an OTTB model ($kT \approx 70$ keV) over the full energy range in which the source was detected (up to 400 keV), but it was inconsistent with PL and a marginal fit at best to ST above 200 keV (Grebelsky et al. 1995). During almost all of B1−B4, PL gives unacceptable fits to the BATSE data, while the OTTB and ST models are both adequate and fit equally well. Table 2 shows a comparison of PL and OTTB model fits during selected intervals. While an OTTB model also always works during B5−B8, there are also times during these outbursts when PL gives equally good fits. During these times, the possibility that the spectrum is a power law that also extends to higher energies...
can not be ruled out, though it is also possible that an OTTB spectrum is always correct.

The spectral evolution during each outburst is presented in a plot of OTTB-fit temperature versus time in Figure 2. During outbursts B1–B4, the temperature peaked early and declined gradually. In contrast, it remains roughly constant during B5–B8.

3. ANALYSIS OF THE OUTBURST PATTERN

We have used the information in Table 1 to examine the possibility of correlations between the outburst fluence, peak flux, duration, and time between outbursts.

The left-hand panel of Figure 3 shows that peak flux is roughly linearly correlated with the total outburst fluence, over a factor of 3.5 in each parameter, as first reported in Robinson et al. (1996). Peak outburst luminosities depend on source distance, which has been estimated between 1.3 kpc (Predehl et al. 1991) and 4 kpc (Cowie et al. 1987). The peak luminosities range from $2.2 \times 10^{38} d_{\text{kpc}}^2$ ergs s$^{-1}$ for B5 to $7.6 \times 10^{37} d_{\text{kpc}}^2$ ergs s$^{-1}$ for B3, where $d_{\text{kpc}}$ is the source distance in kiloparsecs.

In the right-hand panel of Figure 3, the time elapsed since the previous outburst $T_{\text{pa}}$, the time between the end of the previous burst, $B(i-1)$, and the start time of $B_i$ is plotted versus outburst fluence. An approximate linear correlation between $T_{\text{pa}}$ and fluence is observed, with the possible exception of B5, which appears underluminous for this relation. If we consider instead the time until the next outburst, the deviations of B1 and B3 from the trend are quite large. Thus, taking the time since the previous outburst as the underlying variable correlated with outburst energy release is the better description of source behavior. This correlation implies that the time-averaged luminosity, $L = 1.6 \times 10^{38} d_{\text{kpc}}^2$ ergs s$^{-1}$, is roughly constant. Outburst durations show no clear trend when plotted against fluence.

4. OUTBURST TIMESCALES

Spectral fits in which flux is the only free parameter were used to obtain a flux estimate for each day of data. In each fit, the temperature is held fixed at the temperature determined from the corresponding 10 day spectral fit. We have attempted to model the first, third, and fourth outbursts with an initial fast exponential rise followed by a second, much slower, rise. The second outburst and the last four outbursts have only a single rise, and each outburst has a single decay.

Figure 4 shows the 1 day resolution light curves of B1 and B5. Information about rise and decay times of all of the outbursts is given in Table 3. In each case, the rise (including variable break time) and decay intervals were fit separately.

For comparison, we have also fit power-law models to each rise/decay portion of the light curve. F-test probabilities that the power-law model is preferred range from 3% to 85% and are typically about 30%. Only on the fall of B1 and the rise

| Outburst | Beginning Time (JD -2,440,000.5) | Ending Time (JD -2,440,000.5) | Peak Time* (JD -2,440,000.5) | Peak Flux* (photons cm$^{-2}$ s$^{-1}$) | Fluence (ergs cm$^{-2}$) |
|----------|-------------------------------|-----------------------------|-----------------------------|--------------------------------|------------------------|
| B1 ...... | 8437                          | 8537                        | 8505                        | 0.107 ± 0.002                     | 0.038                  |
| B2 ...... | 8887                          | 8982                        | 8958                        | 0.086 ± 0.002                     | 0.048                  |
| B3 ...... | 9345                          | 9438                        | 9398                        | 0.106 ± 0.001                     | 0.054                  |
| B4 ...... | 9620                          | 9691                        | 9658                        | 0.077 ± 0.001                     | 0.032                  |
| B5 ...... | 9851                          | 9937                        | 9865                        | 0.040 ± 0.001                     | 0.014                  |
| B6 ...... | 9956                          | 10025                       | 9956                        | 0.036 ± 0.002                     | 0.016                  |
| B7 ...... | 10107                         | 10168                       | 10126                       | 0.043 ± 0.001                     | 0.016                  |
| B8 ...... | 10268                         | 10347                       | 10288                       | 0.043 ± 0.001                     | 0.023                  |

* Peak fluxes in each outburst are calculated as the largest average of three consecutive time integrations. Peak times are at the center of these averages.
of B3 is this probability above 50%. Exponential models are thus marginally preferred.

5. DISCUSSION

In the past, GX 339–4 has been mostly observed sporadically by pointed instruments, which makes it difficult to discern any long-term outburst pattern. Our analysis suggests that during the observations presented here, there is a pattern in hard X-rays consisting of a sequence containing two types of outbursts with declining fluence in the 20–300 keV band.

Nearly continuous observations made with the *Ginga* all-sky monitor in the 1–20 keV band between early 1987 and the fall of 1991 indicate that this hard X-ray pattern may also be followed in soft X-rays (Kitamoto 1992). During this time, *Ginga* observed three outbursts that also follow a pattern of declining fluence and that could be an earlier part of the sequence observed by BATSE. The first and brightest outburst occurred after a long quiet period (>1.5 yr). During this outburst, the very high state was observed, probably the only time it has been observed in this source. The third outburst, which occurred near the end of the operational life of *Ginga* and which was only partially observed, was coincident with B1. A hard-to-soft transition occurred ~50 days into this outburst, but there was otherwise no unusual soft X-ray activity. These observations suggest the possibility that the first outburst observed by *Ginga* initiated the subsequent declining sequence. However, determining whether and to what extent the patterns observed here in the BATSE data are also relevant below 20 keV, and in particular the effect of X-ray spectral state changes, will require more careful analysis of existing multi-instrument data.

For a constant mass accretion rate from the companion into an accretion disk, the correlation between fluence and recurrence time found here implies that just the excess mass that accumulates in the disk between outbursts falls into the compact object during the outbursts. The rise and decay profiles of the outbursts are related to how the matter passes through the disks and therefore to the properties of nonstationary accretion disks. For example, exponential timescales in nonstationary disks have been shown to imply a linear relation between the diffusion coefficient and surface density; a nonlinear relation would imply power-law profiles (Liubarskii & Shakura 1987).

A thermal instability in an outer thin disk can account for the recurrence, rise, and decay times of soft X-ray transients (SXT) (Mineshige 1996). The outburst recurrence time is identified with the viscous timescale in the "cool" (low α) branch of the outer disk and the decay timescale with the "hot" branch (α is the dimensionless viscosity). Thus, $t_{\text{vis}} = \ldots$

### Table 2

| Outburst* | Timesb | OTTB Temperature | $\chi^2_{\text{OTTB}}$ | PL Indexc | $\chi^2_{\text{PL}}$ | $\nu^d$ |
| --- | --- | --- | --- | --- | --- | --- |
| B1 (R2) ...... 8504–8511 | 61 ± 3 | 20 | 2.4 | 94 | 16 |
| B2 (M) ...... 8950–8957 | 78 ± 5 | 33 | 2.2 | 65 | 25 |
| B3 (R2) ...... 9368–9384 | 70 ± 3 | 51 | 2.2 | 108 | 34 |
| B4 (R2) ...... 9643–9657 | 65 ± 3 | 59 | 2.2 | 79 | 34 |
| B5 (M) ...... 9874–9898 | 86 ± 7 | 93 | 2.1 | 93 | 70 |
| B6 (R) ...... 9951–9967 | 77 ± 9 | 16 | 2.2 | 23 | 16 |
| B7 (M) ...... 10126–10147 | 87 ± 6 | 45 | 2.0 | 79 | 46 |
| B8 (D) ...... 10308–10322 | 96 ± 22 | 41 | 2.0 | 47 | 32 |

* The portion of the outburst from which the data are drawn is given in parentheses; R equals rise, R2 equals second rise, M equals middle, and D equals decay.

b Tim es are in JD −2,440,000.5 (truncated Julian days).

c Uncertainties in the power-law index are 0.1 or less.

d The number of degrees of freedom in each of the spectral fits. Nine channels from each detector in each spacecraft pointing interval were used. Most of the fits encompass multiple pointing intervals.

Fig. 3.—Outburst parameters vs. outburst fluence in the 20–300 keV band. In each of these plots, the number near each data point labels the corresponding outburst (B1–B8). See Tables 1 and 3 for the values used in the plots. Left: outburst fluence vs. peak flux. Error bars are statistical only. The dotted line shows the best-fit straight line to the plotted data. Right: outburst fluence vs. time to the previous outburst, $T_p$. Vertical error bars are statistical only, and horizontal bars show an approximate uncertainty of 10 days in $T_p$. The dashed line is the best-fit straight line.

Fig. 4.—One-day-resolution outburst light curves and model fits. Top: B1. Time zero on the horizontal scale corresponds to JD 2,448,430. Bottom: B5. Time zero corresponds to JD 2,449,840. Vertical error bars are statistical only, and horizontal bars show the data integration interval. The solid lines show the exponential rise and decay models discussed in the text. The rise and decay timescales obtained from the fits are listed in Table 3.
inside the thin disk, then the fast rise time represents the propagation of the heating front throughout the disk, while the slow rise time is the viscous timescale on which the hot outer disk shrinks as it pushes matter into the inner disk. In this scenario, the first four outbursts are “inside-out” with a shrinking disk, while the last four, with behavior closer to SX T, may be “outside-in.” Time differences between the origin of optical and X-ray radiation at the beginning of an outburst can discriminate the direction of the outburst. For example, an outburst of GRO J1655−40 was seen to be outside-in (Orosz et al. 1997). Such observations are strongly encouraging.

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