THE ASTROPHYSICAL JOURNAL, 207:333–340, 1976 July 1

HIGH-ENERGY X-RAY OBSERVATIONS OF THE SOUTHERN SKY*

G. R. RICKER, M. GERASSIMENKO, J. E. MCCLINTOCK, S. G. RYCKMAN, AND W. H. G. LEWIN
Center for Space Research, Massachusetts Institute of Technology
Received 1974 August 5

ABSTRACT

On 1972 April 5, we carried out high-energy (>17 keV) X-ray balloon observations in the southern sky. At least five sources were detected. Three of them are very likely GX 331−1 (not listed in the 3U catalog) and the high-energy X-ray sources earlier designated by us as GX 1+4 and GX 301−2. The latter two sources are almost certainly 3U 1728−24 and 3U 1223−62, respectively. The flux from GX 301−2 varied continuously as it also did during our previous balloon observations on 1970 October 15–16. The largest flux change in GX 301−2 observed on 1972 April 5, was an increase by a factor of at least 5 in about 4 minutes. The average flux of GX 301−2 was about a factor of 2 lower than during our observations of 1970 October 15–16, whereas the average intensity of GX 1+4 was about a factor 3 higher. Spectra are presented. No flux was detected from GX 3+1. Upper limits to periodic fluctuations of the detected fluxes in the 0.01 to 100 Hz frequency range are given.

In 1972 we reported a flux from a region in the sky which did not contain any *Uhuru* source. Since then the eclipsing binary source 3U 1700−37 was reported and it is located within our error region. It is likely that this source produced the high-energy X-ray flux that we detected on 1970 October 16. The source flux was about 1.3 keV cm^{-2} s^{-1} in the ~18–50 keV energy range. A spectrum is presented.

Subject headings: X-rays: sources — X-rays: spectra

I. INTRODUCTION

During a 24 hour balloon flight from Alice Springs, Australia on 1972 April 5, we carried out X-ray observations in the southern sky. We used a 45 cm^2 NaI(Tl) scintillation detector surrounded by a NaI(Tl) anticoincidence jacket, mounted in an altazimuth configuration. A tungsten slat collimator defined a slit field of view of ~1°.4 × 11° FWHM. A 46 million cubic feet (1.3 × 10^6 m^3) balloon manufactured by Winzen Research, Incorporated, carried our payload to a maximum altitude of ~151,000 feet (46 km) (1.3 g cm^{-2}). The lowest float altitude (reached during the night) was ~133,000 feet (40.5 km) (2.8 g cm^{-2}). The data were both recorded on board and telemetered to a ground-based station. X-rays were recorded in eight energy channels covering the range from 17 to 115 keV. The arrival time of individual X-rays is known to an absolute accuracy of 1 ms. Aspect during the night is known to ~10′ (star photography); during the day it is known to ~20′ (Sun sensors, magnetic sensors). In-flight calibration with an ^{241}Am source demonstrated no change of any significance in the energy channel boundary settings.

Eight scans were performed during the flight. For each scan the telescope was oriented toward a particular azimuth and elevation, and the diurnal motion of the Earth caused sources to move through the field of view in 20 to 30 minutes. For more details see Lewin, Ricker, and McClintock (1971) and McClintock, Ricker, and Lewin (1971). The areas of the sky covered during each scan are shown in Figure 1. Earlier we published upper limits from 16 X-ray sources and 10 pulsars (Ricker *et al.* 1973*a*). We discuss here our observations of sources which produced excess counts above background with a significance of 4 or more standard deviations.

A maximum-likelihood technique was used to determine the bands in the sky containing the sources. The results are given in Figures 2, 3, and 4. The width of the bands is the uncertainty in the source locations (±1 standard deviation), due to counting rate statistics, source variability, and aspect uncertainties. The length of each sky band is ~20° as determined by the field of view of the detector.

II. GX 301−2 (3U 1223−62)

The sky band from which we detected a strong signal lies within a degree of the position of GX 301−2 (see Fig. 2), which we previously observed on 1970 October 15–16 (McClintock, Ricker, and Lewin 1971). As during our 1970 observations, the source was again highly variable on a time scale of minutes and less (see Fig. 5). On 1972 April 5, the largest flux change observed in the 17–42 keV energy range was an increase by a factor of at least 5 in 4 minutes (from 0.02 ± 0.08 counts s^{-1} near UT = 50,110 s to 0.63 ± 0.12 counts s^{-1} near UT = 50,350 s). Spectral analysis of the data shows that the time-averaged spectrum can be fitted by either an exponential energy

* This work was supported by the National Aeronautics and Space Administration, NGL-022-009-015, the National Science Foundation, and the Office of Naval Research.

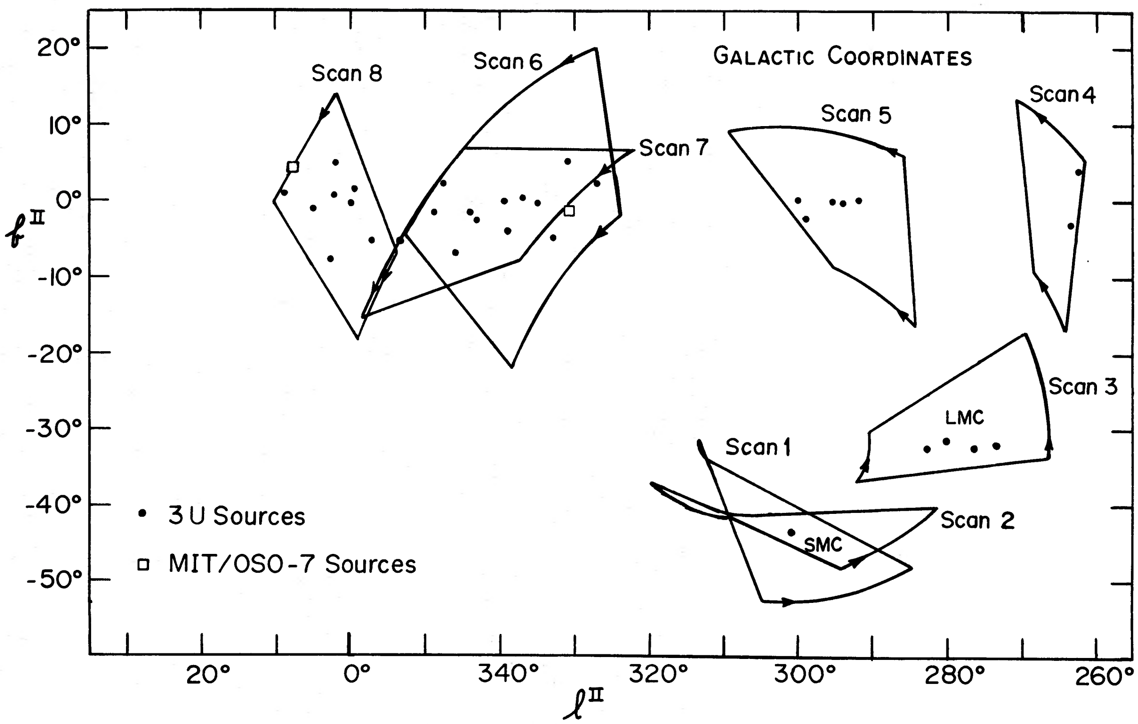

FIG. 1.—The areas scanned on 1972 April 5. 3U sources and MIT/OSO-7 sources (not reported in the 3U catalog) are shown in the eight areas scanned by us.

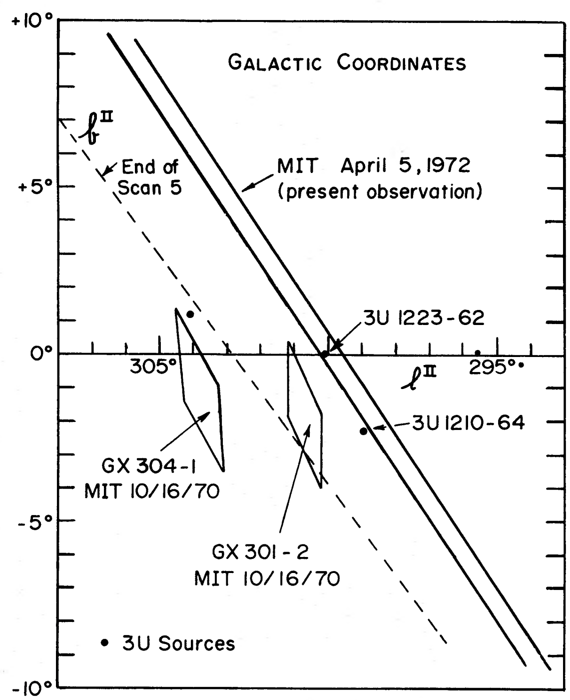

FIG. 2.—Band in the sky indicates area where a strong hard X-ray source is located. The source 3U 1223−62 lies in this band and is almost certainly the source of hard X-rays. We believe that GX 301−2 (as detected by us on 1970 October 15–16), and 3U 1223−62 are the same source (see text).

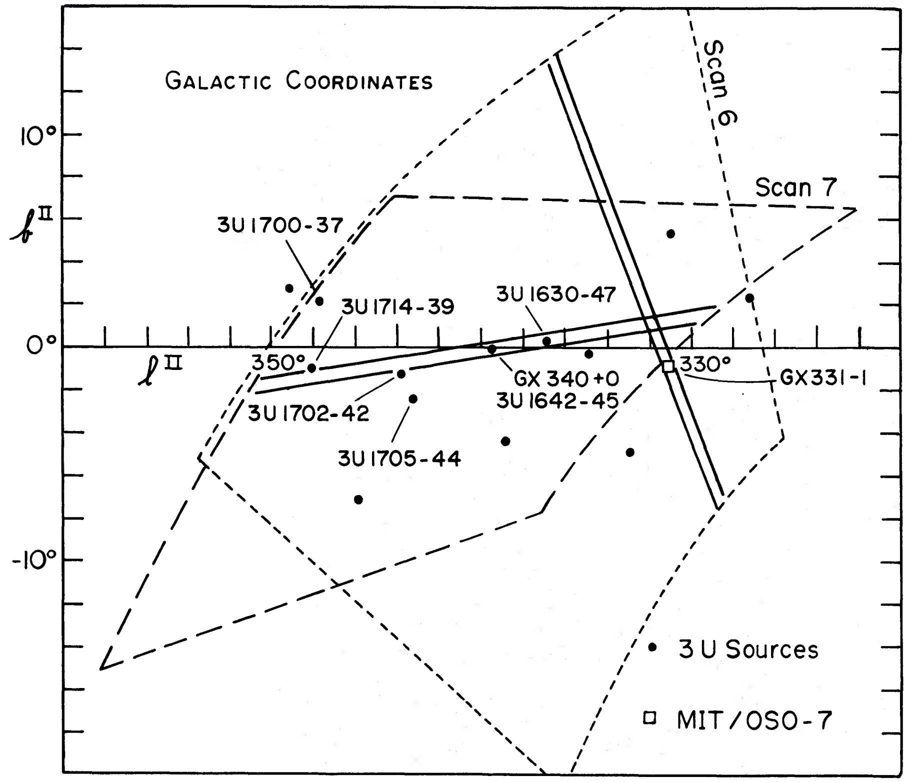

FIG. 3.—Areas scanned on 1972 April 5, during scans 6 and 7. Two bands indicate areas in the sky where high-energy X-ray sources are located. Positions for 3U sources and for GX 331−1 (not reported in the 3U catalog) are shown.

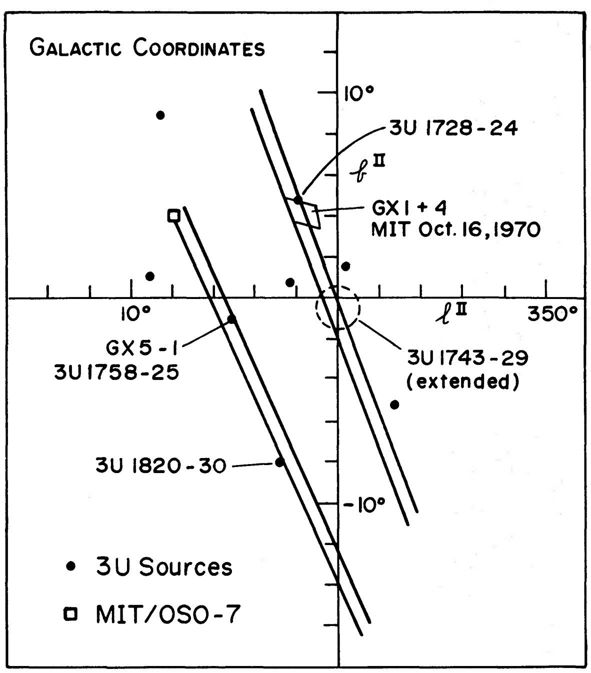

FIG. 4.—Two bands indicate areas in the sky where hard X-ray sources are located. Positions for 3U sources, for GX 8+4, and for GX 1+4 are shown; GX 1+4 is the dominant high-energy X-ray source in the galactic center region.

spectrum $J(E) \propto e^{-E/kT}$ with $kT = 6(+2, -1)$ keV or a power-law energy spectrum $J(E) \propto E^{-\alpha}$ with $\alpha = 3.7 \pm 0.3$ (see Fig. 6). These spectral characteristics are, within the indicated uncertainties, the same as those for GX 301−2 observed on 1970 October 15–76 (Ricker *et al.* 1973*b*).

The similarity in spectral shape, the same time scales and magnitudes of flux changes, and the proximity of source locations make it very likely that GX 301−2, which we observed in 1970 October, is the same source we observed on 1972 April 5. This high-energy X-ray source is almost certainly 3U 1223−62. Based on the source location derived from our present observations, we cannot distinguish between 3U 1223−62 and 3U 1210−64 (see Fig. 2). However, our 1970 position for GX 301−2 is closer to 3U 1223−62 than to 3U 1210−64. Additional arguments that the high-energy source GX 301−2 is the same source as 3U 1223−62 are that this 3U source is noted to have a flat spectrum (Giacconi *et al.* 1974) and that it is listed in the 3U catalog as variable (by a factor of 3), whereas 3U 1210−64 is not noted as variable.

Time-averaged spectral data are presented in Figure 6; our 1970 results (Ricker *et al.* 1973*b*) are also sketched in the same figure for comparison. The data points shown in Figure 6 are obtained by assuming that the source of the detected radiation is at the location of 3U 1223−62. An extrapolation of our 1970 and 1972 data to low energies does not match the flux

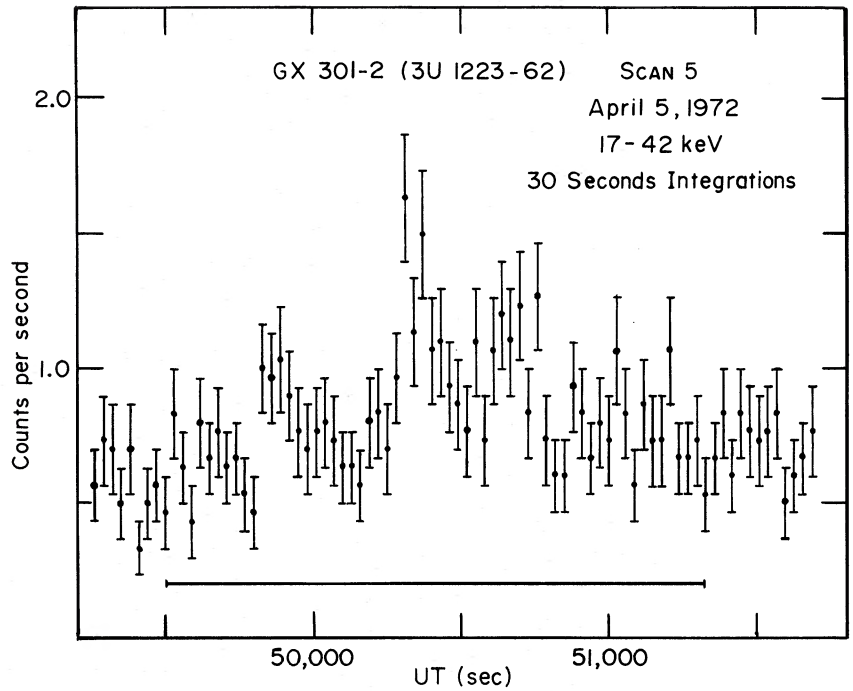

FIG. 5.—Counting rate versus time for scan 5. Each data point represents the counting rate observed in a 30 s period ($\pm 1\ \sigma$ error bars). The horizontal bar indicates the time during which 3U 1223−62 was in the field of view of our detector. The source flux is varying continuously. A large change of at least a factor of 5 is observed near UT 50,250 s.

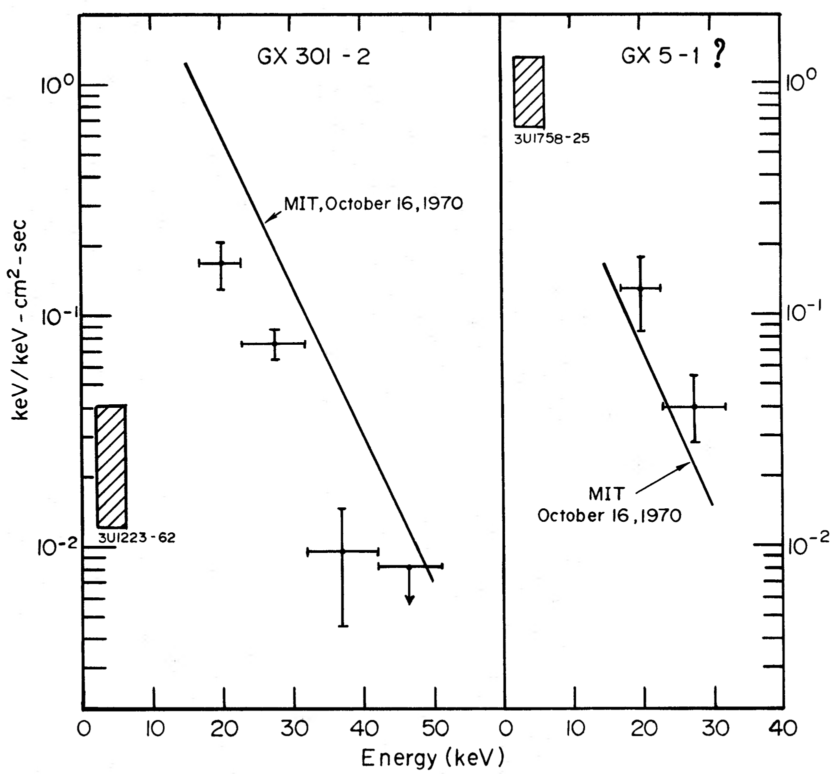

FIG. 6.—Energy spectra of GX 301−2 and GX 5−1 (and/or 3U 1820−30). The error bars indicate a 1 σ confidence level due to counting statistics; the upper limit is a 2 σ confidence level. The data points of both spectra were derived by assuming exponential spectra with a value for $kT = 6$ keV. Low-energy data shown as crosshatched rectangles are from the *Uhuru* satellite. The heights of the rectangles indicate source variability (Giacconi *et al.* 1974). Spectra measured by us on 1970 October 15–16, are sketched for the purpose of comparison.

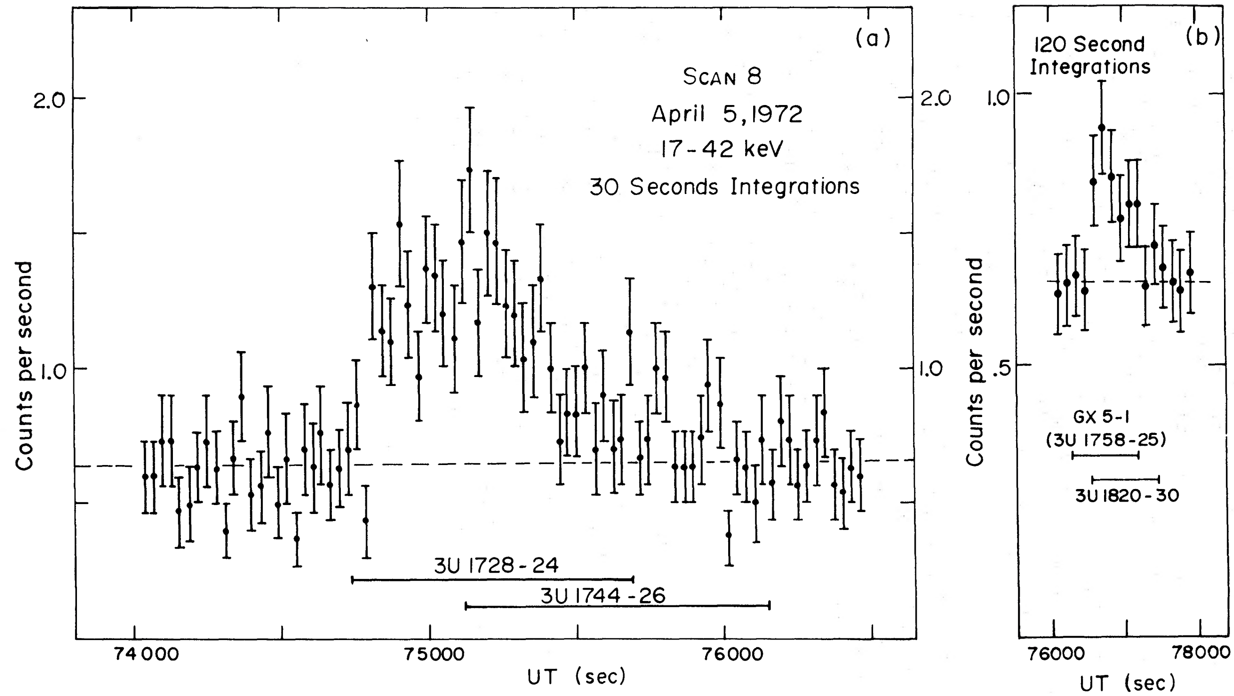

FIG. 7.—Counting rate versus time during scan 8. Horizontal bars indicate the times that 3U 1728−24, 3U 1744−26, 3U 1758−25, and 3U 1820−30 were in our field of view. (*a*): Each data point represents the counting rate observed in a 30 s period ($\pm 1\ \sigma$ error bars). (*b*): Each data point represents the counting rate as observed in a 2 min period ($\pm 1\ \sigma$ error bars). Only part of the data are shown here in a compressed time scale.

from 3U 1223−62 determined from *Uhuru* as shown in Figure 6. However, our observations are not simultaneous with *Uhuru*'s. It is possible that this extrapolation of the spectrum is not valid or that the source was about 50–100 times less intense during the reported *Uhuru* observations. Our earlier balloon observations in 1969 and 1970 have shown large fluctuations (by a factor of more than 35) of the high-energy X-ray flux from GX 301−2 (McClintock, Ricker, and Lewin 1971). As earlier suggested by us (Ricker *et al.* 1973*b*), the existence of a very high cutoff energy (near ~10 keV) cannot be excluded on the basis of presently reported observations.

III. GX 1+4 (3U 1728−24)

Two sources were recorded during scan 8 (Fig. 7). The two error regions containing the sources are shown in Figure 4. The positions of several 3U sources, the position of GX 1+4 established during our 1970 October 16 observations (Lewin, Ricker, and McClintock, 1971), and the position of a newly discovered source GX 8+4 ($l^{\rm II} = 7\overset{\circ}{.}73$, $b^{\rm II} = 3\overset{\circ}{.}76$) by the MIT OSO-7 group (T. Markert, private communication) are also shown.

Our present position band overlaps the position of GX 1+4 which includes the location of 3U 1728−24. Our position band also overlaps the position of the extended (~2°) soft source(s?) 3U 1743−29 located in the direction of the galactic center. In view of our earlier results (Lewin, Ricker, and McClintock 1971; Ricker *et al.* 1973*b*), it is very likely that the radiation detected by us is primarily due to GX 1+4, which is almost certainly the high-energy counterpart of 3U 1728−24.

Spectral data for the source are presented in Figure 8; our 1970 results are also sketched in the same figure for comparison. The data points shown in Figure 8 are obtained by assuming that the source of the observed radiation is at the location of 3U 1728−24. The data can be fitted by an exponential energy spectrum with $kT = 18 \pm 2$ keV or by a power-law energy spectrum with $\alpha = 1.6 \pm 0.2$. It is evident that the source intensity in the range 20–50 keV was greater by a factor ~3 during our 1972 observations than it was during our 1970 observations.

An extrapolation of our spectral data to lower energies yields a flux in the 2–6 keV range which is an order of magnitude larger than the flux reported for 3U 1728−24. If all or most of the flux measured by us between UT 74,750 and 75,450 s on 1972 April 5, is due to 3U 1728−24, then this source must have increased its flux in the 2–6 keV range by a factor ~10 between 1970 October 16 and 1972 April 5. This 3U source is not reported as variable in the 3U catalog.

The 1970 data suggested periodic fluctuations of the flux from GX 1+4 with a period of about 2.3 minutes (Lewin, Ricker, and McClintock 1971); the 1972 data do not (see Fig. 8). Using a superposition analysis, we find from the 1972 data that the fraction of the source flux in the 17–42 keV energy range, which varied with

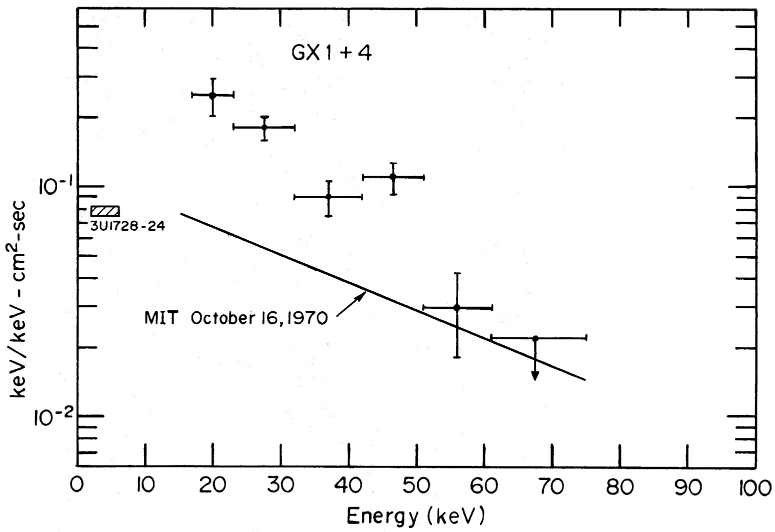

FIG. 8.—Energy spectrum of GX 1+4. The error bars indicate a 1 σ confidence level due to counting statistics; the upper limit is a 2 σ confidence level. The data points were derived by assuming an exponential spectrum with a value for $kT \approx 20$ keV (power-law energy spectrum $\alpha \approx 1.5$). The low-energy data for 3U 1728−24 shown as a crosshatched rectangle are from the *Uhuru* satellite. The heights of the rectangles indicate source variability (Giacconi *et al.* 1974). A spectrum measured by us on 1970 October 16 is sketched for the purpose of comparison.

the 2.3 minute period, was less than ~25 percent (2 σ upper limit). A rectangular pulse shape and a 50 percent duty cycle were assumed. Lowering the duty cycle to 10 percent reduces the pulsed fraction to less than 8 percent.

IV. GX 5−1 (3U 1758−25); 3U 1820−30

A second source was observed during scan 8, detected at a confidence level of ~4.5 standard deviations (see Fig. 7). The band in the sky from which the radiation was received contains the source GX 5−1 (3U 1758−25), and it is close to 3U 1820−30 (Fig. 4). Earlier in 1970 we observed X-rays from a band in the sky including the same two 3U sources (Lewin, Ricker, and McClintock 1971). At the time that we published our error region, 3U 1820−30 had not yet been reported.

Spectral data for the source are presented in Figure 6; our 1970 balloon results are also sketched for comparison. In both cases the intensities shown are obtained by assuming that the source of the observed radiation is at the location of GX 5−1 (3U 1758−25). If the flux from 3U 1758−25 as measured by *Uhuru* (see Fig. 6) is used in conjunction with our balloon data, we find spectral parameter values of $kT = 7 \pm 2$ keV for an exponential energy spectrum, and $\alpha = 1.8 \pm 0.5$ for a power-law energy spectrum. A 1967 MIT rocket observation of GX 5−1 gave comparable values for kT of 5.5 (+4.0, −1.5) keV and for α of 1.2 (+0,3 −0.2) (Rappaport *et al.* 1969). This suggests that the detected radiation is due to GX 5−1; however, we cannot exclude the possibility that some or all of the flux is due to 3U 1820−30.

V. GX 3+1 (3U 1744−26)

During scan 8, GX 3+1 (3U 1744−26) was not completely resolved from GX 1+4 (see Fig. 7). In the 17–42 keV energy range the 2 σ upper limit to the flux from GX 3+1 is about 1.2 keV cm^{-2} s^{-1} if a spectral shape similar to that of GX 1+4 is assumed. This is less than 30 percent of the flux measured from GX 1+4 during the 1972 April observations. This result is consistent with our 1970 October observations, when a flux of about 1 keV cm^{-2} s^{-1} was detected in the same energy range from a band in the sky containing GX 3+1 (Lewin, Ricker, and McClintock 1971).

VI. GX 331−1

During scan 6 a source was detected at a ~4 σ confidence level. Figure 3 shows the band in the sky from which the radiation was received. 3U sources and GX 331−1 are also shown in the figure.

The source observed during scan 6 is very likely GX 331−1; there is no other source reported that lies in our error region. The flux in the 17–42 keV range is about 1.3 keV cm^{-2} s^{-1} if a power-law energy spectrum with $\alpha \approx 1.5$ is assumed. GX 331−1 is not reported in the 3U catalog; it was discovered by the MIT OSO-7 X-ray detectors near $l^{\text{II}} = 330\overset{\circ}{.}95$, $b^{\text{II}} = -0\overset{\circ}{.}81$; the spectrum was observed to be very hard (G. Sprott, private communication).

During our 1970 October 16 observations we did not scan over GX 331−1; during our 1967 and 1969 observations we did scan over GX 331−1; however, at that time we had insufficient angular resolution (Lewin *et al.* 1969) to make a comparison with the present observations meaningful.

VII. OTHER SOURCES IN THE $l^{\text{II}} \approx 330$–350° REGION

The observed radiation during scan 7 (~5 σ confidence level) came from a band in the sky which contains two *Uhuru* sources, 3U 1642−45 (GX 340+0) and 3U 1630−47, while two others (3U 1714−39 and 3U 1702−42) are close to it (see Fig. 3). The fractional detector area exposed to 3U 1714−39 never exceeded 0.25. In addition, this source is by far the weakest of all four sources in the 2–6 keV range (intensity of 12 in 3U catalog). It is, therefore, unlikely that it contributed significantly to the flux we detected during scan 7. During the preceding scan 6 the observed fluxes from each of the remaining three sources (3U 1642−45, 3U 1630−47, and 3U 1702−42) were less than 0.2, 0.3, and 0.9 keV cm^{-2} s^{-1}, respectively (assumed power-law spectrum with $\alpha \approx 1.5$), and the observations of scan 6 and scan 7 are consistent, without invoking source variability on a time scale of 1 hour. In the event that only one of the remaining three sources was responsible for the observed radiation during scan 7, the source flux must have changed between scans. The intensity would then be about 1 keV cm^{-2} s^{-1} (3U 1642−45) or about 1.3 keV cm^{-2} s^{-1} (3U 1630−47 or 3U 1702−42) in the 17–42 keV energy range for an assumed power-law energy spectrum with $\alpha \sim 1.5$.

Comparing the 1970 and the 1972 results we can conclude that the strong signal from "region 2" in 1970 (McClintock *et al.* 1972) is absent during scan 6 in 1972, and therefore that the flux must have decreased by at least a factor of 4. However, combining the 1970 and 1972 results does not tell us whether 3U 1702−42 or 3U 1705−44 or an unreported source caused the strong signal from region 2 in 1970. Any effort to combine the two observations to further pinpoint source positions is meaningless in view of the variability of so many high-energy X-ray sources. We plan to observe this area again in 1976 with better angular resolution using our new ~700 cm^2 telescope, which has a considerably improved sensitivity.

VIII. SEARCH FOR PERIODICITIES

We searched for periodicities in the flux of the five sources in the frequency range 0.01–100 Hz. Table 1 gives upper limits to the periodic fluxes. The upper limits (99% confidence level) were derived using discrete Fourier analysis; we assumed that the periodic component was pulselike with a duty cycle of 20 percent.

TABLE 1

UPPER LIMITS TO PERIODIC FLUXES

Source	Observation UT 1974 April 5 (seconds)	Energy Range (keV)	Upper Limit to Periodic Component (%)
GX 301−2..........	50,700	17–32	35
GX 331−1..........	55,000	17–42	80
Unidentified (scan 7)...	67,600	17–42	60
GX 1+4...........	75,300	17–51	20
GX 5−1 and/or 3U 1820−30.......	76,800	17–32	40

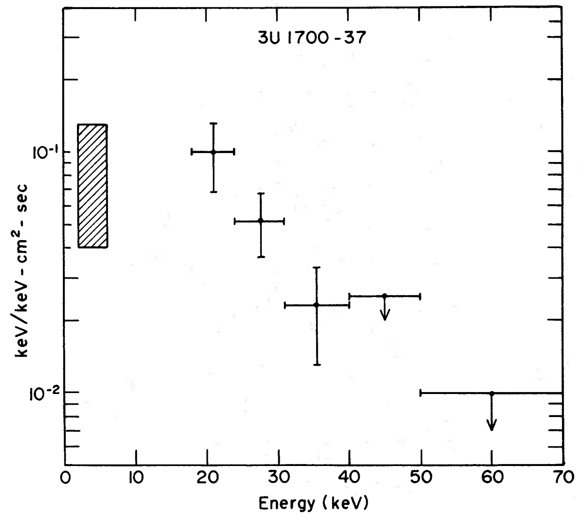

FIG. 9.—High-energy spectrum probably due to the eclipsing binary source 3U 1700−37 as measured by us on 1970 October 16. The error bars indicate a 1 σ confidence level due to counting statistics; the upper limit is a 2 σ confidence level. The data points were derived by assuming an exponential spectrum with a value for $kT \approx 10$ keV. The low-energy data shown as a crosshatched rectangle are from the *Uhuru* satellite. The height of the rectangle indicates source variability in the noneclipsed state (Giacconi *et al.* 1974).

IX. 3U 1700−37

In 1972 we reported a flux (measured on 1970 October 16) from a region in the sky which did not contain any reported *Uhuru* source ("region 3" in McClintock *et al.* 1972). Since then the eclipsing binary source 3U 1700−37 was reported, and it is located in our region 3. It seems likely that the high-energy X-ray flux we measured in 1970 was due to 3U 1700−37, which has a very flat spectrum in the 2–20 keV energy range (Jones *et al.* 1973). We measured a flux of about 1.3 keV cm^{-2} s^{-1} in the ~18–50 keV energy range. A spectrum is given in Figure 9. The flux quoted above and the results shown in Figure 9 were obtained by assuming that the source of the observed radiation is at the location of 3U 1700−37. For an assumed exponential spectrum, the value for $kT = 10$ $(+10, -4)$ keV; for an assumed power-law spectrum the value for $\alpha = 2.8 \pm 1.3$ (see § I).

The source was observed by us on JD 2,440,875.81 (from UT ~ 07^h25^m–07^h42^m 1970 October 16). At that time the phase of the binary source 3U 1700−37 was -0.23 ± 0.10; this number was derived from an extrapolation of data given by Jones *et al.* (1973). The eclipse lasts from phase -0.16 ± 0.01 to $+0.16 \pm 0.01$. If our identification of 3U 1700−37 is correct, it would appear very likely that the X-ray source was not eclipsed. This is consistent with a phase of -0.23 ± 0.10 during our observations.

We thank the following persons for their valuable contributions: John Hillier, Bob Leslie, and Don Scott of the Department of Supply in Australia; Don

Brooks and Al Shipley of the National Center for Atmospheric Research; Bill Cross, Walter Martin, and Ed Melton of the Office of Naval Research; Jean Nelson of Winzen Research, Inc.; and Jerry Namery and Mike Schönberg of the Massachusetts Institute of Technology.

REFERENCES

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.
Jones, C., Forman, W., Tananbaum, H., Schreier, E., Gursky, H., Kellogg, E., and Giacconi, R. 1973, *Ap. J.* (*Letters*), **181**, L43.
Lewin, W. H. G., Clark, G. W., Gerassimenko, M., and Smith, W. B. 1969, *Nature*, **223**, 1142.
Lewin, W. H. G., Ricker, G. R., and McClintock, J. E. 1971, *Ap. J.* (*Letters*), **169**, L17.
McClintock, J. E., Ricker, G. R., and Lewin, W. H. G. 1971, *Ap. J.* (*Letters*), **166**, L73.
McClintock, J. E., Ricker, G. R., Ryckman, S. G., and Lewin, W. H. G. 1972, *Ap. J.* (*Letters*), **173**, L57.
Rappaport, S., Bradt, H. V., Naranan, S., and Spada, G. 1969, *Nature*, **221**, 428.
Ricker, G. R., Gerassimenko, M., McClintock, J. E., Ryckman, S. G., and Lewin, W. H. G. 1973*a*, *Ap. J.* (*Letters*), **186**, L111.
Ricker, G. R., McClintock, J. E., Gerassimenko, M., and Lewin, W. H. G. 1973*b*, *Ap. J.*, **184**, 237.

M. Gerassimenko: American Science and Engineering, 955 Massachusetts Avenue, Cambridge, MA 02139

W. H. G. Lewin, J. E. McClintock, and G. R. Ricker: M.I.T. Center for Space Research, Bldg. 37, 77 Massachusetts Avenue, Cambridge, MA 02139

S. G. Ryckman: Environmental Research and Technology, Inc., Concord, MA 01742