LUMINOUS X-RAY FLARES FROM LOW-MASS X-RAY BINARY CANDIDATES IN THE EARLY-TYPE GALAXY NGC 4697

GREGORY R. SIVAKOFF,1 CRAIG L. SARAZIN,1 AND ANDRÉS JORDÁN2,3

Received 2005 January 28; accepted 2005 March 21; published 2005 March 29

ABSTRACT

We report results of the first search specifically targeting short-timescale X-ray flares from low-mass X-ray binaries in an early-type galaxy. A new method for flare detection is presented. In NGC 4697, the nearest, optically luminous, X-ray–faint elliptical galaxy, three out of 157 sources are found to display flares at >99.5% probability, and all show more than one flare. Two sources are coincident with globular clusters and show flare durations and luminosities similar to (but larger than) type I X-ray superbursts found in Galactic neutron star (NS) X-ray binaries (XRBs). The third source shows more extreme flares. Its flare luminosity (∼6 × 10^38 erg s⁻¹) is very super-Eddington for an NS and is similar to the peak luminosities of the brightest Galactic black hole (BH) XRBs. However, the flare duration (∼70 s) is much shorter than are typically seen for outbursts reaching those luminosities in Galactic BH sources. Alternative models for the flares are considered.

Subject headings: binaries: close — galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 4697) — X-rays: binaries — X-rays: bursts — X-rays: galaxies

1. INTRODUCTION

Galactic X-ray binaries (XRBs) exhibit a wide-range of short-timescale variability. X-ray bursts from XRBs were first studied in the mid-1970s (e.g., Grindlay et al. 1976; Belian et al. 1976). Type I bursts, found in low-mass X-ray binaries (LMXBs), are due to thermonuclear flashes on the neutron star (NS) surface with luminosities peaking at the Eddington limit. Eight bursts lasting several hours, but otherwise like type I bursts, have been observed (Kuulkers 2004). These superbursts are relatively rare and appear to recur on year timescales.

Short-timescale variability has also been seen in high-mass X-ray binaries (HMXBs). LMC X-4, an HMXB pulsar, has a persistent luminosity of ∼2 × 10^38 ergs s⁻¹ and super-Eddington flares (up to ∼2 × 10^39 ergs s⁻¹) with durations of ∼70 s (Moon et al. 2003). Since black holes (BHs) lack a surface, type I bursts do not occur. Typical short flares observed in BH XRBs tend to last on the order of days (McClintock & Remillard 2005) as opposed to minutes, as in NS XRBs; however, rapid flares have been seen (e.g., Greiner et al. 1996; Wijnands & van der Klis 2000). In GRS 1915+105, which has been relatively luminous (∼3 × 10^38 ergs s⁻¹) since its discovery, these rapid flares typically last for minutes or less, have peak-to-persistent flux ratios ≥10, and often recur on both regular and irregular intervals of minutes or less (Yadav et al. 1999). V4641 Sgr, an HMXB, showed variations of a factor up to 500 on the timescale of minutes (Wijnands & van der Klis 2000).

In this Letter, we perform the first search specifically targeting short-timescale flares from LMXBs in an early-type galaxy. Since nearby early-type galaxies have many bright LMXBs (>10^37 erg s⁻¹; e.g., Sarazin et al. 2000), they have a high potential for having sources with interesting flare behaviors. We targeted NGC 4697, the nearest (11.7 Mpc; Tonry et al. 2001) optically luminous (M_V < −20) elliptical galaxy. As an X-ray–faint galaxy (low L_x/L_B; most of its X-ray emission is resolved into 158 point sources (G. R. Sivakoff et al. 2005, in preparation, hereafter Paper IV). Five Chandra observations of NGC 4697 give extended time coverage for searching for variability. We discuss a new method for detecting flares in the low count regime and characterize short-timescale flares in three LMXBs. All errors refer to 90% confidence intervals. Count rates and fluxes are in the 0.3–10 keV band.

2. OBSERVATIONS AND DATA REDUCTION

Chandra has observed NGC 4697 five times (observations 0784, 4727, 4728, 4729, and 4730), 2000 January 15, 2003 December 26, 2004 January 6, February 2, and August 18, using the Advanced CCD Imaging Spectrometer S3 detector. After removal of background flares, ONTIME values were 37651, 40447, 36072, 32462, and 40574 s. All observations were analyzed under CIAO 3.1 with CALDB 2.28. We detected 158 point sources (G. R. Sivakoff et al. 2005, in preparation). The Chandra observations of NGC 4697 are among the most extended in this galaxy, making it similar to Jordań et al. (2004), leading to a list of globular clusters (GCs) and other optical sources. Details concerning the HST ACS observation, data analysis, and source properties will be given in A. Jordań et al. (2005, in preparation).

3. DETECTION OF FLARING SOURCES

A bright LMXB (10^38 erg s⁻¹) will have only ~25 counts in an ~40 ks Chandra observation of NGC 4697, making it difficult to search for intraobservation variability. Tests that require binning the events and the Kolmogoroff–Smirnov test are not useful for detecting flares with small numbers of events. Instead, we consider arrival times of individual events and compare them to a constant rate Poisson distribution. We searched for the shortest time t_n over which n consecutive pho-

1 Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903-0818; grs8g@virginia.edu, sarazin@virginia.edu.
2 European Southern Observatory, Karl-Schwarzschild-Strasse 2 85748 Garching bei München, Germany; ajordan@eso.org.
3 Astrophysics, Denys Wilkinson Building, University of Oxford, 1 Keble Road, Oxford, OX1 3RH, UK.
tons (hereafter an n-tuple) arrived. Assuming there are N photons in the entire ONTIME ($t_{\text{exp}}$), the probability that at least n photons are seen in $t_n$ because of Poisson fluctuations is given by the incomplete gamma function,

$$P(n \text{ in } t_n \text{ given } N \text{ in } t_{\text{exp}}) = \frac{1}{\Gamma(n-1)} \int_0^{N/N_{\text{exp}}} e^{-a}a^{n-2} da.$$  

(1)

Since we search $N-n+1$ n-tuples, the probability that the n observed photons are seen in $t_n$ are not due to random fluctuations is given by

$$P_{\text{flare}}(n) = (1 - P(n \text{ in } t_n \text{ given } N \text{ in } t_{\text{exp}}))^N - n + 1,$$  

(2)

assuming the n-tuples are independent. The probability that the flare resulted from a statistical fluctuation is $P_{\text{constant}}(n) = 1 - P_{\text{flare}}(n)$.

With each observation, we search through $N-1$ different sets of n-tuples; i.e., $n = 2$, $\ldots$, $N$. Thus, equation (2) overestimates the probability a detected flare of n photons is real. However, the $N-1$ sets of n-tuples are not independent. To derive accurate probabilities, we determined the number of false flares detected by our algorithm due to statistical fluctuations by running sets of >200,000 Monte Carlo simulations, assuming the source emitted at a constant rate. From the simulations, which were analyzed identically to the actual observations and included the effects of finite frame times, readout time, and background, we derived a correction factor to equation (2) to give the correct probability that a flare was real, $P'_{\text{flare}}$. We determined the ratio between $P_{\text{constant}}$ and $P_{\text{constant}}$ when $P_{\text{constant}} < 5\%$; this ratio $A(N) \equiv P_{\text{constant}}'P_{\text{constant}}$ depended only on the mean number of counts N for a set of simulations and was typically 2–3. We linearly interpolated between simulation sets with different N to find $P_{\text{constant}}$ for each flare. For each flaring source, we checked all n-tuples for other less probable but still significant flares within the same observation. We did not find multiple flares in the same observation. As a caveat, note that the use of the total observed counts in equation (1) creates a bias against detecting multiple intraobservation flares.

We found that several of the sources showed flares in different observations with similar properties. Detecting multiple flares from a source makes it even less likely that the flares are due to statistical fluctuations. Let $P'_{\text{constant}, i}$ be the probability that the most significant flare within a given observation $i$ is due to a statistical fluctuation. When $P_{\text{constant}, i} > 5\%$, we conservatively set $P'_{\text{constant}, i} = 1$. We only consider sequences of flares with properties that are all identical within the errors. With five observations, the joint probability that the flare sequence is a statistical fluctuation is

$$P_{\text{constant, joint}} = \left(\frac{5}{k}\right)\prod_{i=1}^{5} P'_{\text{constant, i}}$$  

(3)

where k is the number of observations with $P_{\text{constant, i}} < 5\%$.

Whenever $P_{\text{constant, joint}} < 0.32\%$, we considered a source to be a flaring source. At this level, we expect <0.5 sources with apparent flares due to random fluctuations; in actuality, we find four sources with significant flares, all of which have joint probabilities more consistent with <0.1 sources being due to random fluctuations.

One of the significant flaring sources is CXOU J124836.3–055333, one of the brightest objects in our sample [($\sim$5–9) x \(10^{-14}\) ergs s$^{-1}$ cm$^{-2}$]. This source is within 0.5 of a Galactic star, TYC 4955-1175-1, and is very likely to be associated with this star; we exclude it from further discussion since it is unlikely to be an LMXB in NGC 4697.

In Table 1, we list observed properties of the significant flaring sources associated with NGC 4697. Columns (1)–(4) list the source name, position, and observation number in which the flare occurred. Columns (5)–(8) list the total number of events N from the source during this observation, the number of events in the flare $n$, the flare duration $\Delta t$, and the Modified Julian Date (MJD) of the first event, $t_0$. Column (9) lists the probability that a given n-tuple is a statistical fluctuation, and column (10) gives the probability, including all of the n-tuples that were searched. Column (11) gives the joint probability that sequences of similar flares during several observations are all just statistical fluctuations.

For each event in a flaring source, we examined the chip coordinates and ASCA grades to eliminate previously unknown flickering pixels as possible false-positive flares. Although the four flare events in observation 0784 of source C occur at only two chip positions, their ASCA grades (2 and 0, 6 and 2) indicate that they are unlikely to be due to flickering pixels. We note that the time intervals between events at the same chip positions in observation 0784 of source C are 6.4 and 12.8 s, much less than the aspect motion periods. Thus, it is likely that subsequent events from the same source can occur at the same detector position. The other sources, which all had longer flare durations, did not have duplicate chip positions in their flares.

**TABLE 1**

| Source Name (1) | R.A. (2) | Decl. (3) | Obs. (4) | N (5) | $\Delta t$ (6) | $t_0$ (7) | $P_{\text{constant}}$ (8) | $P_{\text{constant}}$ (9) | $P_{\text{constant, joint}}$ (10) |
|----------------|---------|-----------|---------|-------|---------------|----------|--------------------------|--------------------------|------------------------------|
| CXOU J124837.8–054652 (source A) ....... 12 48 37.86 −05 46 52.9 | 0784 | 14 | 5 | 1047 | 51,558.79424 | 0.700 | 1.787 |
| | 4727 | 16 | 4 | 628 | 52,999.75883 | 2.729 | 7.006 |
| | 4729 | 14 | 4 | 509 | 53,010.70296 | 1.212 | 3.096 |
| | 0784, 4727, 7278 | 0.039 |
| CXOU J124831.0–054828 (source B) ....... 12 48 31.04 −05 48 28.8 | 4727 | 9 | 5 | 1329 | 53,000.43427 | 0.224 | 0.552 |
| | 4728 | 9 | 4 | 1420 | 53,010.72445 | 3.368 | 7.982 |
| | 4729 | 6 | 5 | 5654 | 53,047.59917 | 4.327 | 9.007 |
| | 4727, 4728, 7278 | 0.441 |
| CXOU J124839.0–054750 (source C) ....... 12 48 39.03 −05 47 50.2 | 4727 | 20 | 4 | 68 | 51,558.97571 | 0.013 | 0.034 |
| | 4728 | 20 | 3 | 50 | 53,000.05857 | 0.547 | 1.420 |
| | 0784, 4727 | 0.005 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
It is likely that the observed flare duration underestimates the actual duration because of the small number of photons detected and that other properties may be biased by the flare detection algorithm. On the other hand, if a photon due to emission outside of the flare duration arrives just before or after a flare, this could lead to an overestimate of the flare properties. To assess these effects, we adopted a simple model for the temporal development of the flare and used Monte Carlo simulations to derive the best-fit model flare parameters and their uncertainties. For the flare, we used a top-hat model, characterized by a constant flare rate, \( r_{\text{flare}} \), over a burst duration, \( \Delta t_{\text{flare}} \) beginning at a given time, \( t_{\text{0,flare}} \). Outside of the flare duration, we assumed a constant persistent source rate \( r_{\text{persistent}} \). For a given model flare rate \( r_{\text{flare}} \), duration \( \Delta t_{\text{flare}} \) and beginning time \( t_{\text{0,flare}} \), we performed 200,000 Monte Carlo simulations. We varied the model parameters until we found the model that was most likely to have reproduced the observed flare properties. For this best-fit model, the symmetric 90% confidence region for each model parameter was determined from the simulations. The rates and durations were used to calculate X-ray luminosities and fluences for each observation using conversion factors based on the best-fit model for the cumulative X-ray spectrum of all the sources (a power-law with \( \Gamma = 1.47 \); Paper IV). The spectral model was corrected for Galactic absorption and the quantum efficiency degradation for each observation.

In Table 2, we list the best-fit model properties of the flaring sources. Columns (1) and (2) list the source name and observation number. Columns (3)–(8) list the best-fit flare properties: number of flare photons (\( n_{\text{flare}} \)), flare rate (\( r_{\text{flare}} \)), flare duration (\( \Delta t_{\text{flare}} \)), ratio of flare rate to persistent rate, flare luminosity (\( L_{\text{flare}} \)), and flare fluence (\( E_{\text{flare}} \)). Rows with multiple observations listed display the averages of the flare duration, ratio of flare rate to persistent rate, flare luminosity, and flare fluence of the matching flares.

Given our limited temporal coverage, it is difficult to place strong limits on the recurrence timescale (\( \Delta T \)) of the flares. Our simulations show that the probability that our algorithm will detect a flare is only \( \sim 50\% \). However, the fact that two flares were not seen in any single observation and that there are observations without observed flares for each of the sources implies that \( \Delta T \approx 5 \) hr. One upper limit on \( \Delta T \) is given by the shortest observed time between observations with flares; this is 11 days for sources A and B, and 1441 days for source C. However, detections of flares in two or three out of five observations lasting \( \sim 10 \) hr suggest that the recurrence time is much shorter than this, \( \Delta T \approx 10 \) hr. One caveat is that it is possible that most of the LMXBs in NGC 4697 are undergoing flares with a longer recurrence timescale, and we have just selected the three sources where flares occurred within several of our observing windows.

4. DISCUSSION

4.1. CXOU J124837.8–054652 (Source A) and CXOU J124831.0–054828 (Source B): Type I X-Ray Superbursts?

Sources A and B both show similar flares, with average durations of \( 844^{+1399}_{-1105} \) and \( 3155^{+1012}_{-871} \) s, respectively. In source B, the longer flare in observation 4729 is less probable; however, the error bars of all its inferred properties overlap with the error bars of the other flares in source B. If one removed the observation 4729 flare, the average flare duration decreases to \( 1573^{+1425}_{-1305} \) s. Although the durations are larger than typical type I bursts, they are consistent within the uncertainties with type I superbursts. Since type I bursts are Eddington-limited, observations of distant galaxies may be selecting for longer bursts, given the small numbers of photons in each burst. Thus, we may be observing relatively rare, extreme forms of type I superbursts.

The average luminosities for the flares in sources A and B are \( 5.8^{+2.5}_{-1.3} \times 10^{38} \) erg s\(^{-1} \), respectively, higher than the Eddington luminosity of \( 1.4 \times 10^{38} \) erg s\(^{-1} \). If one removed the observation 4729 flare from source B, the average flare luminosity increases to \( 3.8^{+0.9}_{-0.6} \times 10^{38} \) erg s\(^{-1} \). The reported luminosities are for the 0.3–10 keV band, and the bolometric luminosities would be even higher. Furthermore, the uncertainties quoted do not include the systematic uncertainty in the distance to NGC 4697 (although this is smaller than the statistical uncertainties) or in the spectral model for the source. Typically, Galactic type I bursts can be modeled as \( \sim 2 \) keV blackbodies; if this model were used, the observed luminosities would increase by a factor of \( \sim 2.7 \).

The average flues of the flares in these two sources are \( 4.3^{+1.4}_{-1.2} \) and \( 6.0^{+2.6}_{-1.7} \times 10^{39} \) ergs, respectively. Assuming the flares are powered by the fusion of hydrogen and that the thermonuclear efficiency to the iron-peak elements is 0.007–0.01 (Lewin et al. 1995), this requires the accretion of \( \sim 4 \times 10^{11} M_{\odot} \). For accretion of helium and an efficiency of 0.002–0.01, the mass is \( \sim 1 \times 10^{10} M_{\odot} \). The persistent luminosities of the sources are \( \sim 4 \times 10^{37} \) erg s\(^{-1} \), respectively, implying accretion rates of \( \sim 4 \) and \( \sim 1 \times 10^{-9} M_{\odot} \) yr\(^{-1} \) for an NS. Thus, it would require days to weeks to build up a layer sufficient to produce the observed flares as thermonuclear flashes. As noted above, the recurrence time for the flares is probably shorter than this, \( \Delta T \approx 10 \) hr. However, if most of the LMXBs in NGC 4697 produce similar flares, then
the only limit is $\Delta T \lesssim 11$ days. The durations and fluences are similar to superbursts; however, the intervals between Galactic superbursts are much longer, on the order of a year.

Both sources are close to GCs in NGC 4697; thus, it is unlikely these sources are background active galactic nuclei (AGNs). Source A is 0.01 from an HST ACS GC with $g - z = 0.89$ and $z = 20.91$. This source is a highly probable match. Source B is 0.08 from an HST ACS GC with $g - z = 1.32$ and $z = 19.15$. Within 0.08 at this projected position in the galaxy, the probability of a match occurring at random is 1%. Thus, both of these flaring sources are probably located in GCs.

4.2. CXOU J124839.0−054750 (Source C)

By itself, the flare in observation 0784 of source C is highly significant. The combination of a similar flare in observation 4727 makes it the most probable (99.995%) flaring source in this Letter.

There is no clear optical counterpart for source C. The nearest globular cluster is 1.8 away. Given the rms of 0.4 for X-ray/optical matches, we do not think that this is a likely match. At this source’s radius from the center of NGC 4697 (48"), one only expects ~0.3 background sources at this flux level. There are 18 other sources as bright as source C and interior to it. Therefore, there is only a 1.6% probability that the source is a background AGN from the X-ray data alone. The source is even less likely to be an AGN given the lack of an optical detection. We have estimated the 50% completeness limit near the source to be 24.9 in the $z$ band. Since the X-ray flux in the 0.5−8.0 keV band is $4.2 \times 10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2}$, log ($F_X/F_{o,m}$) is greater than 0.5. If we relax this to log ($F_X/F_{o,m}$) $> 0.25$ ($z > 24.3$), and look at GOODS X-ray−selected sources (Treister et al. 2004), only 9.6% of the sources have log ($F_X/F_{o,m}$) $> 0.25$. Combining the expected X-ray background with the results for obscured AGNs in the GOODS fields, we estimate that there is a 0.15% probability that source C is an AGN.

The flare behavior of source C has no clear analog in our Galaxy. Its peak luminosity of $5.5^{+11.2}_{-2.3} \times 10^{39} \text{ ergs s}^{-1}$ ($\approx 8$ times the Eddington luminosity of a helium-burning NS) is clearly super-Eddington for an NS. These flares are not type I X-ray bursts. Since NGC 4697 is an elliptical galaxy, this source is unlikely to be an HMXB like LMC X-4 or V4641 Sgr.

The outburst need not exceed the Eddington limit by much if the compact object is a 10 $M_\odot$ BH. The flare timescale is similar to rapid transients seen in the BH XRBs, GRS 1915+105 and V4641 Sgr. Compared to GRS 1915+105, the ratio of flare rate to persistent rate for short flares is too high, and the recurrence timescale too long, arguing against accretion behavior like that in GRS 1915+105. The rapid transient in V4641 Sgr, seen at the tail of a flare event with the Rossi X-Ray Timing Explorer (Wijnands & van der Klis 2000), has the correct duration and peak luminosity (assuming a distance of ~10 kpc; Orosz et al. 2001); however, its quiescent luminosity is lower than that of source C by more than a factor of 10. The activity in V4641 Sgr has been attributed to super-Eddington accretion onto a black hole with the formation of an extended envelope (Revnivtsev et al. 2002). This variability might look like source C if it occurred during a long-term luminous stage, as has been seen in GRS 1915+105.

Since its behavior is most like LMC X-4, one might suggest that they have a similar phenomenology. That is, the flare might be due to density inhomogeneities in the accretion columns on neutron star polar caps (Moon et al. 2003). This would require that source C have a large magnetic field. Since most Galactic LMXBs do not appear to have strong fields, it is thought that magnetic fields in NS binaries decay with time or as a result of accretion (Bhattacharya & Srinivasan 1995). Since an NS in NGC 4697 is unlikely to be newly formed, a strong magnetic field in an NS binary could only occur if accretion causes the magnetic field decay in LMXBs and millisecond pulsars, and if the neutron star in this binary has only recently begun to accrete from its donor.

One possibility is that source C (and possibly sources A and B as well) are related to Galactic microquasar sources. Microquasars are XRBs with accreting BHs that produce relativistic jets (e.g., Mirabel & Rodríguez 1999). In most of the known Galactic examples, we are observing the sources at a large angle from the jet axis (see, however, Orosz et al. 2001). The very high luminosity of source C might be explained if we are seeing this source along the jet axis. Analogous to their AGN counterparts, microquasars observed along the jet axis are referred to as microblazars (Mirabel & Rodríguez 1999). Blazars are known to undergo relatively short timescale outbursts; the same phenomena, scaled to microblazars, might account for the X-ray flares in source C.

We thank Adrienne Juett and Eric Pfahl for their very helpful comments. Support for this work was provided by NASA through HST Award GO-10003.01-A and Chandra Awards GO4-5093X, AR3-405X, GO3-4099X, and AR4-5008X. G. R. S. acknowledges the receipt of an ARCS fellowship and support provided by the F. H. Levinson Fund.

REFERENCES

Belian, R. D., Conner, J. P., & Evans, W. D. 1976, ApJ, 206, L135
Bhattacharya, D., & Srinivasan, G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradis, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 495
Greiner, J., Morgan, E. H., & Remillard, R. A. 1996, ApJ, 473, L107
Grindlay, J., Gursky, H., Schnopper, H., Parsignault, D. R., Heise, J., Brinkman, A. C., & Schrijver, J. 1976, ApJ, 205, L127
Jordán, A., et al. 2004, ApJS, 154, 509
Kuulkers, E. 2004, Nucl. Phys. B Proc. Suppl., 132, 466
Lewin, W. H. G., van Paradijs, J., & Taam, R. E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradis, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 175
McClintock, J. E., & Remillard, R. A. 2005, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press (astro-ph/0306213)

Mirabel, I. F., & Rodríguez, L. F. 1999, ARA&A, 37, 409
Moon, D., Eikenberry, S. S., & Wasserman, I. M. 2003, ApJ, 586, 1280
Orosz, J. A., et al. 2001, ApJ, 555, 489
Revnivtsev, M., Gilfanov, M., Churazov, E., & Sunyaev, R. 2002, A&A, 391, 1013
Sarazin, C. L., Irwin, J. A., & Bregman, J. N. 2000, ApJ, 544, L101
Tonry, J. L., Dressler, A., Blakeslee, J. P., Ajhar, E. A., Fletcher, A. B., Luppino, G. A., Metzger, M. R., & Moore, C. B. 2001, ApJ, 546, 681
Treister, E., et al. 2004, ApJ, 616, 123
Wijnands, R., & van der Klis, M. 2000, ApJ, 528, L93
Yadav, J. S., Rao, A. R., Agrawal, P. C., Paul, B., Seetha, S., & Kasturirangan, K. 1999, ApJ, 517, 935