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SURVEY OF INTENSITY VARIABILITY OF STRONG GALACTIC X-RAY SOURCES FROM *UHURU*

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ABSTRACT

X-ray observations made with the *Uhuru* satellite have been used to study the characteristics of the intensity of 19 strong galactic sources. On a time scale of 0.1–1.0 s all but two of these sources showed variability at a significance level greater than 3 σ. On longer time scales—minutes to hours—all but three sources showed variations above the 3 σ level.

In addition to characterizing in a systematic way the broad range of variability of the galactic X-ray sources, we have applied our results to specific models of Cygnus X-1 and Cygnus X-3. We also comment on the similar nature of the strong galactic center X-ray sources and the globular cluster sources.

Subject heading: X-rays: sources

I. INTRODUCTION

Observations have shown that several galactic X-ray sources are members of binary systems. In the most widely accepted model for these binary systems the observed X-ray emission is produced by accretion of material from a normal primary star onto a compact secondary object—a white dwarf, neutron star, or black hole. By studying the variability of galactic X-ray sources we can differentiate between compact and noncompact sources and hence test the hypothesis that all galactic X-ray sources are systems containing a collapsed star. The data presented are from the *Uhuru* satellite and thus limit the time scale for variations to greater than 0.1 s. Statistical limitations constrain the 2–6 keV source intensity to be greater than 200 counts s^{-1}. In addition to our analysis of source variability on short time scales, we obtained source intensities for each observation. A brief discussion of the resulting light curves points out types of variability seen on time scales of minutes to hours.

II. OBSERVATIONS

Nineteen X-ray sources were included in this study. For each source approximately 100 observations were analyzed. Since we wanted to study the intensity variations on the shortest possible time scales, we used only observations with a duration of about 2 s and a time resolution (the shortest possible for *Uhuru*) of 0.096 s. These observations were obtained with the narrow collimator (FWHM $\frac{1}{2}^\circ \times 5^\circ$) and a normal spin mode for the satellite (approximately $0\overset{\circ}{.}5$ s^{-1}). Use of the broad collimator would have added to source confusion, especially in the galactic center region and would have degraded our time resolution to 0.384 s.

We have analyzed the short-time-scale source variability in two ways. We have characterized the fluctuations first by the fraction of pulsed power and second by the observed number of intensity bursts compared to that expected for a nonvariable source. For both methods, we first performed a minimum χ^2 fit of the collimator response as measured before launch to the observed source counting rates with the centroid and amplitude as free parameters. Figure 1 shows two examples: one observation exhibits no variability and the other shows strong fluctuations. For each χ^2 fit, we used only the center three quarters of the observation to avoid possible statistical problems arising from the low counting rates when the source is near the edge of the collimator field of view. For the majority of data in this study, the duration of a source observation was calculated from the equation of motion of the spacecraft determined from star sensor data and is accurate to better than 1 percent. For data obtained after the star sensor failure in 1971 November for which an accurate equation of motion was not available, the spin rate of the satellite was established from sightings of X-ray sources. Since the positions of these sources had been determined earlier, the spin rate, and therefore the width of the triangular collimator response, could be computed, again with an accuracy of better than 1 percent. The background for each observation was found using data taken immediately before and after each sighting of the source.

For deciding whether an X-ray source exhibited significant fluctuations and for determining the amount of power pulsed, we used the values of χ^2 determined from fitting each observation to the collimator response. The expression for χ^2 is

$$\chi^2 = \sum_i (O_i - E_i)^2/E_i ,$$

where O_i and E_i are the observed and expected counting rates in the ith bin for a single sighting of the source with E_i determined from the minimum χ^2 fit.

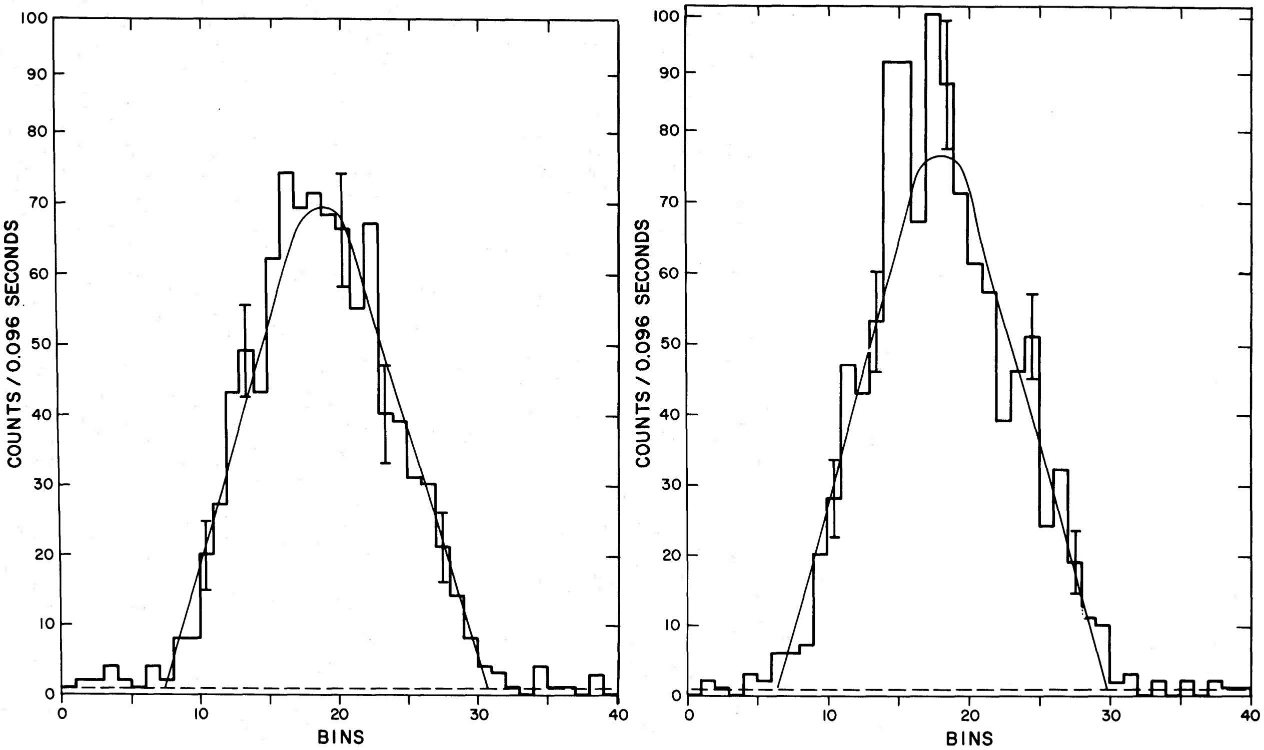

FIG. 1.—Two observations from 1971 March 15 of Cyg X-1 (3U 1956+35) are shown. The histograms show the counts observed in each 0.096 s interval. The triangular shaped figures superposed on the histograms are the minimum χ^2 fits to the collimator response. The background levels are indicated with dashed lines. The minimum χ^2 fit for the observation shown in the right-hand portion of the figure yielded $Q(\chi^2) = 0.00005$, which implies that variability is present in the observed data, as can easily be seen. The familiar property of underestimation of the area by minimum χ^2 fits is readily apparent in the right-hand portion of the figure (Bevington 1969).

The number of degrees of freedom, ν, is the number of data points, N, minus the number of restrictions imposed on the data. In our analysis there are three restrictions resulting from the two fitted parameters plus the restriction of a fixed total number of counts during the observation (Hoel 1954).

The evidence for intensity variability can be tested by summing up the total χ^2 and the total number of degrees of freedom, ν_t, from every observation of a source. A measure of the significance of the variability can be determined by dividing the difference between the observed χ^2 and the expected χ^2 by the standard deviation, where the expected is simply ν_t (one per degree of freedom) and the standard deviation is $(2\nu_t - 1)^{1/2}$.

The results of this study are given in Table 1. For each source, the total χ^2, the total number of degrees of freedom, the significance of each result, and a parameter characterizing the percentage of pulsed radiation are given to summarize the variability. The last parameter, the average percentage pulsed, was determined using the method described by Forman *et al.* (1974) which assumes that the source intensity can be divided into two components, a steady component and a variable fraction. If one assumes that the variable fraction $\beta_i = \pm\beta$ as a model of the variability, that is, each 0.096 s bin is assumed to differ by $\pm\beta$ from the expected intensity, then Forman *et al.* showed that the power in the variable component could be defined as

$$\beta^2 = (\chi^2 - 1)/I ,$$

where χ^2 is the value of χ^2 per degree of freedom and I is the average intensity per 0.096 s bin.

The values of β tabulated in the last column of Table 1 are useful in characterizing the variability of X-ray sources, since unlike measures of either the total χ^2 or the significance of the variability, β does not depend directly on the observed intensity of the source. However, the uncertainty in the percentage does depend on the observed source intensity and the total number of degrees of freedom. Thus, the uncertainty varies from source to source and from day to day for a given source. The uncertainty on the average fraction pulsed has been computed for each source in our survey and ranges from 0.5 to 1.8 percent for the average β given in Table 1. Table 2 shows the variability of the X-ray sources in this survey for the individual days on which they were observed. For the individual days, the uncertainty in β computed, for example, for Cyg X-1, Cir X-1, and the Crab generally falls between 0.5 and 3.5 percent.

TABLE 1

VARIABILITY VIA TOTAL χ^2 TEST

Source	Chi Square	Degrees of Freedom	Sigma	Percent
3U 1956+35 (Cyg X-1):	4589	2930	21.7	18.4 ± 0.5
Before transition............	2475	1770	11.9	11.0 ± 0.5
After transition.............	2114	1160	19.8	22.0 ± 0.6
3U 1837+04..................	1338	1154	3.8	13.1 ± 1.8
3U 1516−56 (Cir X-1).........	3230	2474	10.8	12.5 ± 0.6
3U 1744−26 (GX 3+1)........	2393	2047	5.4	11.6 ± 1.1
3U 1735−28 (GC tran)........	672	518	4.8	11.5 ± 1.3
3U 1636−53..................	2556	2308	3.7	11.2 ± 1.7
3U 1820−30 (NGC 6624)......	2336	2046	4.5	11.0 ± 1.3
3U 1811−17 (GX 13+1).......	2542	2230	4.7	10.8 ± 1.2
3U 1758−20 (GX 9+1)........	3563	3044	6.7	10.7 ± 0.8
3U 1702−36 (349+2)..........	3019	2589	6.0	10.0 ± 0.9
3U 2030+40 (Cyg X-3)........	2388	2107	4.3	9.2 ± 1.1
3U 1705−44..................	2229	1988	3.8	9.1 ± 1.3
3U 1642−45..................	2179	1911	4.3	8.8 ± 1.1
3U 2142+38 (Cyg X-2)........	2492	2186	4.6	8.7 ± 1.0
3U 0531+21 (Crab)...........	1959	1670	5.0	8.3 ± 0.9
3U 1758−25 (GX 5−1)........	2261	1991	4.3	6.7 ± 0.8
3U 1813−14 (GX 17+2).......	3586	3102	6.1	6.1 ± 0.5
3U 1728−16 (GX 9+9)........	2009	1875	2.2	...
3U 1658−48..................	1159	1164	...	...

The observations in Table 1 demonstrate that most of the X-ray sources in this survey exhibit significant variability on short time scales. The data presented in Table 2 show that many of the sources have a range in variability so that it is difficult to classify or predict their short time scale behavior. Also, by analysis of Cyg X-1 data taken at different collimator elevations we have determined that the χ^2 technique becomes insensitive when the observed counting rate is below ~ 200 counts s^{-1}. Nineteen galactic sources have observed intensities greater than 200 counts s^{-1} on enough occasions to have been included in this survey.

The method described above of using the total χ^2 is well suited for detecting small amounts of frequently occurring random variability in strong galactic sources. However, if the radiation from an X-ray source is usually constant, but has infrequent, strong bursts, this method may not be sensitive since the χ^2 is averaged over the entire observation. A method better suited for examining burst phenomena is to use individual bins to form a normal distribution.

We begin as with the previous method with a minimum χ^2 fit of the collimator response to each observation. We then compute the residual for each bin by taking the difference between the observed and the expected number of counts and normalize to remove the effect of varying effective area due to the collimator response. This can be expressed as

$$\delta_i = \frac{O_i - E_i}{\sigma_i} ,$$

where O_i and E_i are the observed and expected counts on the ith bin and σ_i is the uncertainty in E_i.

We then compare the distribution of these normalized deviations with the expected distribution for a nonvariable source. We choose to compute the number of expected deviations greater than 2.5 sigma and compare that with the actual number observed. The number of expected deviations greater than 2.5 σ is

$$N = (2\pi)^{-1/2} \int_{2.5}^{\infty} \exp\left(-\tfrac{1}{2}x^2\right) dx \times \text{total number of samples} .$$

One can then compute the probability of observing M events when N were expected. The results of this "burst" analysis are given in Table 3, where we tabulate for each source studied the expected number of deviations greater than 2.5 σ, the number observed, and the probability of this occurrence. The majority of X-ray sources were not observed to have intensity bursts. However, Cyg X-1 exhibits frequent intensity bursts, and Cir X-1 and 3U 1758−20 show evidence of bursts in their emission. Figure 2 shows the histograms for the observed and expected distributions for two sources; in the top half for 3U 1702−36 (GX349+2), which does not show significant bursts, and in the bottom half for 3U 1956+35 (Cyg X-1), which exhibits strong bursts.

III. DISCUSSION

The principal result of this survey is that, with two exceptions, all of the strong galactic sources exhibit rapid intensity variability and as a consequence are inferred to be compact stellar objects. One of the exceptions, 3U 1658−48, was observed on only two separate occasions when the source was clearly separated from other nearby sources. In view of the erratic character of the variability it may be that two observations are too few to observe variability for this source.

1976ApJ...208..849F

TABLE 2

DAILY SHORT-TIME-SCALE VARIABILITY

Source	Month/Day/Year	Chi Squared	Degrees of Freedom	Percent
3U 0531+21	2/21/71	476	436	4.0 ± 1.9
	3/12/71	386	362	7.2 ± 7.2
	3/16/71	789	657	7.9 ± 1.1
	4/25/71	141	121	7.0 ± 3.0
	7/29/72	432	367	8.0 ± 1.9
3U 1516−56	1/16/71	1459	942	15.2 ± 1.9
	1/22/71	262	193	14.6 ± 2.1
	2/14/71	445	413	5.0 ± 3.5
	2/18/71	563	543	7.6 ± 7.6
	3/17/71	502	383	13.4 ± 1.7
3U 1636−53	2/17/71	463	413	10.9 ± 4.0
	2/21/71	412	338	16.8 ± 3.3
	2/25/71	411	364	10.0 ± 3.5
	3/17/71	426	366	19.6 ± 5.1
	3/19/71	833	811	5.9 ± 5.9
3U 1642−45	2/25/71	399	356	7.9 ± 3.0
	3/12/71	654	499	12.8 ± 1.4
	3/17/71	425	412	3.9 ± 3.9
	7/29/72	700	644	7.4 ± 3.0
3U 1658−48	2/17/71	437	419	8.2 ± 8.2
	2/21/71	374	372	2.6 ± 2.6
3U 1702−36 (GX 349+2)	2/14/71	483	431	8.4 ± 2.9
	2/17/71	511	418	10.9 ± 1.8
	2/21/71	663	547	19.0 ± 3.0
	3/16/71	647	586	10.0 ± 3.4
	7/29/72	698	592	8.0 ± 1.4
3U 1705−44	2/17/71	414	381	8.0 ± 4.6
	2/21/71	372	369	2.5 ± 2.5
	3/17/71	470	399	10.1 ± 2.3
	3/19/71	974	839	10.3 ± 1.7
3U 1728−16	2/14/71	367	394	...
	2/17/71	440	370	13.0 ± 2.8
	3/13/71	534	424	14.5 ± 2.0
	3/15/71	353	359	...
	4/25/71	315	328	...
3U 1735−28	3/12/71	672	518	11.4 ± 1.3
3U 1744−26	3/12/71	595	498	11.2 ± 2.0
	3/19/71	889	795	12.8 ± 3.1
	7/29/71	909	754	11.1 ± 1.5
3U 1758−25	3/12/71	571	567	1.2 ± 1.2
	3/19/71	991	797	9.2 ± 1.0
	4/ 1/71	258	253	...
	7/29/72	425	357	8.6
3U 1758−20	2/21/71	457	389	14.2 ± 3.3
	3/12/71	665	601	7.0 ± 2.3
	3/19/71	783	756	6.5 ± 6.5
	4/24/71	239	189	25.0 ± 5.4
	4/25/71	420	343	11.2 ± 2.1
	7/29/72	999	788	26.2 ± 2.6
3U 1811−17	3/12/71	683	619	7.8 ± 2.6
	3/19/71	879	771	12.8 ± 2.6
	4/ 1/71	297	272	11.1 ± 8.2
	4/24/71	230	207	8.4 ± 5.5
	7/29/72	453	361	13.7 ± 2.2
3U 1813−14	3/12/71	689	585	9.2 ± 1.7
	3/16/71	335	335	...
	3/19/71	843	782	9.2 ± 3.7
	4/ 1/71	352	340	6.2 ± 6.2
	4/24/71	261	208	19.7 ± 4.3
	7/29/72	1105	852	10.9 ± 0.9
3U 1820−30	3/17/71	418	368	13.5 ± 4.4
	4/ 1/71	370	339	9.5 ± 5.7
	4/ 2/71	338	310	9.7 ± 6.5
	4/25/71	382	365	6.8 ± 6.8
	4/ 4/73	709	580	11.3 ± 1.6
3U 1837+04	4/ 1/71	349	323	9.4 ± 8.0
	5/14/72	734	633	13.3 ± 2.6
	7/29/72	254	198	16.2 ± 3.2
3U 1956+35	12/29/70	452	360	16.0 ± 2.5
	1/16/71	409	285	11.5 ± 1.2
	2/11/71	462	356	12.9 ± 1.8

TABLE 2—*Continued*

Source	Month/Day/Year	Chi Squared	Degrees of Freedom	Percent
3U 1965+35................	3/12/71	591	516	9.8 ± 2.4
	3/13/71	552	368	9.4 ± 0.8
	3/15/71	461	245	12.2 ± 0.7
	3/19/71	822	711	14.8 ± 2.5
	3/31/71	625	366	19.9 ± 1.0
	5/14/72	1028	588	22.3 ± 0.8
	7/29/72	461	206	25.2 ± 1.0
3U 2030+40................	2/ 5/71	361	362	...
	5/14/72	1105	951	10.0 ± 1.5
	7/29/72	921	794	9.1 ± 1.6
3U 2142+38................	1/ 4/71	837	725	7.9 ± 1.5
	3/17/71	606	511	12.6 ± 2.3
	4/16/71	360	331	7.0 ± 4.7
	6/20/71	688	619	8.7 ± 2.6

Table 2 shows that many of the X-ray sources were observed to be variable only a fraction of the time and exhibited a considerable range of variability from one day of observations to another. For example, 3U 1642−45 was observed to be variable on only one of four separate days of observations. In addition, the intensity of 3U 1658−48 was near the limit of 200 counts s^{-1} on the two observing days so that the source may have been too weak for us to detect variability at a statistically significant level. The other source which did not show rapid intensity variability is 3U 1728−16 (GX 9+9). As is discussed below, this source also did not show variability on time scales of minutes to hours, and the evidence for variability from day to day is also marginal. This suggests that this source may be very different from the compact X-ray sources, raising the possibility that it is associated with a more extended emitting region such as a supernova remnant. On the other hand, the authors of the 3U Catalog (Giacconi *et al.* 1974) searched the catalogs of Downes (1971) and Milne (1970) and found no radio supernova remnants at the location of 3U 1728−16 although the location of the X-ray source 9° off the galactic plane may mean that this region has not been surveyed. It may be that a more sensitive radio search and an improved X-ray location could help in identifying this source and eventually understanding the emission process.

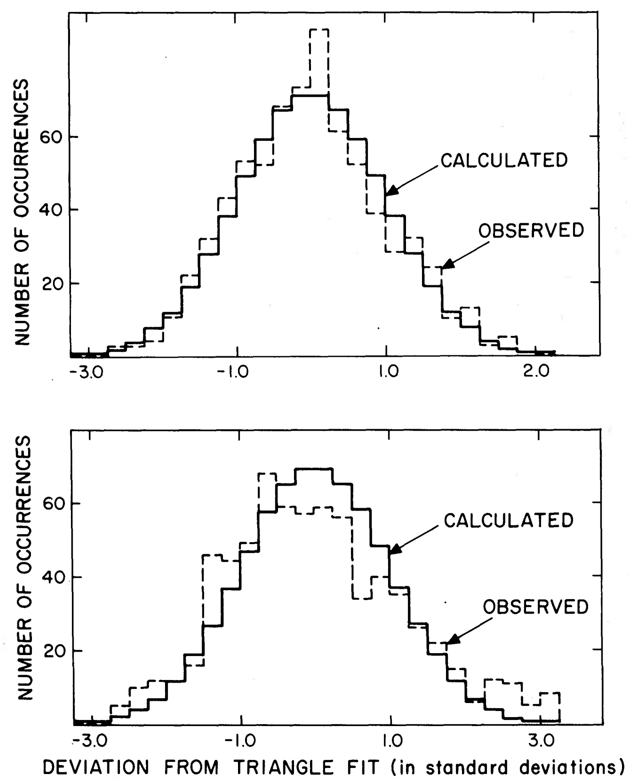

FIG. 2.—Two so-called burst histograms, one for 3U 1702−36 (GX 349+2) and one for 3U 1956+35 (Cyg X-1), are shown. The dashed-line histograms give the observed number of occurrences of deviations of magnitude (see text) from the best fit triangle as a function of σ. The solid-line histogram is that expected if no variability were present. The upper figure shows no excess of deviations greater than 2.5 σ while the lower figure shows 24 observed bursts when 4.4 were expected from a normal distribution. The probability of this occurring by chance is less than 0.00001.

The erratic nature of the intensity variability for the remaining 17 sources can explain differing results of observations of the same source taken at different times. For example, two observations of Cyg X-1 resulted in conflicting conclusions. Rothschild *et al.* (1974) reported that Cyg X-1 showed significant variability on a time scale of milliseconds while Rappaport, Doxsey, and Zaumen (1971) found no very short time scale variations. This study shows that one cannot necessarily expect the intensity behavior of galactic X-ray sources to be similar from one relatively short interval to another.

We have attempted, therefore, to obtain sufficient numbers of observations separated in time that some averaging of this erratic nature of the X-ray sources could occur. In general, our use of narrow-collimator observations prevented any possible source confusion. In particular, we note that the transient X-ray source A0535+26 was not in the field of view during our

TABLE 3

VARIABILITY VIA BURSTS

Source	Month/Day/Year	Expected Bursts ≥ 2.5 σ	Observed Bursts ≥ 2.5 σ	Probability
3U 0531+21..........	2/21/71	1.6	1	
	3/12/71	2.5	2	
	3/16/71	3.7	10	0.004
	4/25/71	0.9	0	
	7/29/72	2.7	5	0.14
	Total	11.4	18	0.044
3U 1516−56..........	1/16/71	7.1	22	0.00003
	1/22/71	1.5	3	0.19
	2/14/71	3.0	4	0.35
	2/18/71	4.0	6	0.21
	3/17/71	1.5	3	0.19
	Total	17.1	38	0.0001
3U 1636−53..........	2/17/71	3.0	3	
	2/21/71	2.5	3	0.46
	2/25/71	2.8	4	0.31
	3/17/71	2.7	9	0.0019
	3/19/71	6.1	5	
	Total	17.1	24	0.063
3U 1642−45..........	2/25/71	2.6	4	0.26
	3/12/71	3.4	8	0.023
	3/17/71	3.0	2	
	7/29/72	4.9	2	
	Total	13.9	16	0.33
3U 1658−48..........	2/17/71	3.1	6	0.094
	2/21/71	2.7	1	
	Total	5.8	7	0.36
3U 1702−36..........	2/14/71	3.2	3	
	2/17/71	3.1	3	
	3/16/71	4.4	6	0.27
	7/29/72	4.5	6	0.30
	Total	15.2	18	0.25
3U 1705−44..........	2/17/71	2.8	3	0.53
	2/21/71	2.7	2	
	3/17/71	2.9	3	0.55
	3/19/71	6.3	9	0.19
	Total	14.7	17	0.30
3U 1728−16..........	2/14/71	2.9	2	
	2/17/71	2.7	4	0.29
	3/13/71	3.1	6	0.090
	3/15/71	4.3	5	0.43
	4/25/71	2.5	1	
	Total	15.5	18	0.30
3U 1735−28..........	3/12/71	3.8	8	0.040
3U 1744−26..........	3/12/71	2.7	3	0.49
	3/19/71	3.6	8	0.031
	7/29/71	5.9	8	0.24
	Total	12.2	19	0.043
3U 1758−25..........	3/12/71	4.1	3	
	3/19/71	6.0	14	0.0034
	4/ 1/71	2.0	1	
	7/29/72	2.7	3	0.49
	Total	14.8	21	0.076
3U 1758−20..........	2/21/71	2.8	4	0.31
	3/12/71	4.4	9	0.038
	3/19/71	5.7	9	0.12
	4/24/71	1.3	3	0.14
	4/25/71	2.6	4	0.26
	7/29/72	5.8	13	0.0068
	Total	22.6	42	0.0001
3U 1811−17..........	3/12/71	4.4	3	
	3/19/71	5.8	7	0.36
	4/ 1/71	2.1	1	
	4/24/71	1.6	1	
	7/29/72	2.7	5	0.13
	Total	16.6	17	0.49
3U 1813−14..........	3/12/71	4.3	9	0.030
	3/16/71	2.5	1	
	3/19/71	5.8	5	
	4/ 1/71	2.5	4	0.24
	4/24/71	1.6	0	
	7/29/72	6.3	10	0.10
	Total	23.0	29	0.16

TABLE 3—*Continued*

Source	Month/Day/Year	Expected Bursts ≥ 2.5 σ	Observed Bursts ≥ 2.5 σ	Probability
3U 1820−30..........	3/17/71	3.3	8	0.020
	4/ 1/71	2.5	4	0.24
	4/ 2/71	2.3	2	
	4/25/71	2.8	5	0.15
	4/ 4/73	4.4	3	
	Total	15.3	21	0.097
3U 1837+04..........	4/ 1/71	2.4	2	
	5/14/72	5.1	9	0.075
	7/29/72	1.1	2	0.30
	Total	8.6	13	0.097
3U 1956+35..........	1/16/71	2.1	8	0.0015
	2/11/71	2.6	2	
	3/12/71	3.7	3	
	3/13/71	2.7	8	0.0066
	3/15/71	1.8	13	0.00001
	3/19/71	5.3	8	0.17
	3/31/71	2.7	10	0.0005
	5/14/72	4.4	24	0.00001
	7/29/72	1.5	12	0.00001
	Total	26.8	88	0.00001
3U 2030+40..........	2/ 5/71	2.7	1	
	5/14/72	6.2	13	0.011
	7/29/72	3.7	4	0.49
	Total	12.6	18	0.091
3U 2142+38..........	3/12/71	3.8	5	0.33
	3/17/71	3.6	5	0.29
	1/ 5/71	5.0	10	0.032
	4/16/71	2.4	0	
	6/21/71	2.2	2	
	6/22/71	2.6	2	
	Total	19.6	24	0.19

observations of the Crab (3U 0531+21). Thus, the results given in Table 1 characterize the average variability of each source while the fraction of pulsed power given in Table 2 provides an estimate of the range in variability for the sources.

The range of average variability extends from 6 percent to about 20 percent. If we eliminate Cyg X-1 from our sample, the fraction power pulsed reaches to only 13 percent. Although the difference between 6 and 13 percent for the power pulsed is statistically significant, there is no clear division of the X-ray sources into groups which can be characterized by different pulsed fractions. Instead, we find a continuum of pulsed fractions between 6 and 13 percent, with only Cyg X-1 having a higher average fraction of 18 percent. This is a strong indication that of the 19 sources studied, Cyg X-1 was exceptional in its variability.

Cygnus X-1 is also unique for the large number of intensity bursts which are observed. Several other X-ray sources exhibit intensity bursts, but none of these sources shows the frequency of bursts that Cyg X-1 shows. Although Cir X-1 and 3U 1758−20 show overall significant numbers of bursts, Cir X-1 was active on only one of five individual days of observation and 3U 1758−20 was active on two of six days. Since the burst analysis is dependent on the source intensity, a weaker source will not show statistically significant bursts, although the fractional increase in intensity may be as great or greater than for a stronger source. With this possibility in mind, we have examined the relative intensities of Cyg X-1, Cir X-1, and 3U 1758−20 on the days these sources were observed and found that the differences in the behavior of these sources cannot be explained simply by differences in their intensities.

Although considerably less variable than Cyg X-1, the X-ray sources Cir X-1 and 3U 1758−20 can be considered to be in a class of elevated activity based on analysis with the burst technique. These sources are worthy of further study as members of an interesting class of X-ray sources.

Although this survey is not definitive in classifying X-ray sources based on their variability, it yields interesting results which can be compared with models of specific sources. In a model for Cyg X-1, Thorne and Price (1975) have made specific predictions regarding the intensity variability on short time scales. Also, for Cyg X-3, detailed models have been derived by Davidsen and Ostriker (1974) and by Pringle (1974). Our results can be compared with the predictions of models for both these X-ray sources.

In the case of Cyg X-1, one of the remarkable features is the unusual spectral and intensity transition which occurred in the spring of 1971 (Tananbaum *et al.* 1972). We now find that across this transition the fraction of pulsed radiation doubled, increasing from an average of 11 percent to 22 percent. Note that we can see that the power pulsed increased *during* the transition by examining Table 2. There is a clear indication of β increasing from around 10 percent to 20 percent during 1971 March, the time of the transition. Prior to the transition, the 2–6 keV observations used in this study consisted primarily of X-rays from the soft, low-energy component which dominated the spectrum below 10 keV. After the transition, this component was no longer observed from 2 to 20 keV, the *Uhuru* energy range. Instead the posttransition data from 2 to 6 keV were dominated by the harder, underlying spectral component for which we found the pulsed fraction considerably increased. This result suggests that the soft, less variable component originates in a more extended region around the compact star than the harder radiation. The increase in variability supports the model recently proposed by Thorne and Price (1975) to explain the Cyg X-1 transition. In their model the low-energy X-rays are produced in the spatially thin, optically thick outer region of the accretion disk and the high energy X-rays originate from the spatially thick, optically thin inner, hotter region. Thorne and Price, therefore, predicted that on short time scales the harder X-ray component would exhibit more variability than the softer component, as our results have now demonstrated.

Although our observations of other X-ray sources are generally less extensive than for Cyg X-1, we have compared the percentage power pulsed found for individual days with the actual source intensity for each day of observation to test if the power pulsed and the 2–6 keV source intensity were correlated. With the exception of Cyg X-1, which was discussed above, and possibly Cir X-1 (3U 1516−56), none of the sources in this survey showed evidence for this type of correlated behavior.

Let us now consider the observed variability of Cyg X-3. As Table 1 shows, Cyg X-3 exhibits a moderate amount of variability on short time scales. Our observation of the average variability can be compared with the predictions of the basic model of a binary system with an X-ray object (neutron star, white dwarf, or black hole) enveloped in the dense stellar wind of the companion star (Pringle 1974; Davidsen and Ostriker 1974). The parameter we have used to characterize the variability can be used to obtain a strict upper limit on the optical depth to X-rays in the cloud. Since $\beta = 9.2 \pm 1.0$ percent for Cyg X-3, then at least 9.2 percent of the radiation from the source (or from a region of size $\leqslant 0.1$ lt-sec) must escape unscattered (assuming the initial radiation to be 100% variable). Therefore, $\tau < 2.4$ on the average. If, however, we take the intrinsic variability to be that observed for Cyg X-1, or about 22 percent, then $\tau < 0.8$ for Cyg X-3. These values are roughly in agreement with those derived by Pringle but conflict with the nominal parameters of the Davidsen and Ostriker model whose minimum optical depth is ~ 5.3. The difference arises from the differing assumptions for the wind velocity (Pringle uses $v_{\text{wind}} \sim 500$ km s^{-1} while Davidsen and Ostriker use 100 km s^{-1}). The Davidsen and Ostriker model might be made consistent with the observed optical depth by scaling the velocity parameter. Certain difficulties do arise; for example, their calculated value for the radius of the emitting cloud agrees only poorly with the observed value from the infrared assuming the cloud to be optically thick. While the model with certain parameters changed may be consistent, the short time scale observations do constrain models for Cyg X-3 which require very dense clouds. More generally, models for any source which use dense circumstellar clouds must take into account the short-time-scale behavior of the source.

IV. LIGHT CURVES: OBSERVATIONS AND DISCUSSION

The last results obtained from our analysis were light curves derived from the amplitudes found in the minimum χ^2 fits of each observation. These light curves are of interest because they show a degree of variability not yet generally recognized.

The amplitude for each observation was corrected for the elevation of the source in the field of view using the rough equation of motion determined from star sensor data which is accurate to 0°.1. This latter error was incorporated with the statistical counting error when we computed the uncertainty in the intensity (counts s^{-1}).

Table 4 gives a summary of the variability on a time scale of minutes (the spin period of the satellite) to hours (one day of about 24 hours is the typical time spent scanning a single band of the sky). This table gives for each source on each day of observation the maximum observed intensity, the ratio of maximum to minimum intensity, the time between the maximum and the minimum intensity, and the probability, $Q(\chi^2)$, that the observed intensities are consistent with a constant source intensity.

The results summarized in Table 4 show that about half (9) of the 19 sources studied varied by more than a factor of 2 in less than one day. An additional six sources varied by factors between 1.5 and 2.0. Of the remaining four sources which varied by less than 50 percent and whose significance of variability was also less than 3 σ—3U 0531+21, 3U 1728−16, 3U 1735−28, and 3U 1837−04—the latter three are known to vary from day to day (Giacconi *et al.* 1974). For 3U 1837+04 and 3U 1735−28, we had only one day of observations with good aspect solutions which permitted corrections to the intensity. Hence, we do not have sufficient data to say that 3U 1735−28 and 3U 1837+04 show less variability than the other sources. That this is accurate is supported by the fact that 13 of 19 sources did not vary significantly during at least one day. We do have sufficient observations of 3U 1728−16 to suggest that it shows substantially less variability within a day than the other sources. Rechecking the data in the 3U catalog, we also find that the evidence for variability from day to day is marginal for this source, depending on two sightings when the source was

TABLE 4

INTENSITY VARIATIONS WITHIN A DAY

Source	Month/Day/Year	Maximum Intensity	I_{max}/I_{min}	$T_{max} - T_{min}$ (in days)	$Q(\chi^2)$
3U 0531+21........	2/21/71	1020 ± 37	1.12 ± 0.06	0.23	0.46
	3/12/71	1135 ± 69	1.31 ± 0.12	0.22	0.11
	3/16/71	1021 ± 49	1.20 ± 0.09	0.27	0.79
	4/25/71	1060 ± 58	1.16 ± 0.09	0.07	0.60
3U 1516−56........	1/16/71	575 ± 26	1.95 ± 0.16	0.42	< 0.00001
	1/22/71	386 ± 23	1.47 ± 0.14	0.09	0.00026
	2/14/71	878 ± 40	12.50 ± 1.90	0.27	< 0.00001
	2/18/71	524 ± 43	2.14 ± 0.31	0.44	< 0.00001
	3/17/71	485 ± 26	1.89 ± 0.17	0.13	< 0.00001
3U 1636−53........	2/17/71	325 ± 22	1.53 ± 0.17	0.02	0.011
	2/21/71	308 ± 23	1.48 ± 0.16	0.07	0.033
	2/25/71	337 ± 20	1.43 ± 0.14	0.04	0.0061
	3/17/71	461 ± 69	2.22 ± 0.42	0.56	0.00001
	3/19/71	353 ± 32	1.67 ± 0.21	0.98	0.00006
3U 1642−45........	2/25/71	466 ± 25	1.41 ± 0.12	0.07	0.0027
	3/12/71	400 ± 23	1.78 ± 0.17	0.09	< 0.00001
	3/17/71	590 ± 40	1.33 ± 0.12	0.55	0.048
3U 1658−48........	2/17/71	150 ± 12	1.96 ± 0.26	0.23	< 0.00001
	2/21/71	180 ± 14	1.73 ± 0.22	0.15	0.00006
3U 1702−36........	2/14/71	926 ± 61	1.75 ± 0.19	0.54	< 0.00001
	2/17/71	1071 ± 58	2.20 ± 0.19	0.09	< 0.00001
	2/21/71	1158 ± 174	2.29 ± 0.54	0.20	< 0.00001
	3/16/71	895 ± 79	2.21 ± 0.30	0.29	< 0.00001
3U 1705−44........	2/17/71	269 ± 16	1.46 ± 0.14	0.08	0.029
	2/21/71	321 ± 21	1.50 ± 0.16	0.06	0.0021
	3/17/71	367 ± 21	1.41 ± 0.13	0.13	0.0113
	3/19/71	347 ± 20	1.62 ± 0.15	0.21	< 0.00001
3U 1728−16........	2/14/71	241 ± 17	1.42 ± 0.16	0.21	0.58
	2/17/71	271 ± 17	1.35 ± 0.14	0.49	0.15
	3/13/71	254 ± 15	1.30 ± 0.12	0.01	0.46
	3/15/71	264 ± 18	1.35 + 0.14	0.05	0.27
	4/25/71	289 ± 25	1.35 ± 0.17	0.20	0.25
3U 1735−28........	3/12/71	662 ± 39	1.31 ± 0.11	1.05	0.088
3U 1744−26........	3/12/71	405 ± 25	1.52 ± 0.14	0.68	< 0.00001
	3/19/71	482 ± 46	1.93 ± 0.26	1.06	< 0.00001
3U 1758−25........	3/12/71	1036 ± 40	1.22 ± 0.07	0.99	0.026
	3/19/71	834 ± 35	1.64 ± 0.12	0.94	< 0.00001
	4/ 1/71	1068 ± 258	2.47 ± 0.77	0.32	0.29
3U 1758−20........	2/21/71	568 ± 47	1.68 ± 0.23	0.14	0.011
	3/12/71	588 ± 29	1.50 ± 0.12	0.22	< 0.00001
	3/19/71	608 ± 66	1.78 ± 0.32	0.26	0.00003
	4/24/71	602 ± 75	1.76 ± 0.30	0.19	0.026
	4/25/71	628 ± 41	1.58 ± 0.15	0.15	< 0.00001
3U 1811−17........	3/12/71	430 ± 22	1.79 ± 0.15	0.08	< 0.00001
	3/19/71	380 ± 32	2.00 ± 0.27	0.91	< 0.00001
	4/ 1/71	422 ± 43	1.72 ± 0.27	0.10	< 0.00001
	4/24/71	383 ± 25	1.49 ± 0.15	0.20	0.00007
3U 1813−14........	3/12/71	583 ± 30	1.35 ± 0.11	0.77	0.00002
	3/16/71	624 ± 43	1.56 ± 0.17	0.13	0.00001
	3/19/71	866 ± 96	2.15 ± 0.38	0.15	0.00025
	4/ 1/71	810 ± 64	1.97 ± 0.27	0.29	< 0.00001
	4/24/71	834 ± 56	1.54 ± 0.14	0.35	0.00006
3U 1820−30........	3/17/71	250 ± 24	1.51 ± 0.21	0.22	0.16
	4/ 1/71	321 ± 20	1.51 ± 0.15	0.30	0.012
	4/ 2/71	297 ± 20	2.56 ± 0.33	0.49	< 0.00001
	4/25/71	250 ± 19	1.54 ± 0.18	0.30	0.13
3U 1837+04........	4/ 1/71	286 ± 20	1.41 ± 0.15	0.01	0.013
3U 1956+35........	12/29/70	1553 ± 131	2.80 ± 0.39	0.22	< 0.00001
	1/16/71	1048 ± 54	1.47 ± 0.12	0.08	< 0.00001
	2/11/71	1676 ± 102	2.46 ± 0.26	0.35	< 0.00001
	3/12/71	1546 ± 143	2.68 ± 0.37	0.93	< 0.00001
	3/13/71	1004 ± 36	1.20 ± 0.06	0.49	0.014
	3/15/71	1225 ± 43	1.48 ± 0.08	0.20	< 0.00001
	3/19/71	2076 ± 424	3.64 ± 1.07	0.60	< 0.00001
3U 2030+40........	2/ 5/71	267 ± 21	2.55 ± 0.46	0.65	< 0.00001
3U 2142+38........	1/ 4/71	490 ± 25	1.38 ± 0.11	0.10	0.00008
	3/17/71	447 ± 28	1.55 ± 0.15	0.31	< 0.00001
	4/16/71	474 ± 37	1.72 ± 0.20	0.21	< 0.00001
	6/20/71	383 ± 22	1.34 ± 0.11	0.91	0.00043

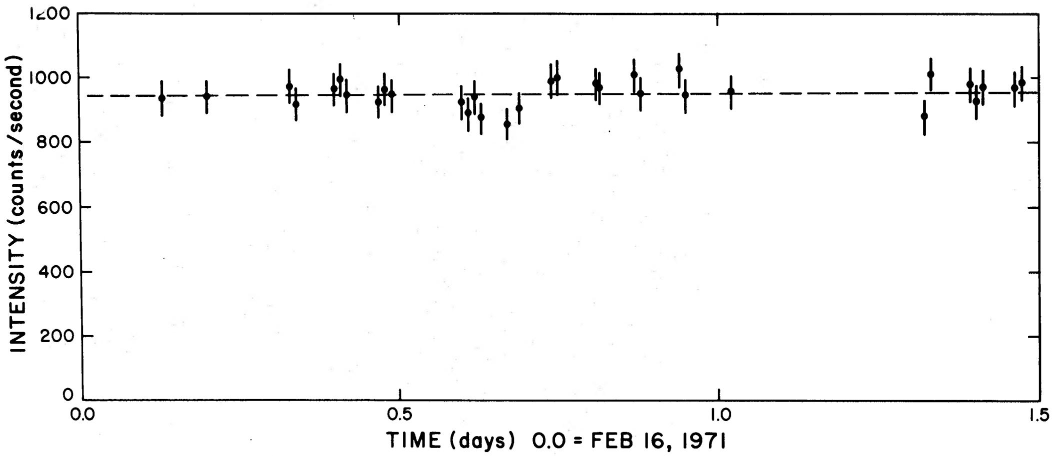

FIG. 3.—The intensity as a function of time for the X-ray source 3U 0531+21 (Crab) is shown. The error bars include both statistical errors and 0°.1 aspect uncertainty. Testing the observed intensities against the hypothesis that the source is constant gave $Q(\chi^2) = 0.79$ confirming quantitatively the absence of variability on this time scale. This confirms that our procedure is correct.

more than halfway to the edge of the collimator field of view. The last source which was not observed to vary on time scales from minutes to days is the Crab Nebula, which is not expected to exhibit such variations and is a check on the correctness of our technique. Figure 3 shows graphically our results for one day of observations for the Crab.

Table 4 and the general remarks above characterize in only a general way the remarkable range of variability we have observed. Figures 4–8 show clearly the difficulty in trying to quantify such varied behavior.

Figure 4 shows different types of behavior for Cir X-1. In the upper portion of the figure we see a transition from an intensity of about 800 counts s^{-1} to one of about 80 counts s^{-1}. The intensity change of a factor of 10 occurs in less than 1.5 hours. While such large changes do occur, the intensity in the first two-thirds of the higher state and the intensity in the lower

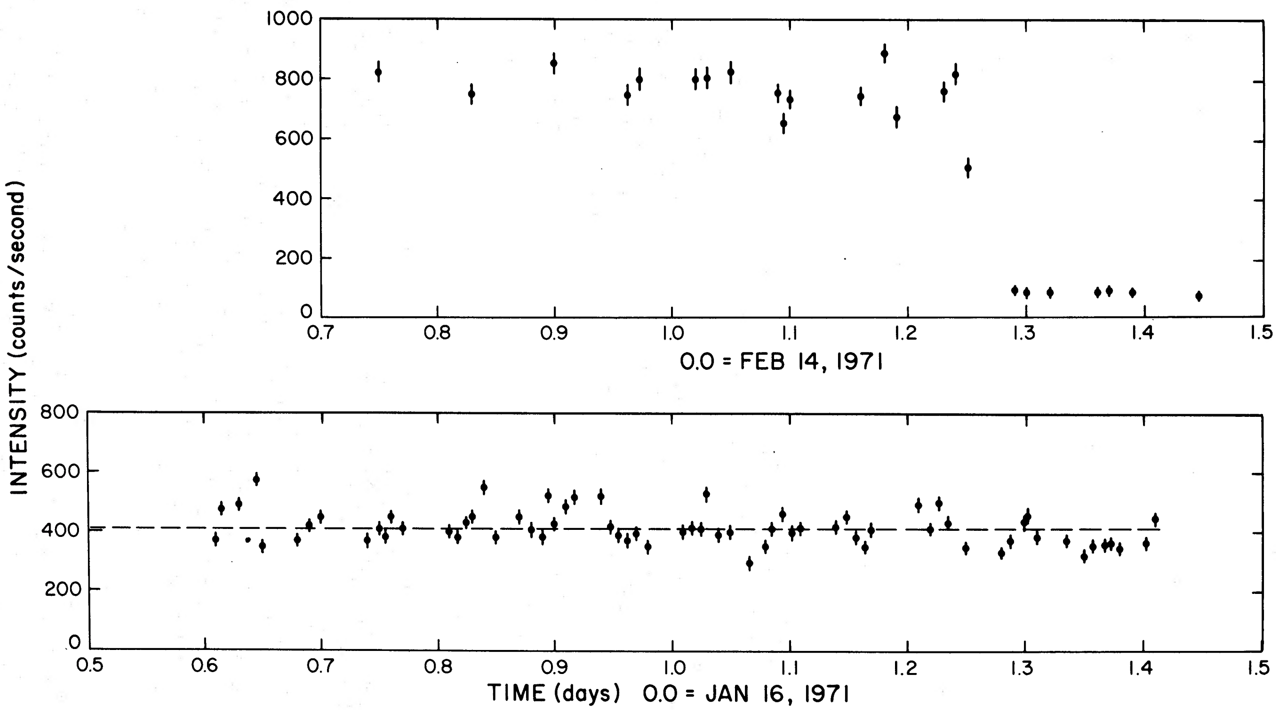

FIG. 4.—Two light curves for Cir X-1 (3U 1516−56) are shown. The upper portion shows a "transition" from an average intensity state of 772 ± 8 counts s^{-1} to one at 82 ± 6 counts s^{-1}. The time for this change of the intensity by almost a factor of 10 is less than 80 minutes. The lower portion of the figure shows an intermediate intensity level, 400 counts s^{-1}, with 30% changes occurring in less than 15 minutes.

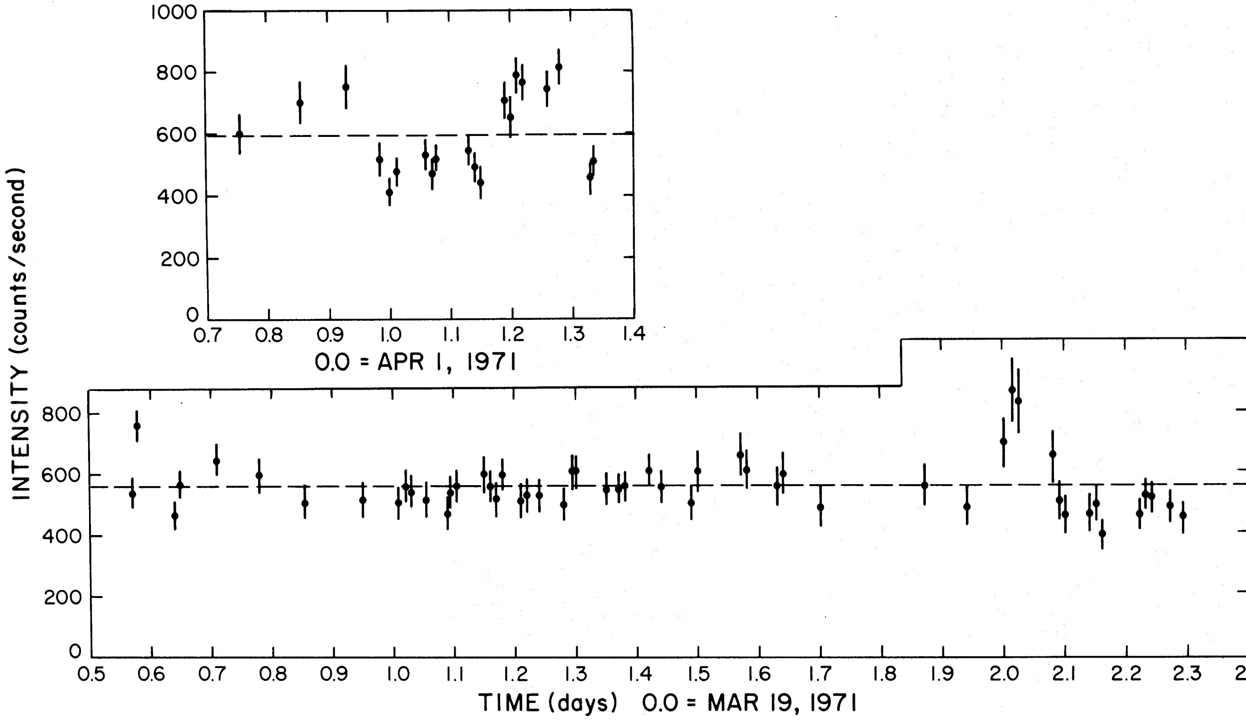

FIG. 5.—Two light curves for GX 17+2 (3U 1813−14) show different types of behavior. The first gives a suggestion of a Cyg X-3–like behavior with a period of about 0.35 days while the second shows a more constant behavior with occasional flaring.

state both appear to be constant. The only variability apparent appears for about 2 hours before the transition. This behavior is not the rule for Cir X-1, as the lower portion of Figure 4 shows. On this day, the intensity was intermediate between the two extremes shown in the top half of the figure. The intensity varied by almost a factor of 2 in less than 1 hour (just after 0^h January 17; see Fig. 4).

Figure 5 (*top*) suggests a Cyg X-3–like intensity behavior for GX 17+2 (3U 1813−14). The intensity varies by almost a factor of 2 between two states, peaking at 800 counts s^{-1} with a minimum at about 400 counts s^{-1}. The intensity shown in this figure starts with an intermediate value, rises to a maximum, then falls to a minimum and repeats with a possible period of about 0.35 days. The bottom portion of the figure, however, shows a different type of behavior for this source in which the intensity slowly varies with widely separated flares (March 19.55 and 21.05). During the flares we find almost a factor of 2 change in about 1 hour, but no evidence for a 0.35 day periodicity is evident in the figure. The X-ray source 3U 1642−45 also exhibited Cyg X-3–like behavior with a period of approximately 1.5 days as is shown in Figure 6. Such behavior was not always observed in our data.

The last two figures (Figs. 7 and 8) show light curves of two different sources, namely, 3U 1705−44 and 3U 1702−36. The intensity of the former source is among the lowest we studied while that for the latter is among the strongest (in excess of 1000 counts s^{-1}). Neither light curve can be described simply or be characterized by a particular property other than what appears to be a random pattern of intensity variability. This kind of behavior appears to be more the rule than any other.

IV. CONCLUSION

We find that most strong galactic X-ray sources (17 of 19) exhibit variability on a time scale of 0.1–1.0 s. Hence, we can draw a fundamental conclusion: the X-ray emission is produced through a mechanism involving a compact object—white dwarf, neutron star, or black hole—since the luminosity is of the order of 10^{38} ergs s^{-1} and the emitting region must be of a size comparable to that of the object. This observed variability is also consistent with the hypothesis that most strong galactic X-ray sources are members of binary systems and that the X-rays are produced by accretion of material from a normal member of the binary onto a compact member.

A second conclusion of our analysis, based on our light curve studies, is that the Crab and possibly GX 9+9 (3U 1728−16) are the only X-ray sources in our sample whose emission is dominated by a supernova remnant. No other source maintains a constant intensity during a day or from day to day. A further extension of our light-curve analysis to sources of lower intensity would allow the possible discovery of other candidate supernova remnants.

Another conclusion concerns the variability of the

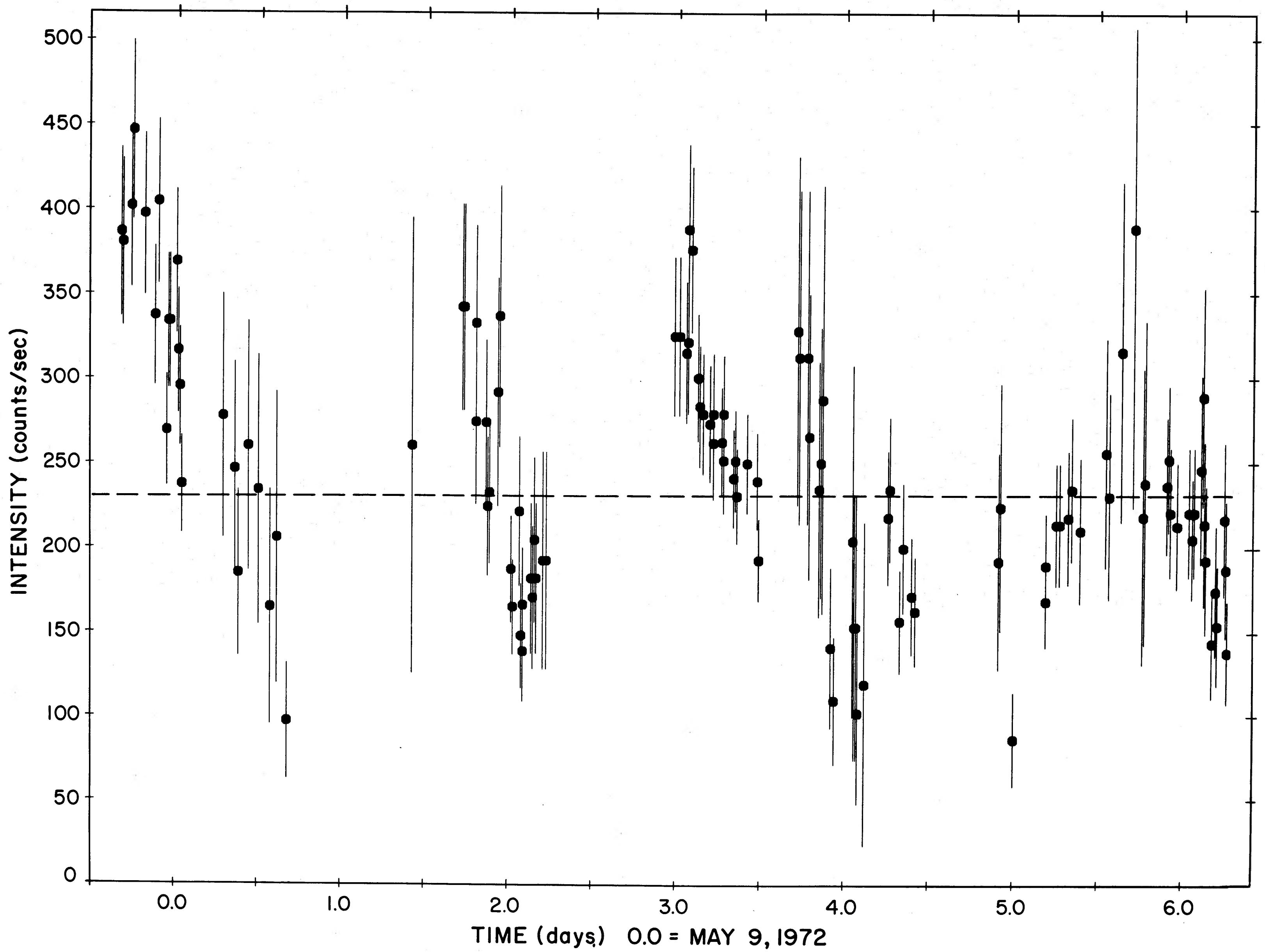

FIG. 6.—A light curve for 3U 1642−45 (GX 340) shows a Cyg X-3 type modulation

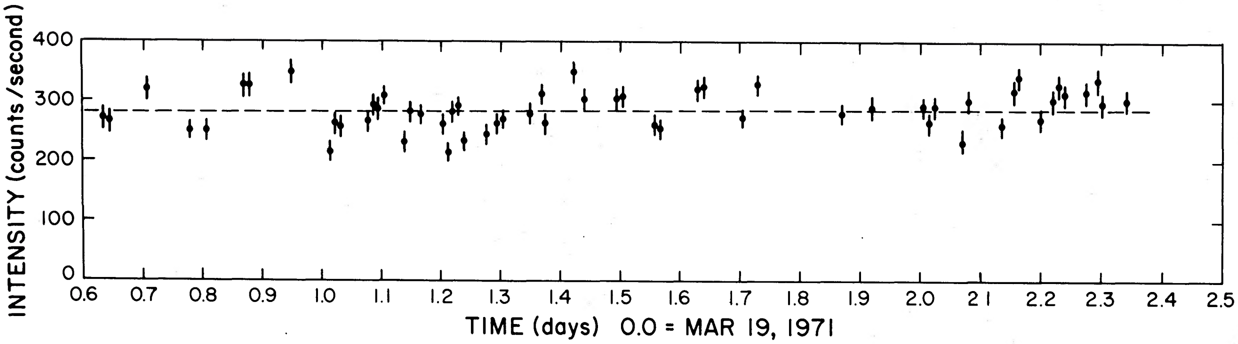

FIG. 7.—A light curve of the X-ray source 3U 1705−44 is shown. The intensity of this source was among the weakest in our sample. The probability of obtaining the observed scatter in intensity from a source of constant intensity is less than 10^{-5}.

sources and a possible correlation with spectrum. First, Cyg X-1 (3U 1956−35) shows an outstanding amount of variability based on both its high percentage of randomly pulsed emission and the large number of intensity bursts. Both Cir X-1 (3U 1516−56) and 3U 1758−20 merit further detailed study since they show the most significant burst-type behavior, other than Cyg X-1. At the low end of the scale of variability are 3U 1728−16 (GX 9+9) and 3U 1658−48. If 3U 1658−48 indeed does not vary on short time scales, then it is also interesting to note that its spectrum is very steep (Jones 1975) and that Cyg X-1 showed much less variability when its spectrum was steep. Also, Cir X-1 shows the least amount of variability on short time scales (Table 2) on 1971 February 14 when its 2–6 keV intensity is highest (Table 4) and when its spectrum is also steep. We speculate that the steep spectra originate in the outer portion of the disk (spatially thin, optically thick) where the size of the emitting region is more stable, thereby leading to much less variability on times less than 1 s.

We conclude with a remark concerning the nature of the strong X-ray sources which lie toward the center of the Galaxy (e.g., 3U 1702−36, 3U 1744−26, 3U 1758−25, 3U 1758−20, 3U 1811−17 and 3U 1813−14). Observationally, this group of sources is similar to the globular cluster X-ray sources. Specifically, we found that 3U 1820−30 = NGC 6624 was similar in its general variability to the galactic center sources (as well as most of the others in Table 2). Furthermore, 3U 1820−30 and 3U 1746−37 = NGC 6641 have X-ray spectra characterized by exponentials with $kT = 5.5 \pm 2.5$ which are similar to what we observe for the galactic center sources (Jones 1975). These temperatures are in strong contrast to those of the eclipsing binary X-ray sources with $kT > 15$ keV (Jones *et al.* 1972). In addition to this difference in temperature, none of the strong galactic center sources have been observed to eclipse, with periods from 1 to 7 days, although this may simply be due to the inclination angle of the observer. The similarities of the galactic center sources to the globular cluster sources and their differences from

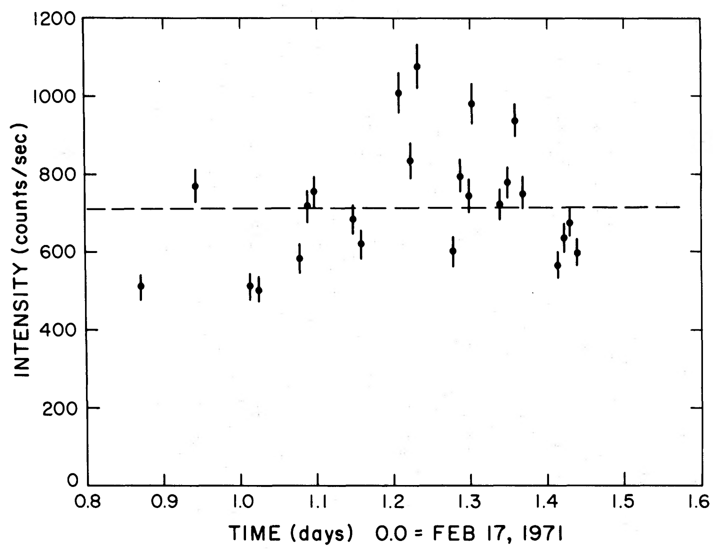

FIG. 8.—A light curve of 3U 1702−36 (GX 349) is shown. The intensity of this source is among the highest in our sample. Strong variations are clearly present with changes of a factor of 2 occurring in one hour.

the eclipsing binary X-ray sources are in accord with the possibility that the galactic center sources produce X-rays through accretion onto massive black holes as Bahcall and Ostriker (1975) have suggested for the globular cluster sources. While the galactic center sources could belong to undiscovered globular clusters (Ostriker 1975), we suggest that they could also be isolated black holes, possibly disrupted globular clusters, accreting material from the interstellar medium. The luminosity of a black hole in a cloud of gas (derived by Bahcall and Ostriker) is $L_x = 7 \times 10^{37} E_{0.1} N_{15} M_{1000} V_{25}^{-3}$ ergs s^{-1}, where $E_{0.1}$ is the efficiency of converting rest mass to X-rays in units of 10 percent, N_{15} is the number density in units of 15 cm^{-3}, M_{1000} is the mass of the hole in units of 1000 $M_{\odot}$, and V_{25} is the relative velocity of the hole with respect to the gas in units of 25 km s^{-1}. A 1000 $M_{\odot}$ black hole moving through an H II region, for example, with $N \sim 100$ cm^{-3} at a velocity of 25 km s^{-1} would produce an X-ray luminosity in excess of 10^{38} ergs s^{-1} and would satisfy the observed energy requirements. Finally, we note that the characteristic temperature of emission should decrease with increasing mass, with the precise dependence requiring a specific model. This general trend is consistent with the softer X-ray spectra of the galactic center and globular cluster sources arising from accretion onto massive black holes compared to the harder spectrum produced by the lower-mass black hole, Cyg X-1.

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