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X-RAY OBSERVATIONS OF LMC X-3 WITH THE MONITOR PROPORTIONAL COUNTER ABOARD THE *HEAO 2 EINSTEIN OBSERVATORY:* A COMPARISON WITH CYGNUS X-1

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ABSTRACT

We present a comparison of the black hole candidates LMC X-3 and Cygnus X-1 based on *Einstein* observations of LMC X-3 with the monitor proportional counter. Our spectral analysis shows LMC X-3 to be more like the typical bright galactic X-ray source than Cygnus X-1. A search for periodic pulsations over a period range from 0.2 ms to over 1000 s set upper limits at the 90% confidence level of the order of 10%. An analysis of the aperiodic variability of LMC X-3 shows none of the shot noise behavior characteristic of Cygnus X-1. The absence of distinctive X-ray properties common to both sources suggests that the identification of black hole candidates on the basis of X-ray properties similar to Cygnus X-1 (or LMC X-3) is not reliable.

Subject headings: black holes — X-rays: sources

I. INTRODUCTION

The recent discovery by Cowley, Crampton, and Hutchings (1983; see also Cowley *et al.* 1983) that the radial velocity of the optical counterpart of LMC X-3 varies with an orbital period of 1.7409 days and that the optical mass function implies a massive ($> 6\ M_\odot$), unseen companion has focused new attention on LMC X-3. The possibility that LMC X-3 might be a black hole has prompted us to examine, in detail, the spectral properties and the time variability of the X-ray source. In particular we have examined these properties to see whether there are any characteristics similar to those observed from Cygnus X-1, the only previously firmly established stellar black hole candidate.

II. OBSERVATIONS

LMC X-3 was observed on six different occasions (see Table 1) with the monitor proportional counter (MPC) aboard the *HEAO 2* spacecraft. The MPC, a sealed, argon-filled proportional counter with a 1.5 mil beryllium window, was co-aligned with the X-ray telescope onboard the observatory. Spectral data, spanning the energy range from 1.1 to 21 keV were divided into eight logarithmically spaced energy channels, each of which was integrated for and read out every 2.56 s. The time interval processor (TIP) circuitry of the MPC also measured the time interval between events to within 1 μs or 1.6%, whichever was larger, for a count-rate–dependent fraction of all events in the 1.1–21 keV bandwidth. Gaillardetz *et al.* (1978), Grindlay *et al.* (1980), and Weisskopf *et al.* (1981) give detailed discussions of the MPC and the TIP.

III. SPECTRAL ANALYSIS

In Table 1, we list derived spectral parameters for each orbit applicable to both power-law and thermal bremsstrahlung (exponential with a Gaunt factor) continuum models. The thermal models generally provide a better description of the data as evidenced by lower χ^2 values, although neither fit is acceptable for most of the orbits, even after inclusion of systematic uncertainties. As can be seen, these spectra are typically soft, characterized by bremsstrahlung temperatures of approximately 3 keV or power-law indices less than -2. In contrast, the spectrum for Cyg X-1 has been shown to be considerably harder in this range; typical derived power-law indices for that source are approximately -1.3. The softer X-ray spectra observed from LMC X-3 are more characteristic of the galactic bulge or globular cluster X-ray sources (see the review by Lewin and Joss 1981).

The data in Table 1 also suggest a possible correlation between the derived spectral parameters and the overall intensity of LMC X-3 in the sense that the spectrum hardens as the source brightens. This is supported by Figure 1 which shows a plot of a hardness ratio as a function of source intensity. Such a correlation has also been observed for a number of the bulge and cluster

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TABLE 1

SPECTRAL PARAMETERS FOR LMC X-3

MIDPOINT OF OBSERVATION (JD 2,443,000 +)	INTENSITY (COUNTS s^{-1})	BINARY PHASE[a]	BREMSSTRAHLUNG kT[b] (kev)	BREMSSTRAHLUNG E_A[b,c] (keV)	POWER - LAW INDEX[b]	POWER - LAW E_A[b,c] (kev)
835.27	23.2 ± 0.4	0.51	3.0 ± 0.5	< 1.2	−2.2 ± 0.3	1.5 ± 0.3
882.54	10.6 ± 0.2	0.24	2.3 ± 0.5	< 1.4	−2.3 ± 0.2	1.5 ± 0.3
882.62	10.7 ± 0.2	0.29	2.0 ± 0.5	< 1.3	−2.2 ± 0.2	1.4 ± 0.2
923.51	35.1 ± 0.6	0.27	2.5 ± 0.5	< 1.8	−2.5 ± 0.5	1.8 ± 0.6
923.55	35.2 ± 0.5	0.29	2.5 ± 0.5	< 1.6	−2.5 ± 0.5	1.8 ± 0.6
926.81	39.8 ± 0.6	0.20	3.0 ± 0.5	< 1.2	−2.4 ± 0.5	1.8 ± 0.6
926.84	40.1 ± 0.6	0.22	3.0 ± 0.5	< 1.2	−2.5 ± 0.5	1.8 ± 0.6
956.73	72.4 ± 1.1	0.59	3.5 ± 0.5	< 1.5	−1.9 ± 0.3	1.7 ± 0.6
977.73	46.0 ± 0.7	0.07	3.0 ± 0.5	< 1.5	−2.5 ± 0.5	1.8 ± 0.6
977.78	46.9 ± 0.7	0.10	3.0 ± 0.5	< 1.5	−2.4 ± 0.5	1.8 ± 0.6

[a] Based on a binary period of 1.7049 days and phase zero at JD 2,445,283.56.

[b] Errors are 90% confidence.

[c] E_A is an absorption energy approximately related to N_H by the relation: $N_H = 5.08 \times 10^{21} E_A^{2.72}$.

sources (Mason *et al.* 1976; Stella, Kahn, and Grindlay 1983), but not for Cyg X-1. Cyg X-1 does exhibit spectral changes connected with its long-term high-state to low-state transitions (Tananbaum *et al.* 1972), but they have the opposite sense; the spectrum softens as the source brightens.

Thus, in terms of both its average spectrum and spectral variability properties, LMC X-3 differs from Cyg X-1. In fact, LMC X-3 is rather typical of most bright X-ray sources, whereas Cyg X-1 is quite unusual.

IV. TIME VARIABILITY

The counting rates and 1.7409 day binary phases are also listed in Table 1. Although the overall intensity varied by as much as a factor of 7, and despite the

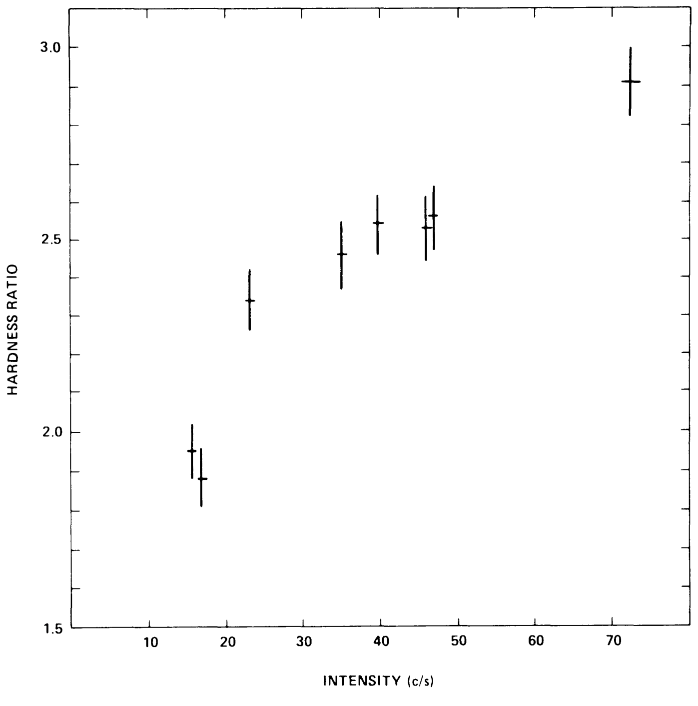

FIG. 1.—The hardness ratio, defined as the ratio of counts in the 2.4–11.5 keV band to the counts in the 1.2–2.4 keV band, as a function of source intensity.

TABLE 2

UPPER LIMITS TO PERIODIC PULSATIONS

Method	Period Range (s)	Upper Limit[a] (%)
FFT........	0.0002–1.024	12.6[b]
Rayleigh ...	1.015–10.15	8.6
	10.02–1182.1	3.0

[a] These amplitudes are based on a sinusoidal pulse shape.

[b] The upper limit is frequency dependent and is equal to $12.6(\pi j/N)/\sin(\pi j/N)$, where $j = 1, 2 \ldots N/2$ and $N = 1024$ for the frequencies j/T, where $T = 1.024$ s.

sparse coverage, there appears to be no correlation with binary phase. In particular the observations, at different epochs, at binary phase 0.29 show a variability by almost a factor of 3.

The data on JD 2,443,956, at the highest observed counting rate, were examined for evidence of pulsed X-ray emission. The techniques used, the fast Fourier transform (FFT) and the Rayleigh method, have been described in detail elsewhere by Leahy *et al.* (1983) and Leahy, Elsner, and Weisskopf (1983) and are not discussed here. The upper limits to periodic pulsations are summarized in Table 2, and we caution the reader that the upper limits based on the FFT are frequency dependent. The frequency dependence is given in note *b* accompanying the table. The period search covered a range of frequencies from below the breakup speed of a neutron star to 1000 s with a sensitivity that would have easily detected the pulsed fractions, about 30%, typical of the pulsing X-ray binaries. No evidence for periodic pulsation was obtained and the 90%–90% confidence upper limits (see Leahy *et al.* 1983) are given in the table.

The black hole candidate, Cyg X-1, is characterized by its aperiodic time variability which can be modeled simply as a shot noise source with 30% of the flux in shots of average width of 0.5 s and occurring at the average rate of once per second (Weisskopf *et al.* 1978). The question arises, then, does LMC X-3 also exhibit the shot noise behavior observed in Cygnus X-1? In order to search for such behavior, and to allow for the possibility that LMC X-3 might well have different shot noise parameters, we devised a test for aperiodic variability which we refer to as the "tree."

The tree invokes the axiom that an observation is deemed "interesting" if the ratio of the variance to the mean, for binned data, departs significantly from unity, the value expected on the basis of counting statistics. The technique involves calculating this ratio for data of

TABLE 3

TOP OF THE TREE FOR LMC X-3

366 s/ Section	183 s/ Section		91.5 s/Section				45.7 s/Section							
−1.3	−0.6	−1.3	0.4	−1.2	−1.2	−0.6	−0.1	0.6	−0.6	−1.1	−1.1	−0.6	−0.5	−0.4
−1.3	−0.6	−1.1	−0.2	−0.7	−1.2	−0.5	−0.1	−0.2	−0.3	−0.7	−0.4	1.2	0.4	−1.1
−1.1	−1.5	−0.1	−0.9	−1.1	−0.2	0.0	−0.8	−0.5	−1.1	−1.5	1.0	−1.3	0.2	−0.2
−0.7	−0.2	1.3	−0.9	0.5	1.0	0.7	−2.1	0.8	1.4	−0.7	1.2	0.2	1.4	−0.3
0.9	0.0	1.2	−0.8	0.8	0.9	0.8	−1.1	0.0	1.4	−0.4	0.3	1.1	0.7	0.4
2.9	0.6	3.4	−0.2	1.0	2.4	2.4	−0.6	0.4	2.4	−1.0	1.4	−2.1	1.1	2.3
2.9	1.0	3.1	0.6	0.8	2.4	1.9	0.6	0.2	2.7	−1.6	0.7	2.8	0.8	2.0
2.7	1.2	2.6	0.8	0.9	1.9	1.7	−0.1	1.2	2.0	−0.7	0.0	2.6	0.9	1.5
0.8	−0.6	1.7	−0.3	−0.6	1.8	0.4	−0.5	0.1	−1.0	1.8	0.1	2.4	0.2	0.4
0.6	−0.9	1.7	−1.0	−0.3	1.9	0.3	−0.6	−0.8	1.6	−2.2	0.5	2.2	0.0	0.4
−0.2	−1.3	1.0	−0.8	−1.1	1.9	−0.7	−0.8	−0.3	0.9	−2.6	1.5	1.1	−0.6	−0.4
0.1	−0.2	0.3	−0.6	0.1	1.2	−1.0	−0.2	−0.6	2.0	−1.8	0.3	1.4	−1.0	−0.3
1.5	1.0	1.1	0.3	0.8	0.9	0.3	0.0	0.5	2.3	−1.2	0.0	1.2	0.2	0.4
1.3	1.0	0.9	0.3	0.6	0.3	0.5	0.1	0.4	1.8	−1.0	−0.4	0.8	0.6	0.2
0.5	1.2	−0.4	0.5	0.5	0.3	−1.6	0.4	0.4	1.2	−0.5	0.0	0.2	−0.8	−1.3
1.0	1.2	0.3	0.3	0.4	1.3	−1.8	1.3	−0.7	0.6	−0.2	0.9	0.8	−1.1	−1.4
1.8	1.7	0.9	0.2	0.8	1.5	−1.6	0.3	0.2	1.6	−0.4	1.3	0.6	−0.8	−1.2
1.3	0.7	1.3	−1.2	0.2	0.8	−1.0	−0.7	−0.8	1.0	−0.7	−0.3	1.1	−0.2	1.0
2.4	0.7	2.8	−1.1	−0.5	2.2	−1.1								
3.8	2.8	3.3												
5.9														

NOTE.—The entries in this table are given by $[S - (N - 1)]/[2(N - 1)]^{1/2}$, where N is the number of bins, and the statistic S is given by $S = \Sigma_{i=1}^{N}(x_i - \bar{x})^2/\bar{x}$. Here x_i is the number of counts in bin i and x is the mean number of counts per bin. Since for a steady source S is distributed with mean $N - 1$ and variance $2(N - 1)$, the entries in the table correspond to the number of standard deviations of S above its mean. The first entry in each column corresponds to a bin size of 0.087 ms. In each subsequent entry, the bin size is doubled.

total length T and binned in 2^N ($T = 2^N \Delta t$) bins, where Δt is a small increment of time and N is a large integer. The calculation is then repeated, but now applying the technique to each half of the data separately, each quarter, each eighth, etc. This extension of the technique involves minimal computation since the results of cruder division may all be written in terms of the results calculated for the finest divisions. The tree thus can be used to quickly identify and isolate any transient flares that may be present in the data. Table 3 gives the tree for the observations of LMC X-3 with the highest counting rate. For comparison, Table 4 shows the tree resulting from a Monte Carlo simulation of a shot noise source with Cyg X-1 parameters, but at the same counting rate and approximately the same integration time as for the LMC X-3 observation. Clearly the LMC X-3 tree is much quieter and barely "lit up" when compared with the Monte Carlo simulation. In general, all the trees for the LMC X-3 observations were quiet with the only indication of variability occurring on the longest time scales when the entire data sets were examined. We have seen these variations in the majority of low count rate MPC observations, and they can be partially (if not entirely) attributed to variations in the background counting rate. We thus conclude that LMC X-3 is very quiet especially when compared with Cygnus X-1. This conclusion depends on our assumption that the invariant shot parameters are the shot width, the shot rate, and the shot fraction. At the present time, no theory exists for relating the shot parameters of black hole X-ray sources to other source properties and different assumptions concerning the shot parameters could lead to a different conclusion. For example, if the shot strength (the number of photons emitted per shot) is invariant, then the observed shot strength would be much smaller for LMC X-3, owing to its greater distance, than for Cyg X-1 while the shot rate would be correspondingly higher (holding the shot fraction constant). In this case, the variance in the observed count rate would approach Poisson and the tree would barely light up, as observed.

V. SUMMARY

At the present time, Cyg X-1 and LMC X-3 are the best black hole candidates among binary X-ray sources. For both systems, optical measurements of the radial velocity curve of the companion star indicate that the compact object is too massive to be a white dwarf or a neutron star. In addition, neither X-ray source is known to emit periodic X-ray pulsations. Over time, a number of galactic X-ray sources have been suggested as black hole candidates by virtue of the similarity of some observable property, usually variability on short time scales, to that of Cyg X-1. This has happened despite the lack of convincing evidence that any X-ray property of Cyg X-1 is the direct and unique result of the compact object being a black hole. Comparative studies of LMC X-3 and Cyg X-1 are important in order to establish any unique features of black hole X-ray sources as well as to explore the physics of accretion onto black holes. Dis-

TABLE 4

TOP OF THE TREE FOR A CYGNUS X-1 LIKE SOURCE[a]

410 s/ Section	205 s/ Section		102.4 s/Section				51.25 s/Section							
1.3	1.5	0.3	1.2	0.8	0.4	0.1	1.9	−0.2	0.6	0.6	1.7	−1.1	−0.1	0.2
1.4	1.6	0.4	2.3	−0.1	0.9	−0.4	2.5	0.8	−0.5	0.3	1.3	0.1	0.1	−0.6
3.1	3.8	0.6	3.5	1.8	1.1	−0.2	3.6	1.4	1.3	1.3	1.2	0.3	−0.1	−0.2
5.3	4.3	3.2	2.5	3.6	2.3	2.2	2.8	0.7	3.5	1.7	0.7	2.5	1.8	1.2
6.5	5.2	3.9	3.5	3.9	1.8	3.8	3.0	1.9	3.9	1.7	0.8	1.7	3.7	1.6
9.1	7.0	5.9	5.8	4.0	3.0	5.4	4.8	3.4	3.6	2.1	1.5	2.6	4.4	3.1
13.7	10.3	9.0	9.0	5.6	4.9	7.8	7.8	4.9	4.5	3.4	1.7	5.1	4.4	6.7
17.2	13.9	10.4	11.3	8.4	4.7	10.0	10.5	5.5	6.3	5.5	1.6	4.8	5.7	8.4
24.6	20.2	14.5	16.4	12.2	6.8	13.7	14.1	9.1	9.1	8.1	2.9	6.4	7.9	11.5
32.1	25.9	19.3	20.9	15.7	10.3	17.1	17.9	11.6	13.1	9.2	5.3	8.8	9.4	14.9
40.8	34.1	23.5	28.0	20.2	13.4	19.9	23.6	15.9	17.7	11.0	6.7	11.6	11.6	16.5
50.9	41.9	29.9	34.4	24.9	17.5	24.8	28.3	20.4	21.6	13.8	8.5	15.4	14.2	20.9
55.9	44.7	34.2	38.4	24.9	22.5	25.9	31.6	22.8	20.9	14.4	10.5	20.2	15.6	21.0
49.2	38.9	30.5	35.2	19.9	20.2	23.0	30.6	19.2	18.9	9.5	8.9	18.3	14.9	17.4
41.7	30.9	28.0	29.2	14.7	18.3	21.5	23.2	18.3	12.4	8.5	6.7	17.4	18.3	11.5
32.5	23.7	22.2	22.5	11.4	15.4	16.4	15.4	16.8	9.6	6.7	6.1	13.4	11.6	11.0
14.0	6.2	13.5	5.4	3.7	9.6	9.9	4.7	3.1	3.6	1.8	−0.4	10.6	4.8	8.4
10.9	4.9	10.3	3.1	4.4	12.4	2.9	2.0	2.5	4.4	2.1	0.7	12.5	2.8	−0.6
10.1	0.6	13.5	1.7	−0.4	16.8	4.3								
5.2	0.0	6.9												
0.3														

[a] See note to Table 3. Here the shortest binning time scale is 0.098 ms.

tinctive X-ray properties common to both X-ray sources could be used as promising indicators for the selection of other X-ray sources potentially containing black holes. However, we have found no similarity in the spectral and temporal properties of these two X-ray sources. The X-ray properties of LMC X-3 are more or less typical of other nonpulsing bright binary X-ray sources while those of Cyg X-1 are not. If both Cyg X-1 and LMC X-3 contain black holes, then we draw the following inferences. First, the X-ray properties of binaries containing black holes need not show any similarity to those of Cyg X-1 (or LMC X-3 for that matter). Second, the X-ray properties of Cyg X-1, in particular its rapid shot noise variability, may be related to some aspect of the system other than the presence of a black hole. We note, however, that we cannot exclude the possibility that LMC X-3 is also a shot noise source but with significantly different shot parameters than those of Cyg X-1. In this regard, any theoretical progress leading to the prediction of expected relationships between shot parameters and other source properties (e.g., X-ray luminosity) would greatly facilitate comparative studies of black hole candidates. Third, the observation of X-ray properties similar to Cyg X-1 (or LMC X-3) in another system is not necessarily a reliable indication that a black hole is contained in that system.

An alternate hypothesis is that the lack of similarity in the X-ray properties of LMC X-3 and Cyg X-1 arises because one contains a black hole and one does not. If so, then the possibility remains that accretion onto black holes produces a unique X-ray signature, perhaps shot noise variability on short time scales or perhaps some other X-ray characteristic. However, a dilemma arises if one adopts this point of view. Accepting the optical identifications and radial velocity measurements for each system at face value, the evidence for the existence of a black hole is about as strong for LMC X-3 as for Cyg X-1 (the lower limits on the masses of the compact objects are roughly the same). There is at present no reliable way based on the other properties of these systems to confirm or dispute the black hole hypothesis. Unless further observational clues are found, for example, evidence for the presence of a third massive body in the LMC X-3 system, LMC X-3 and Cyg X-1 appear to be equally good black hole candidates. Finally, we remark that the lack of similarity between LMC X-3 and Cyg X-1 should not itself be construed as evidence that LMC X-3 is not a black hole.

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