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HIGH-ENERGY X-RAY SPECTRA OF FIVE SOURCES*

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ABSTRACT

On 1970 October 15–16, we carried out balloon X-ray observations from Australia at energies above 15 keV. We present the high-energy X-ray spectra of three sources discovered by us, GX 301 − 2, GX 304 − 1, and GX 1 + 4. The data suggest that these high-energy sources correspond to the sources 2U 1223 − 62, 2U 1258 − 61, and 2U 1728 − 24 respectively. We also present the spectra for two additional sources, GX 5 − 1 (2U 1757 − 25) and GX 3 + 1 (2U 1744 − 26). The average intensity of the highly variable source GX 301 − 2 was observed to be as great as Tau X-1 in the energy range 15–50 keV.
Subject heading: X-ray sources

I. INTRODUCTION

On 1970 October 15–16, we carried out balloon X-ray observations from Australia (energies above 15 keV). We have previously reported on the discovery of three X-ray sources, GX 301 − 2, GX 304 − 1, and GX 1 + 4, and we have presented data on their positions and variability (McClintock, Ricker, and Lewin, 1971; Lewin, Ricker, and McClintock 1971*b*; Lewin *et al.* 1971*a*). In this paper we present the energy spectra for these sources, for GX 5 − 1, and for GX 3 + 1.

During the course of the observations, the diurnal motion of the Earth caused sources to move through the slit field of view of the detector (1°.5 × 13° FWHM) in 10–20 minutes. The view direction of the detector was changed seven times, thereby providing seven scans over selected regions of the sky. The number of the scan and the times during which sources were observed are given in table 1. The atmospheric-mass thickness (g cm^{-2}) along the line of sight to the source is also given. The

TABLE 1

SOURCE OBSERVATION PERIODS

Source	Time of Observation 1970 October (UT)	Scan Number	Line-of-Sight Atmospheric Thickness (g cm^{-2})
GX 301 − 2.......	$15^d22^h18^m$–22^h34^m	1	5.9
	15 23 39 –23 53	2	1.9
GX 304 − 1.......	15 22 46 –23 02	1	3.6
	16 00 05 –00 25	2	1.9
GX 1 + 4.........	16 04 18 –04 37	5	1.8
	16 08 43 –08 56	7	2.1
GX 5 − 1.........	16 04 50 –05 09	5	1.8
GX 3 + 1.........	16 09 00 –09 12	7	2.1

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TABLE 2

SOURCE POSITIONS

Our Designation	Galactic Coordinates		Reference	Possibly Associated *Uhuru* Source	Galactic Coordinates	
	l^{II}	b^{II}			l^{II}	b^{II}
GX 301−2...	300°.7 ± 0°.5	−2°.2 ± 2°.7	McClintock *et al.* 1971	2U 1223−62	300.08	−0.02
GX 304−1...	303.8 ± 0.8	−1.2 ± 2.5	McClintock *et al.* 1971	2U 1258−61	304.08	1.24
GX 1+4.....	1.4 ± 0.7	3.9 ± 0.8	Lewin *et al.* 1971*b*	2U 1728−24	1.90	4.94
GX 5−1.....	...	...	Lewin *et al.* 1971*b*	2U 1757−25	5.06	−0.99
GX 3+1(?)	...	...	Lewin *et al.* 1971*b*	2U 1744−26	2.28	0.83

instruments and methods of data analysis are discussed elsewhere (McClintock *et al.* 1971; Clark, Lewin, and Smith 1968).

Subsequent to our balloon flight, the *Uhuru* satellite has observed low-energy sources (Giacconi *et al.* 1972) at positions which are consistent with the three positions first reported by us. Since our positional uncertainties are between 0.5 and 2.0 square degrees, we consider it very likely that in each case the low-energy source and our high-energy source is the same; however, we cannot exclude the possibility that this is not so. Our designations and positions and the designations and positions of the *Uhuru* sources, which are likely to be associated with our high-energy sources, are presented in table 2.

II. GX 301−2 (2U 1223−62)

During both scans over this source we observed a rapidly varying intensity. A flux change of a factor of 5 was observed in 2.5 minutes (McClintock *et al.* 1971). The spectrum obtained during scan No. 2, for the time period $23^{h}39^{m}$–$23^{h}45^{m}$ UT, is shown in figure 1. The data can be fitted by a simple exponential energy spectrum ($e^{-E/kT}$) with $kT = 6 \pm 1$ keV, or less satisfactorily by a power law energy spectrum ($E^{-\alpha}$) with spectral index $\alpha = 4.8 \pm 0.4$. The spectral parameters were determined by comparing the observed counting rates with counting rates calculated for a number of spectra incident above the atmosphere. The range of acceptable values for kT and α were determined by a visual inspection of the fit between the observed and calculated counting rates. The method is thoroughly discussed elsewhere (Clark *et al.* 1968).

We determined spectra for the source at both high and low intensity, and within the statistical uncertainties the values for kT and α are the same. The average source intensity is approximately equal to the intensity of Tau X-1 in the energy range 15–50 keV.

The spectrum determined from scan No. 1 (not shown in figure 1) can be fitted with $kT = 6(+3, -2)$ keV or $\alpha = 5(-0.5, +2.0)$. The average intensity of the source during this scan is comparable to the intensity during scan No. 2.

An extrapolation of our data to low energies implies that GX 301−2 should have been at least half as intense as Sco X-1 in the energy range 1–10 keV. The maximum flux observed by *Uhuru* for the source 2U 1223−62 is more than two orders of magnitude below this value (fig. 1). Since the *Uhuru* observations and our observations were not performed simultaneously, it is possible that the source was ∼100 times less intense during the *Uhuru* observations. Such a large intensity change is not unreasonable since our past balloon observations have established a change of over a factor of 20 (table 3). However, we cannot exclude the possibility that the spectrum has an unprecedented low-energy cutoff at ∼10 keV.

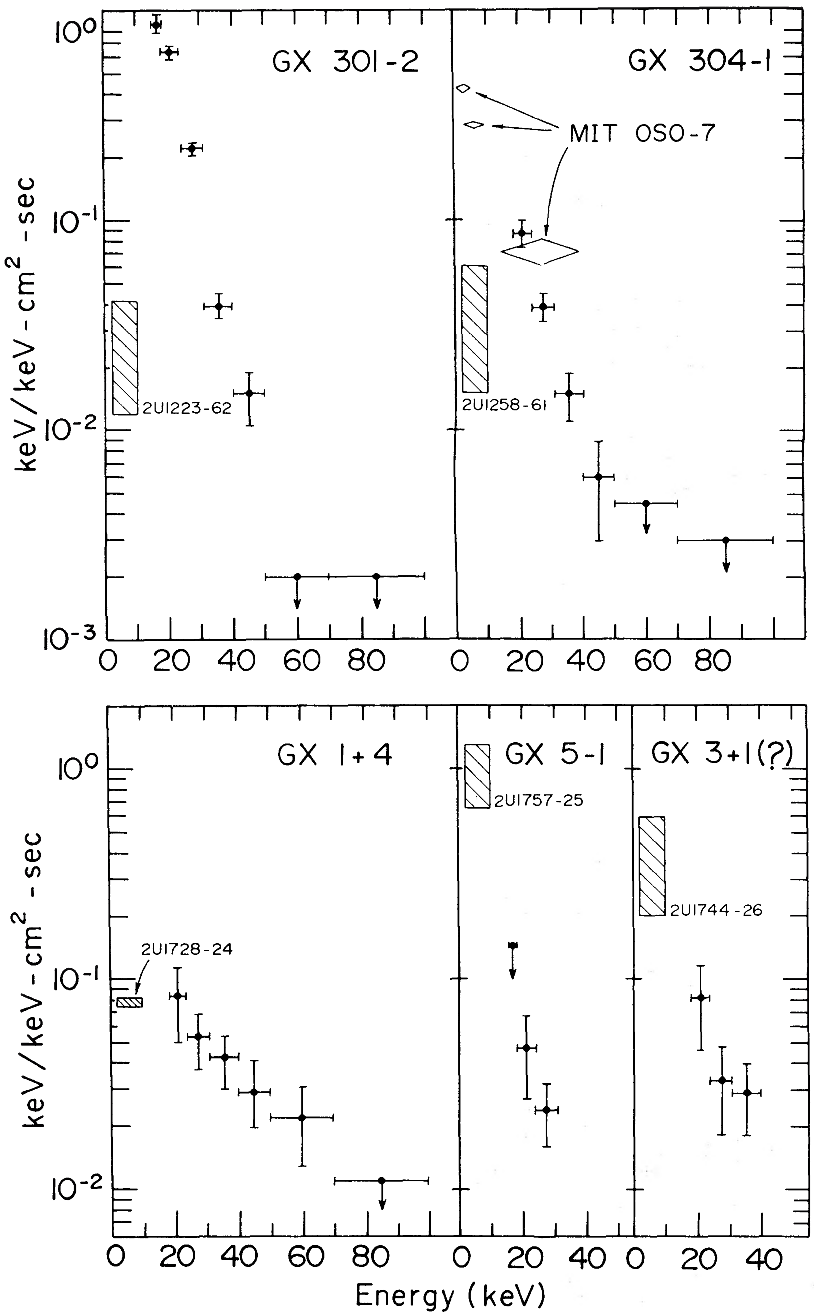

FIG. 1.—Energy spectra of five X-ray sources as measured on 1970 October 15–16. The error bars indicate a 1 σ confidence level and the upper limits are at a 2 σ confidence level. The data points were derived by assuming exponential spectra with the following values for kT: GX 301−2, 6 keV; GX 304−1, 10 keV; GX 1+4, 25 keV; GX 5−1, 6 keV; GX 3+1, 15 keV. Low-energy data shown as cross-hatched rectangles are from the *Uhuru* satellite and were obtained subsequent to our balloon flight. Height of a rectangle indicates source variability (Giacconi *et al.* 1972). Data shown as diamonds are for a state of high intensity of 2U 1258−61 as measured by the MIT OSO-7 X-ray astronomy instrument for the period 1972 March 29–April 2 (McClintock, private communication).

TABLE 3

HIGH-ENERGY X-RAY OBSERVATIONS OF GX 301 − 2

Date of Observation	Average Energy Flux keV cm^{-2} s^{-1} (18–36 keV)	l^{II}	b^{II}	Reference
1969 March 20.....	< 0.27	...	...	Lewin *et al.* 1970
1969 April 16......	{1.90 ± 0.18; 3.25 ± 0.30}	301° ± 3°*	−2° ± 3°	Lewin *et al.* 1971*a*
1970 October 15...	6.0 ± 0.5	301° ± 0°.5	−2°.2 ± 2°.7	McClintock *et al.* 1971

* Contributions from GX 304 − 1 cannot be excluded.

Table 3 summarizes three balloon observations of the region near GX 301 − 2.

III. GX 304 − 1 (2U 1258 − 61)

During scan No. 1 the balloon was still ascending, and the exposure to the source was insufficient to determine a spectral fit to the data. The spectrum determined from scan No. 2 performed at a float altitude of 147,000 feet (45,000-m) (1.5 g cm^{-2}), is shown in figure 1. The data can be fitted equally well by an exponential spectrum with $kT = 10 \pm 3$ keV or by a power law spectrum with spectral index $\alpha = 3.2(-0.4, +1.2)$.

It seems very likely that we earlier observed the same source in 1967 and 1969 (Lewin, Clark, and Smith 1968*b*, *c*; Lewin *et al.* 1971*a*). Because of the positional uncertainties in our balloon observations of GX 304 − 1 (1°–2°) and the positional uncertainties in rocket observations of Cen X–2 (2°–3°), the two sources were mistakenly believed to be the same source (Lewin *et al.* 1968*b*). A reanalysis of a 1967 April 20 rocket observation (Francey 1971) provided an improved position for the transient X-ray source Cen X–2 of $l^{II} = 310°.2 \pm 1°$. Assuming that the latter value is correct, there seems no doubt that GX 304 − 1 and Cen X–2 are different, highly variable X-ray sources.

The observations of the Centaurus region by OSO–3 (Schwartz, Peterson, and Hudson 1972), performed in 1967–1968, are consistent with a stable flux, several single days of enhanced flux, and two periods of flaring on a 10-day time scale. No periodic modulation of the flux was observed for periods in the range 5–20 days at a 5 percent upper limit. As noted by Schwartz *et al.* the 11°.5 (FWHM) OSO–3 collimation permits the measured flux to be due to a combination of GX 304 − 1, GX 301 − 2, Cen X–2, Cen X–3, and Cen X–5.

TABLE 4

HIGH-ENERGY X-RAY OBSERVATIONS OF GX 304 − 1

Date of Observation	Energy Channel (keV)	Energy Flux keV cm^{-2} s^{-1}	l^{II}	b^{II}	Reference
1967 October 15...	20–40	2.06 ± 0.19	304°.8 ± 1°.5	−1°.5 ± 2°	Lewin *et al.* 1968*c*
1967 October 24...	20–42	1.33 ± 0.24	305° ± 3°*	−2° ± 3°	Lewin *et al.* 1968*c*
1969 March 20.....	18–38	< 0.27			Lewin *et al.* 1970
1970 October 16...	18–40	0.88 ± 0.13	303°.8 ± 0°.8	−1°.2 ± 2°.5	McClintock *et al.* 1971, plus this paper

* Contributions from GX 301 − 2 cannot be excluded.

The maximum intensity of 2U 1258 − 61, observed by *Uhuru*, is considerably below the extrapolation of our spectrum to low energies. However, the MIT OSO–7 X-ray astronomy instrument, during 24 days of observation of 2U 1258 − 61, has recorded a 4-day state of high intensity during which both the intensity and spectral shape of the X-ray flux is consistent with our data (fig. 1, McClintock, private communication). Moreover, the MIT OSO–7 observations reveal intensity variations of more than a factor of 20 on a time scale of several days, which is in accord with our past balloon observations of GX 304 − 1 which are summarized in table 4. The OSO–7 results strongly support our suggestion that the high-energy source GX 304 − 1 and the *Uhuru* source 2U 1258 − 61 are the same source.

IV. GX 1 + 4 (2U 1728 − 24)

The source GX 1 + 4 was observed during two scans (Lewin *et al.* 1971*b*). The source was highly variable and exhibited a hard X-ray spectrum. The average spectrum as observed during scan No. 7 is shown in figure 1. The data are consistent with values for $kT = 28 \pm 12$ keV or $\alpha = 1.4 \pm 0.7$. The spectral parameters determined from observations during scan No. 5 are the same (within the statistical uncertainties) as those determined from scan No. 7, but the average source intensity is approximately 40 percent lower.

High-energy balloon observations of this region of the sky have been misinterpreted by various groups as a result of insufficient angular resolution (Buselli *et al.* 1968; Johnson *et al.* 1972). A scan over the galactic center by a balloon-borne telescope ($\sim 8°$ FWHM), performed by the University of Adelaide, showed a hard X-ray source with energy spectral index $\alpha = 1.0 \pm 0.2$ (Buselli *et al.* 1968). The authors argue that GX 3 + 1 must be the source of the flux; however, they do not report a source position as derived from their data. In a thesis detailing the University of Adelaide balloon observations of the galactic-center region, four source positions are presented (Clancy 1970). Although three of the positions are consistent with GX 3 + 1, one is clearly inconsistent. The position given by us for GX 1 + 4 (Lewin *et al.* 1971*b*) is consistent with all four positions presented by Clancy. We believe that at least a significant portion of the flux observed by Buselli *et al.* was due to GX 1 + 4.

The Rice University group observed the galactic-center region with a 24° FWHM detector and detected X-rays between 23 and ~ 400 keV with energy spectral index $\alpha = 1.37 \pm 0.05$ (Johnson, Harnden, and Haymes 1972). The source of hard X-rays is presumed to be GX 5 − 1, although it is also suggested by the authors that perhaps it is GX 3 + 1 in light of the work of Buselli *et al.* Surprisingly, the authors do not consider GX 1 + 4 as the source of X-rays, although they reference the paper in which we detail the discovery of this hard X-ray source (Lewin *et al.* 1971*b*). We believe that a significant contribution to the X-ray flux measured by Johnson *et al.* came from GX 1 + 4.

The value of the spectral index determined from our 1970 October observations of GX 1 + 4 is in agreement with those determined by Buselli *et al.* and Johnson *et al.*

The *Uhuru* results for 2U 1728 − 24 are consistent with an extrapolation of our data for GX 1 + 4 to low energies (fig. 1).

V. GX 5 − 1 (2U 1757 − 25)

A flux at a 4 σ confidence level was observed during a single scan over the region containing GX 5 − 1 (Lewin 1971*b*). During a single scan in a recent flight (1972 April 5), we again obtained a flux slightly in excess of 4 σ from a 1°.5 × 11° region containing GX 5 − 1. Assuming we have observed the same source, the 1970 October and 1972 April observations imply that this high-energy source lies in a 4 square-degree region of the sky containing GX 5 − 1, the strongest low-energy source in the galactic-center region (Bradt *et al.* 1971; Giacconi *et al.* 1972). The source 2U 1820 − 30, which lies just outside the 4 square-degree area, may have contributed both in 1970 and 1972 to the flux that we believe is primarily due to GX 5 − 1.

Combining the nonsimultaneous rocket and *Uhuru* observations with our high-energy observation, we can obtain a fit to the data with the spectral parameters $kT = 6.5 \pm 1$ keV or $\alpha = 1.0 \pm 0.4$ (see fig. 1). A 1967 rocket observation of GX 5 − 1 gave a comparable value for kT of 5.5(+4.0, −1.5) keV (Rappaport *et al.* 1969).

VI. GX 3+1 (2U 1744−26)

During scan No. 5, GX 3+1 was in the field of view but was not resolved from GX 1+4 (Lewin *et al.* 1971*b*). During scan No. 7, an excess flux of 5 σ was observed from a region of approximately 1°5 × 13° containing GX 3+1. However, no background data were obtained following the observation, and no background data were obtained for ~20 minutes prior to the observation of the excess flux possibly due to GX 3+1 (GX 1+4 was in the field of view). Therefore, the spectrum for GX 3+1 shown in figure 1 should be considered tentative.

VII. GX 340 REGION

We obtained a single scan over the galactic equator near longitude 340° and detected a statistically significant flux from at least two 1°5 × 13° areas of the sky (McClintock *et al.* 1972). Because of the large positional uncertainties, no spectra are presented for these sources.

VIII. SEARCH FOR PERIODICITIES

We searched for periodicities in the flux of all five sources from 80 ms to 9.6 s. None were found. Table 5 gives upper limits on the periodic fluxes. The upper limits were derived using discrete Fourier analysis; we assumed that the periodic component was pulse-like with a duty cycle of ~20 percent.

Note added 1973 April 23—Johnson and Haymes (1973) have recently reported on high-energy X-rays from the vicinity of the galactic center. They conclude that GX 3+1 is not the major contributor to the hard X-ray flux from this region, in accordance with the conclusions of this paper and previous papers (Lewin *et al.* 1969 and Lewin *et al.* 1971*b*). The spectrum that they report strongly suggests that they have detected X-rays from GX 1+4.

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TABLE 5

UPPER LIMITS ON PERIODIC FLUXES

Source	Periodic Component (%)
GX 301−2	20
GX 304−1	25
GX 1+4	25
GX 5−1	40
GX 3+1	35

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