THE ASTROPHYSICAL JOURNAL, 207:L105–L108, 1976 July 15

RECURRENT BRIEF X-RAY BURSTS FROM THE GLOBULAR CLUSTER NGC 6624

G. W. CLARK, J. G. JERNIGAN, H. BRADT, C. CANIZARES, W. H. G. LEWIN, F. K. LI, W. MAYER, AND J. MCCLINTOCK
Department of Physics and Center for Space Research, Massachusetts Institute of Technology
AND
H. SCHNOPPER
Center for Astrophysics, Smithsonian Astrophysical Observatory/Harvard College Observatory
Received 1976 March 10; revised 1976 April 16

ABSTRACT

Ten brief bursts of X-rays, recurrent at nearly equal intervals, have been detected in data obtained during a two-day observation of the X-ray source 3U 1820−30 in the globular cluster NGC 6624 by the SAS-3 X-ray observatory during 1975 May. The bursts occurred at times near those in the sequence t_k = JD 2,442,549.4121 + 0.1822k with k = 1, 2, 3, 5, 6, 7, 8, 9, 10, 11. The rms deviation between the actual occurrence times and the corresponding values of t_k is 621 s, which is equivalent to an rms phase jitter of 3.9 percent. The co-added light curve of the five best observed bursts rises to peak intensity in about 1 s, decays exponentially with a time constant of ~3.5 s, and has a total energy flux of approximately 3×10^{-7} ergs cm^{-2} per burst in the 1–10 keV energy range. The spectrum changes from very soft to very hard during the first 4 s, and then remains constant. The observed flux implies a total energy release per burst of ~10^{39} ergs if the source is at a distance of 5 kpc and radiates isotropically.

Subject headings: clusters: globular — stars: neutron — X-rays: sources — X-rays: transient sources

I. INTRODUCTION

Grindlay *et al.* (1976) recently reported the detection of two brief, intense bursts of X-rays during an observation of the variable X-ray source 3U 1820−30 in the globular cluster NGC 6624. The bursts were observed in 1975 September with detectors on the ANS satellite. In 1975 May, we carried out a two-day observation of 3U 1820−30 with the wide-field modulation collimator detectors on the SAS-3 X-ray observatory. Following the early report of Grindlay and Heise (1975), we examined the complete production data for the May observation and found 10 brief bursts similar to those described by Grindlay *et al.* Furthermore, we discovered that the bursts were recurrent at nearly equal time intervals. In this *Letter* we present data showing the properties of these bursts and the location of their source.

Babushkina *et al.* (1975) previously reported the detection of two X-ray bursts, similar in temporal structure to those detected by Grindlay *et al.*, but with a harder spectrum and from a different source.

II. OBSERVATIONS

The observations were made with two independent rotation modulation collimator detectors which have been described previously by Doxsey *et al.* (1975). The detectors are sensitive from 2 to 11 keV, and have 12° × 12° FWHM fields of view centered on the direction of the rotation axis (z-axis) of the satellite.

During the period from 1975 May 17.0 to 19.0 the observatory was operated for the purpose of measuring the position of 3U 1820−30 with improved accuracy by means of the modulation collimator detectors. We found that the source lies within a 90 percent error circle of radius 40″, which includes the optical center of the globular cluster NGC 6624.

Figure 1 is a display of the total numbers of counts accumulated in 3.3 s intervals from both modulation collimator detectors, plotted as a function of time for orbits in which bursts were observed or expected (see below). Superposed on the modulated rate of the steady discrete sources are 10 brief increases labeled k = 1, 2, . . . , 11 (k = 4 missing), which we attribute to bursts of X-rays of cosmic origin. Expanded displays of the time profiles of these bursts in two energy bands are also shown with the 2–6 keV data below and the 6–11 keV data above. In all but the case of k = 5, the distinction between the labeled increase and nearby fluctuations due to collimator modulations is clear and unambiguous.

The bursts exhibit a number of significant regularities. The clearest signals were obtained for the five labeled k = 7, 8, 9, 10, and 11 which occurred when the z-axis was farther from the interfering bright sources near the galactic center. In each case, the 2–6 keV rate rose to its peak value in about 1 s and then decayed to the preburst background level in approximately 10 s. The 6–11 keV rate rose more slowly, reached its maximum ~1 s after the lower energy component, and then decayed in a similar way. These features are shown more clearly by Figure 2 which displays the co-added

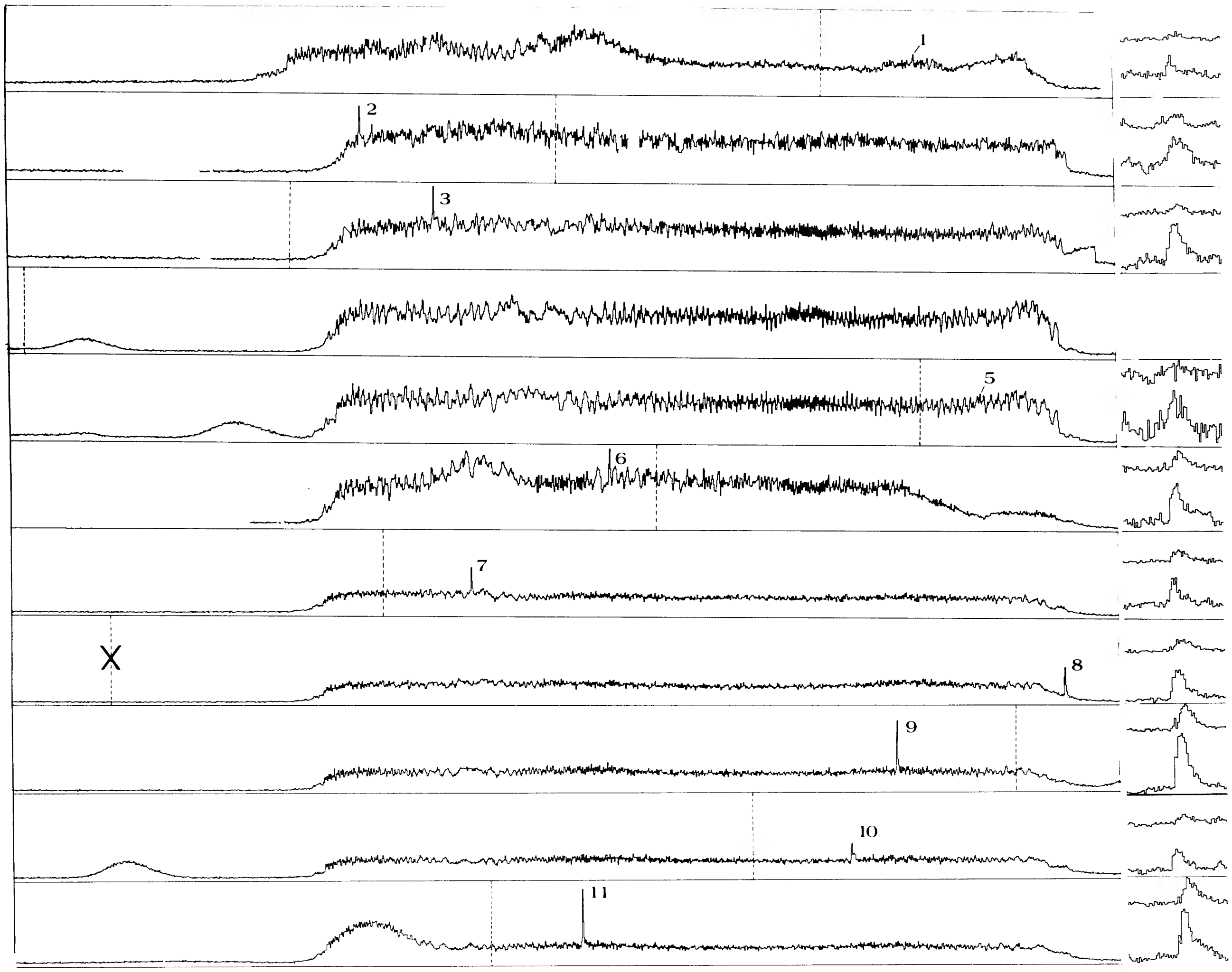

FIG. 1.—Combined 2–11 keV counting rate from the two modulation collimator detectors plotted as a function of time for the 11 satellite orbits in which bursts were detected or expected according to the recurrence formula given in the text. The rates vary systematically during the 95 minute period of the satellite orbit from steady low values when the fields of view are occulted by the Earth to higher modulated values when the detectors record X-rays from discrete sources. The dashed lines indicate the "expected" recurrence times except in the orbit with burst 8, where the dashed line marked with a × indicates the time expected on the next orbit (not shown). For these observations the z-axis of the observatory was moved to a position near NGC 6624 before burst 1, and then to another nearby position just after burst 6. Shown at the right of each orbit with a burst are expanded plots with identical vertical scales of the counting rates during the burst in the 2–6 keV (*lower*) and 6–11 keV (*upper*) energy channels.

light curves for bursts 7 to 11 in the two energy channels The delay in the rise of the higher energy component is reflected in the variation of the spectral hardness ratio which we define to be the quotient of the counts in the high and low energy channels. This ratio, plotted at the bottom of Figure 2, increases from ~0.1 to 1.0 during the first 4 s and then remains approximately constant. For comparison, the hardness ratio of the Crab in these detectors is 0.33. A hardness ratio of 1.0 implies a photon spectral index of ~0.25 for a power law spectrum. A thermal spectrum with $kT \gtrsim 20$ keV could also give this ratio, but only if one includes a low energy cutoff at 3 keV.

Functions of the form exp $(-t/\tau)$ were fitted by least squares to the numbers of counts in intervals 8–30 after subtraction of a background rate equal to the average number of counts in the 15 intervals before the initial rise. The resulting values of the characteristic decay time τ were (3.6 ± 0.1) s and (3.4 ± 0.1) s for the 2–6 and 6–11 keV channels, respectively.

The occurrence times of the 10 observed bursts are not random. The mean interval of exposure time between bursts was 0^d14. We find no bursts separated by exposure times shorter than 0^d11. The probability of this happening if they were random events governed by Poisson statistics is less than 10^{-3}. Furthermore, the bursts march through the orbital phase like a periodic phenomenon with a period that is incommensurate with the orbital period. In fact, the occurrence times are fitted by least squares to the sequence $t_k =$ JD 2,442,549.4121 + 0.1822k (k = 1, 2, 3, 5, 6, 7, 8, 9, 10, 11) with an rms deviation of 621 s, which is equivalent

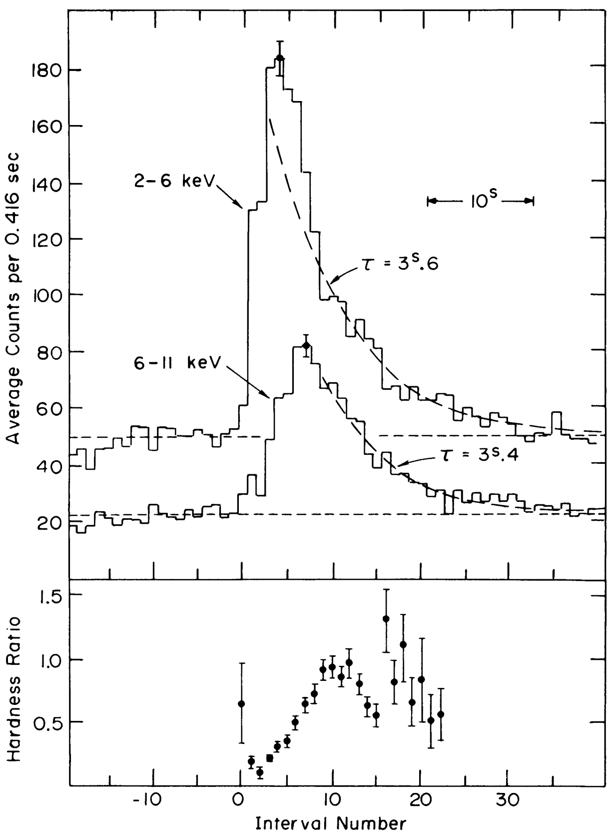

FIG. 2.—Co-added light curves of bursts 7–11, and plot of the hardness ratio of the burst radiation.

to a phase jitter of 3.9 percent. These times are indicated by dashed lines in Figure 1. The time t_4 occurs during a period of complete blockage of the detector field of view by the Earth so that if the $k = 4$ burst occurred near t_4 it would not have been detected.

The region of the sky within which the source of these 10 apparently related bursts lies can be narrowed to the common intersection of the unocculted portions of the fields of view at the ten occurrence times. This region has an area of approximately 130 deg^2. The only two sources in the 3U catalog (Giacconi *et al.* 1974) which lie within this region are the highly variable globular cluster source 3U 1820−30 and the comparatively faint and reportedly steady source, 3U 1822−37.

We estimated the average total flux and average peak intensity of X-ray bursts $k = 7$–11 on the assumption that the source is at the position of NGC 6624 and that the average collimator response during the five bursts was equal to the local average of the transmission function over the rapid modulations. The result for the flux and peak intensity was 2.9×10^{-7} ergs cm^{-2} and 7.1×10^{-8} ergs cm^{-2} s^{-1}, respectively. The latter is approximately twice the intensity of the Crab Nebula in the same energy range. In the cases of two bursts for which precise aspect solutions are available, namely $k = 7$ and 11, we found that the peak intensities, corrected for the exact collimator responses, differed by a factor of $\sim$2.

The $k = 8$ burst occurred 20 s after all the known sources other than 3U 1820−30 and 3U 1822−37 were Earth-occulted. The average rate during these 20 s was 98 counts s^{-1}, of which 83 counts s^{-1} can be attributed to diffuse X-rays and cosmic rays. The difference of 15 counts s^{-1} is, therefore, an upper limit on the counting rate due to the quiescent emission of the source of the bursts. The average peak rate in bursts 7–11 is 442 counts s^{-1}. Therefore, the average peak burst intensity is at least 29 times the quiescent intensity of their source. The average intensity of 3U 1820−30 during these observations was one-fifth of the maximum value reported from the *Uhuru* observations (Giacconi *et al.* 1974). 3U 1820−30 was therefore clearly in a state of low luminosity at the time of the bursts.

III. DISCUSSION

The properties of the 10 bursts reported here and the two discovered in the ANS observations are summarized in Table 1. The similarities between the May and September bursts are convincing evidence that they have a common origin which is probably 3U 1820−30. They differ markedly in their spectrum and repetitive character from the γ-ray bursts discovered by Klebesadel, Strong, and Olson (1973).

Without attempting to address the question of the underlying mechanism responsible for the release of energy in the X-ray bursts, we note that the smooth decay of their averaged light curve suggests to us that the temporal evolution may have a geometrical origin similar to that proposed by Morrison and Sartori (1969) for optical supernova light curves. In this view, the primary X-ray burst lasts only about 2 s. Compton scattering in a surrounding cloud of hot circumsource plasma stretches the pulse out and causes a progressive hardening of the spectrum. Such an idea has also been suggested by Grindlay and Gursky (1976), who concluded that the existence of such a hot extended cloud required the presence of a supermassive object to provide sufficient gravitational binding. Detailed calcula-

TABLE 1

COMPARISON OF THE X-RAY BURSTS OBSERVED BY SAS-3 AND ANS FROM THE REGION OF NGC 6624

Variable	ANS	SAS-3
Dates of occurrence	1975 Sept 27.4–30.7	1975 May 17.0–19.0
Number observed.	2	10
Rise time (seconds)	$\sim$0.5	$\sim$0.4
Decay...........	$\sim \exp(-t/8\,\mathrm{s})$	$\sim \exp(-t/3.5\,\mathrm{s})$
Spectrum.........	$\alpha = 2.1 \rightarrow 0.6$	$\alpha = 3 \rightarrow 0.2$
Average peak intensity (1–10 keV)......	8×10^{-8} ergs cm^{-2}s^{-1}	7×10^{-8} ergs cm^{-2}s^{-1}
Recurrence*......	$t_2 - t_1 \approx 1.90 \times T$	$t_k = t_0 + kT \pm \tau$
Area of location...	$\Delta A \approx 0.01$ deg^2 includes NGC 6624	$\Delta A \approx 130$ deg^2 includes NGC 6624
Intensity state of 3U 1820−30....	low	low

* $T = 0^{\mathrm{d}}1822$, $\tau_{\mathrm{rms}} = 621$ s.

tions of the scattering process by one of us (Canizares 1976) show that the observed burst profile and spectrum can be explained by scattering in a smaller, cooler cloud, thereby obviating the need for the massive central object. The difference in the characteristic decay times of the two sets of pulses then implies that a change occurred in the scattering cloud between May and September. For example, a twofold increase in the size of the cloud with no change in its optical depth would account for the difference.

The large amplitude of the phase jitter in the occurrence times of the 10 bursts raises the question as to whether the bursts are controlled by an underlying, periodic phenomenon such as rotation or orbital motion, or are events in a Markov process (see Feller 1950) such as might be produced by a relaxation oscillator. To explore these two hypotheses, we carried out Monte Carlo simulations of many sets of 11 events. Omitting the $k = 4$ pulses to match the observed May sequence, we counted the relative frequency of various numbers of zero crossings of the phase (changes of sign of $\Delta\phi$ from one pulse to the next) in each sequence of 10 events. The observed number of zero crossings is 6. In the Monte Carlo simulated sets, the relative frequency of 6 or more zero crossings was 43 percent in the case of a periodic phenomenon, versus 16 percent for a Markov process. The result, while not conclusive, suggests that the sequence of occurrence times may not be a pure Markov chain in which the lengths of the intervals between events are uncorrelated. A similar test applied to 20 or more events could be decisive on this question.

We note that if the source lies in NGC 6624 at a distance of 5.0 ± 0.1 kpc as determined recently by Liller and Liller (1976), then the peak intensity of the bursts implies a peak luminosity of 2×10^{38} ergs s^{-1} at the source. This is the Eddington limit for a body of 2 $M_{\odot}$ and is therefore sufficient to perturb the flow of matter toward a compact object of comparable mass. Thus, the occurrence times may be influenced by a feedback mechanism that causes their phase to be more stable than that of a pure Markov process.

We thank Professor T. Gold for comment on the interpretation of the phase jitter. We thank the many people at M.I.T., the Goddard Space Flight Center, the Applied Physics Laboratory of Johns Hopkins University, and the Centro Ricerche Aerospaziali, who have participated in the development and operation of the SAS-3 observatory. This work was supported in part by the National Aeronautics and Space Administration under contract NAS5-11450.

REFERENCES

Babushkina, O. P., Bratolyubova-Tsulukidze, L. S., Kudyavtsev, M.I., Melioranskii, A. S., Savenko, I. A., and Yushkov, B. Yu. 1975, *Soviet Astr. Letters*, **1**, 32.
Canizares, C. 1976, *Ap. J.* (*Letters*), **207**, L101.
Doxsey, R., Jernigan, G., Hearn, D., Bradt, H., Buff, J., Clark, G. W., Delvaille, J., Epstein, A., Joss, P. C., Matilsky, T., Mayer, W., McClintock, J., Rappaport, S., Richardson, J., and Schnopper, H. 1976, *Ap. J.* (*Letters*), **203**, L9.
Feller, W. 1950, *An Introduction to Probability Theory and Its Applications* (New York: Wiley).
Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Koch, D., and Tananbaum, H. 1974, *Ap. J. Suppl.*, No. 237, **27**, 37.
Grindlay, J., and Gursky, H. 1976, *Ap. J.* (*Letters*), **205**, L131.
Grindlay, J., Gursky, H., Schnopper, H., Parsignault, D. R., Heise, J., Brinkman, A. C., and Schrijver, J. 1976, *Ap. J.* (*Letters*), **205**, L127.
Grindlay, J., and Heise, J. 1975, *IAU Circ.*, No. 2879.
Klebesadel, R. W., Strong, I. B., and Olson, R. A. 1973, *Ap. J.* (*Letters*), **182**, L85.
Liller, M., and Liller, W. 1976, *Ap. J.* (*Letters*), **207**, L109.
Morrison, P., and Sartori, L. 1969, *Ap. J.*, **158**, 541.

H. Bradt, C. Canizares, G. W. Clark, J. G. Jernigan, W. H. G. Lewin, F. K. Li, W. Mayer, and J. McClintock: Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139

H. Schnopper: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138