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# OBSERVATIONS OF GALACTIC X-RAY SOURCES BY OSO-7*

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## ABSTRACT

We present the MIT data from the OSO-7 satellite for observations of the galactic plane between 1971 and 1974. A number of sources discovered in the MIT all-sky survey are described in detail: MX 0049+59, MX 0836−42, MX 1353−64, MX 1406−61, MX 1418−61, MX 1709−40, and MX 1608−52 (the persistent source suggested to be associated with the X-ray burst source XB 1608−52). Upper limits to the X-ray emission from a number of interesting objects are also derived.

General results describing all of our observations of galactic sources are presented. Specifically, we display the number-intensity diagrams, luminosity functions, and color-color diagrams for all of the sources we detected. The data are divided between disk and bulge populations, and the characteristics of the two groups are contrasted. Finally, the concept of X-ray source populations and the relationship of globular cluster sources and burst sources to the disk and bulge populations are discussed.

*Subject heading:* X-rays: sources

## I. INTRODUCTION

Detailed studies of individual galactic X-ray sources—for example, extended observations of X-ray binaries and the measurements of X-ray emissions from supernova remnants—have produced the most interesting results. Nevertheless, there are many bright sources which are not understood in spite of long observations. The best one can do for these at present is to search for family characteristics which may provide clues to their nature and origin.

In this paper we discuss the results of a general survey and specific studies of galactic X-ray sources made by the MIT experiment on the OSO-7 satellite. This instrument performed a comprehensive survey of the sky during more than 1000 days in orbit. A discussion of the results on sources at high galactic latitudes ($|b^{\rm II}| > 10°$) has appeared elsewhere (Markert *et al.* 1976). In this paper we consider sources with $|b^{\rm II}| < 10°$ and other objects at higher latitudes which are believed to lie within the Galaxy. In § III we describe in detail several X-ray sources discovered during the course of the sky survey. In § IV we summarize the results for all sources with $|b^{\rm II}| < 10°$, and in § V we discuss the implications of these results and suggest a division of X-ray sources into several distinct groups.

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## II. INSTRUMENT AND METHODS OF ANALYSIS

The MIT OSO-7 experiment has been described in detail elsewhere (Clark *et al.* 1973). In brief, the instrument consisted of two banks of five proportional counters each. These counters, which we designated TW, NE, AR, KR, and XE, were sensitive in the energy ranges 1–1.5 keV, 1–6 keV, 3–10 keV, 15–40 keV, and 30–60 keV, respectively. One bank of detectors was shielded by tubular collimators with angular response functions of full width at half-maximum (FWHM) of ~1°. The other bank had collimators with a field of view of FWHM ~3°. The counters were mounted so that the directions of greatest exposure were at 75° and 105° with respect to the rotation axis of the satellite. The satellite rotated with a period of about 2 s so that the two banks of counters scanned two different small circles in the sky. The counts were recorded in 256 azimuth bins which were read out every 190 s.

We have thoroughly analyzed the data of the first 600 days of observations. A method of analysis which we have found useful is the creation of comprehensive sky maps of the average intensities over long periods of time as measured by each of the counters (Markert *et al.* 1976). In this technique we divided the sky into cells of area 1 square degree (for the 3° collimated counter bank) and ½ square degree (for the 1° bank). Data were accumulated in each cell for those times when the collimator pointing vector lay within the cell. Maps which covered 8 days of continuous observations at a time were made in this manner. Later the data were summed to produce more comprehensive maps covering the entire 600 days of observations.

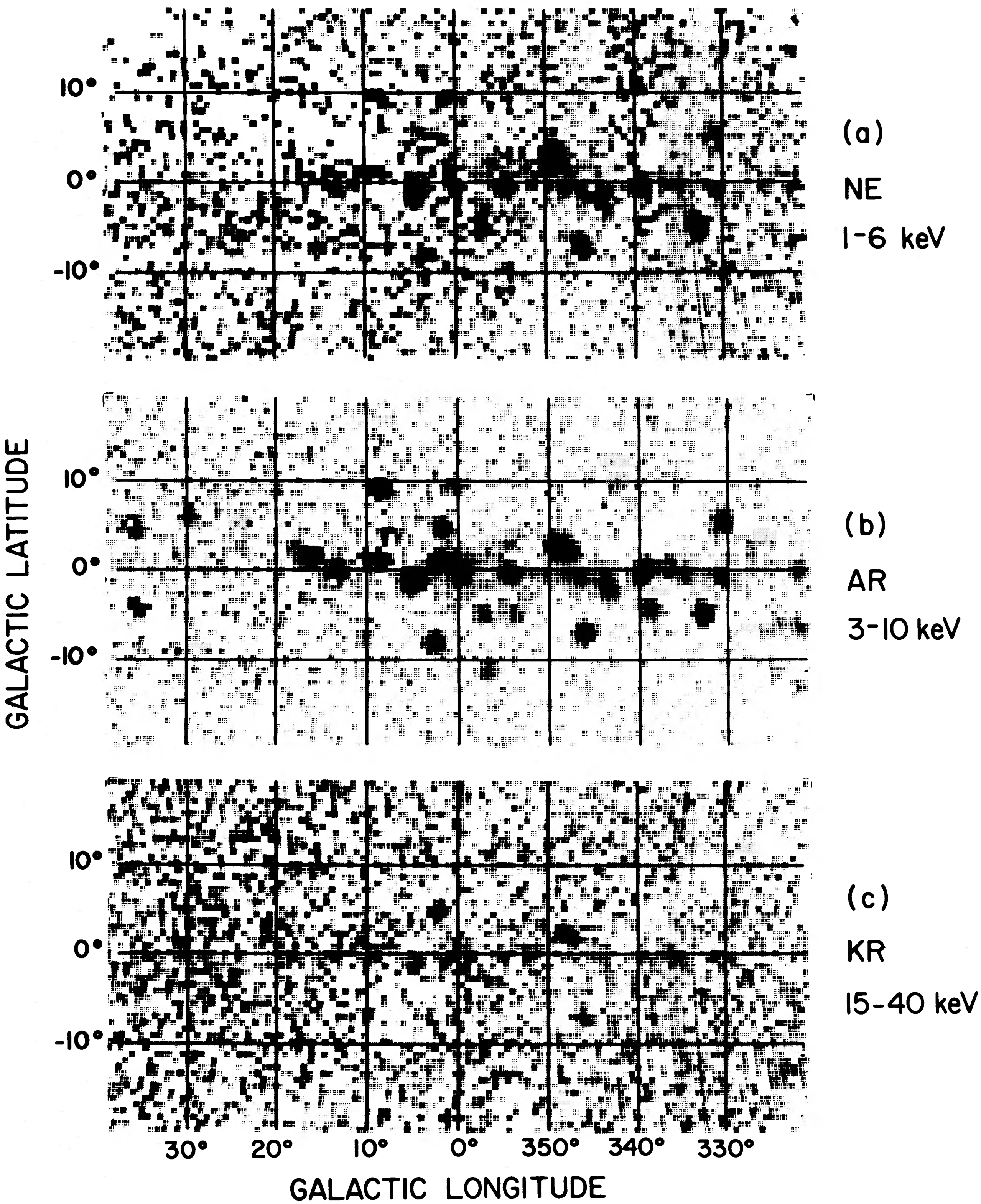


FIG. 1.—Map of the galactic center region as seen by the 1° collimated counters. Note sources (best seen in the AR detector) near ($l^{II}$, $b^{II}$) = (8°, 4°), (331°, −1°), (347°, −1°), and (354°, 3°) not reported by *Uhuru*. More stringent editing criteria applied to the NE detectors resulted in the less complete exposure apparent in (*a*).

Figure 1 shows three such comprehensive maps of the galactic center as viewed by the 1° collimated detectors. In this figure the density of shading is scaled arbitrarily.

In practice, such displays as those of Figure 1 were used in searching for previously unreported X-ray sources or in detecting unexpected changes in known sources. In Figure 1*b*, for example, there is evidence for sources near ($l^{II}$, $b^{II}$) = (8°, 4°), (354°, 3°), (347°, −1°), and (331°, −1°), none of which were reported in the third *Uhuru* catalog (Giacconi *et al.* 1974). When such evidence was found in the maps, we studied the region near the points of interest more carefully with computer programs we have developed to supply more precise information concerning position, intensity, and time variability. These programs are rather time-consuming and have not been run as yet for all the known X-ray sources. Another computer program which is applicable to the data as accumulated in the sky maps has also been developed. This program is somewhat less precise than our standard analysis routines, but runs much more rapidly. We have studied essentially all of the known X-ray sources (as of 1974) with this rapid analysis program. Some general results of this study are presented in § IV.

## III. STUDIES OF INDIVIDUAL OBJECTS

A principal result of the creation and study of the all-sky maps was the discovery of a number of previously unreported sources. The positions of most of these sources have been circulated earlier (Markert *et al.* 1975*b*), and those at high galactic latitudes have been discussed in some detail (Markert *et al.* 1976). The positions and peak intensities of those at low galactic latitude (or those associated with galactic objects) appear in Table 1. Individual studies of a number of these objects have already been published (Markert *et al.* 1973; Clark, Markert, and Li 1975; Markert *et al.* 1975*a*; Winkler and Laird 1976; Markert, Backman, and McClintock 1976). For those sources for which a detailed report has not been published, we present a brief description here.

### *a*) *MX 0049+59*

This source was observed with a statistically significant counting rate (> 3 $\sigma$ above background) on six occasions during the first 600 days of operation. It was quite weak during all the observations, never exceeding 0.7 counts $s^{-1}$ in the AR detectors. Because of the low intensity of the source, we were unable to detect variations—in all cases the counting rate was consistent with the most precisely measured value. We also observed a 5 $\sigma$ counting rate in the NE detectors, but our data from the other counters were insufficient to determine a spectrum.

The large uncertainty in position precluded our finding an optical counterpart for MX 0049+59. Perhaps the most interesting object in the vicinity, although 1°7 away from the X-ray position, is the star $\gamma$ Cas: a bright, variable, shell star with strong hydrogen lines. It has recently been identified with an X-ray source, MX 0053+60, which was discovered by SAS-3 (Jernigan 1976). It is statistically quite unlikely that MX 0049+59 and MX 0053+60 are the same object. However, if MX 0053+60 were as bright

TABLE 1

GALACTIC X-RAY SOURCES DISCOVERED BY OSO-7

| Designation | Position: R.A.; Decl. | Position: $l^{II}$; $b^{II}$ | Peak Intensity (cts $s^{-1}$): 3° AR Rate | Peak Intensity (cts $s^{-1}$): Approximate *Uhuru* Equiv. | Comments |
|---|---|---|---|---|---|
| MX 0049+59 | $0^h50^m0 \pm 5^m0$; $+59°2 \pm 0°8$ | 123°13; −3°37 | 0.66 ± 0.10 | 9.9 | |
| MX 0513−40 | 5 13.4 ± 2.0; −40.1 ± 0.4 | 244.54; −34.87 | 0.87 ± 0.06 | 13.1 | In NGC 1851 (Clark, Markert, and Li 1975) |
| MX 0836−42 | 8 36.2 ± 0.8; −42.6 ± 0.2 | 261.88; −0.93 | 3.56 ± 0.42 | 53 | In Vela Puppis region |
| MX 1353−64 | 13 53.9 ± 2.4; −64.5 ± 0.1 | 309.92; −2.75 | 3.88 ± 0.48 | 58 | Cen X-2? (Francey 1971) |
| MX 1406−61 | 14 6.9 ± 1.5; −61.9 ± 0.3 | 312.04; −0.67 | 1.35 ± 0.09 | 20.3 | |
| MX 1418−61 | 14 18.5 ± 1.8; −61.4 ± 0.2 | 313.51; −0.59 | 1.23 ± 0.09 | 18.5 | |
| MX 1457−41 | 14 57.9 ± 3.2; −41.7 ± 0.6 | 327.5; +14.6 | 0.18 ± 0.03 | 2.7 | SN 1006 (Winkler and Laird 1976) |
| MX 1608−52 | 16 8.8 ± 0.6; −52.3 ± 0.2 | 330.95; −0.81 | 9.67 ± 1.16 | 145 | GX 331−1, 4U 1608−52, Bursting source? (Belian, Conner, and Evans 1976; Tananbaum *et al.* 1976) |
| MX 1658−48 | 16 59.0 ± 0.8; −48.7 ± 0.2 | 338.92; −4.32 | 15.10 ± 1.37 | 227 | GX 339−4, 3U 1658−48 (Markert *et al.* 1973) |
| MX 1709−40 | 17 9.3 ± 0.7; −40.6 ± 0.2 | 346.52; −0.88 | 3.46 ± 0.47 | 52 | |
| MX 1716−31 | 17 16.2 ± 3.2; −31.5 ± 0.2 | 354.52; +3.17 | 2.53 ± 0.40 | 38 | Flaring source (Markert, Backman, and McClintock 1976) |
| MX 1746−20 | 17 46.0 ± 0.5; −20.4 ± 0.2 | 7.72; +3.76 | 9.70 ± 0.44 | 146 | In NGC 6440 (Markert *et al.* 1975*a*) |

during our observations as during the SAS-3 observations, we should have detected it easily. Similarly, SAS-3 should have detected MX 0049+59 if it were as intense as we report here. It seems likely that there are two sources in the vicinity, both of which are variable.

### *b*) *MX 0836−42*

MX 0836−42 was observed during two crossings of the region containing the Vela and Puppis supernova remnants. During the second of these crossings, 1972 January 22–26, MX 0836−42 clearly dominated the region at energies above 3 keV.

The position of MX 0836−42 (Table 1) is almost coincident with that reported by Kellogg *et al.* (1973) for a possible discrete source observed by *Uhuru* with statistical significance too low for inclusion in the *Uhuru* catalog. It therefore seems likely that *Uhuru* also observed MX 0836−42, although the intensity was much lower at the time of their observations (1970 December and 1971 February 9). Figure 2 shows the composite *Uhuru* and OSO-7 light curves for this source, assuming that the source observed by Kellogg *et al.* (1973) was MX 0836−42. The OSO-7 data are converted to *Uhuru* counting rates by the approximate formula: 1 AR count $\approx$ 15 *Uhuru* counts. The uncertainty in this conversion is about $\pm 20\%$.

For the crossing of 1972 January 22–26, the counting rates in our detectors were sufficient to enable us to estimate a spectrum. We found that a thermal bremsstrahlung spectrum (Chodil *et al.* 1968) with a temperature of $kT > 4.1$ keV and a hydrogen column density of $N_H < 3.5 \times 10^{22}$ atoms cm$^{-2}$ gave an acceptable spectral fit. These limits define the 90% confidence interval of the fit. Confidence limits in the parameters used here, as well as those determined for other sources described in this paper, were computed according to the method described by Lampton, Margon, and Bowyer (1976) and Avni (1976) for two interesting parameters $kT$ and $N_H$.

The source MX 0836−42 is coincident with one of the regions of maximum soft X-ray emission from the Vela supernova remnant, as mapped by Gorenstein, Harnden, and Tucker (1974). This region appears to be just within some of the brightest optical filaments at the northern edge of the shell.

### *c*) *MX 1353−64, MX 1406−61, MX 1418−61*

The complex region near $l^{II} = 312°$ was scanned on several occasions by the OSO-7 detectors. During several crossings of this region with the 1° field-of-view detectors, only one source (MX 1353−64) was detected, at the location indicated in Table 1. On several other occasions, observations were made with the 3° field-of-view detectors which were inconsistent with the presence of MX 1353−64 alone. We performed position and intensity fits to sources near $l^{II} = 312°$ and $l^{II} = 314°$ simultaneously with an intensity fit to a source whose position was fixed at that of MX 1353−64. The results of these two additional position fits (MX 1406−61 and MX 1418−61) are summarized in Table 1, as are the mean AR counting rates for all three sources in the region. We note that, because of the apparent complexity of the region and the variability of the sources discovered there, it should be possible to fit the data to more complex models involving more sources.

Seward *et al.* (1976) have examined this region with the *Ariel 5* sky survey instrument. Their results indicate the presence of two sources. One is most probably MX 1353−64; the other is at $l^{II} = 313°.5$, $b^{II} = 0.3°$, a position which may be consistent with MX 1418−61. They did not detect MX 1406−61. As discussed above, our observations do not rule out the presence of more than three sources in the region. They do, however, require the presence of a source near $l^{II} = 312°$.

Wheaton, Baity, and Peterson (1975) reported the presence of an X-ray source at $l^{II} = 313°.5$, $b^{II} = -1°.3$, with an uncertainty circle of radius $\sim 3°$. This circle contains all of the MX and *Ariel* sources discussed here. It is interesting to note that the observations of Wheaton, Baity, and Peterson occur at nearly

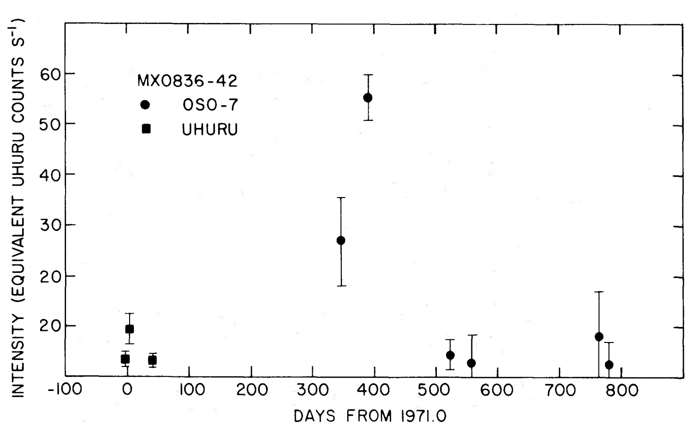


FIG. 2.—Light curve for MX 0836−42. OSO-7 data points (*circles*) normalized to the *Uhuru* 2–6 keV detectors. The *Uhuru* data (*squares*) are from Kellogg *et al.* (1973).

the same time as those of ours during which at least three sources were present.

The error box of MX 1353−64 is consistent with some of the determinations of the position of Cen X-2, a transient X-ray source first observed in 1966 (Francey 1971). The presence of weak X-ray emission after the bright phase of a transient source has been observed for 3U 1543−47 (Li, Sprott, and Clark 1976), and MX 1353−64 may be another instance of such a recurrence.

### *d*) *MX 1608−52*

The position determined for MX 1608−52 (Table 1) lies within the uncertainties quoted for the recently discovered bursting source in Norma (XB 1608−52), which has been observed by the *Vela* satellites (Belian, Conner, and Evans 1976) and by *Uhuru* (Grindlay and Gursky 1976). MX 1608−52 was originally reported as GX 331−1 by Ricker *et al.* (1973), who tentatively identified it with a higher energy (17–42 keV) source for which they had determined a line of position. It has subsequently been discussed by others (Matilsky, Gursky, and Tananbaum 1973; Li 1976; Ricker *et al.* 1976; Tananbaum *et al.* 1976). Because of the large error box associated with the bursting source and the high density of X-ray sources in this vicinity, the identification of MX 1608−52 with the Norma burster (XB 1608−52) is still somewhat uncertain (Lewin 1977).

The long-term intensity fluctuations of this source, as observed by OSO-7 and *Uhuru*, are plotted in Figure 3. The *Uhuru* data are from Tananbaum *et al.* (1976), and the OSO-7 data are converted to *Uhuru* counting rates. Also noted in Figure 3 are the times of burst observations by *Uhuru* (Tananbaum *et al.* 1976; Grindlay and Gursky 1976) and the detection of hard X-rays (Ricker *et al.* 1973, 1976), both of which phenomena may be associated with MX 1608−52.

As can be seen from Figure 3, MX 1608−52 is a highly variable source. The OSO-7 and particularly the *Uhuru* data seem to show large variations over time scales ranging from a day to several months. It is interesting to note that, like some of the X-ray burst sources (e.g., Clark 1976), MX 1608−52 seems to exhibit a "high" state and a "low" state. For example, the burst source associated with the globular cluster NGC 6624 is in a "burst-active" state only when the steady source is in a "low" state. If XB 1608−52 and MX 1608−52 are in fact the same source, then it would seem that the opposite is true—bursts occur when the steady source is in a "high" state.

Because of the relatively long integration time (190 s) of our instrument, we could not have discerned burst behavior, which typically lasts for at most tens of seconds, from the vicinity of MX 1608−52. On time scales between 190 s and one day, we also saw no evidence for variability, although variations of up to 50% could have been hidden in statistical fluctuations.

The spectrum of MX 1608−52 is rather hard. For data obtained during a crossing of the source position in 1971 December, we obtained a fit to a thermal bremsstrahlung spectrum consistent with a temperature $kT > 13$ keV and a hydrogen column density $N_H < 4 \times 10^{22}$ atoms cm$^{-2}$. The best-fit temperature was $kT = 29$ keV, a value consistent with the observations of Ricker *et al.* (1976), who may have observed MX 1608−52 in their 17–42 keV band.

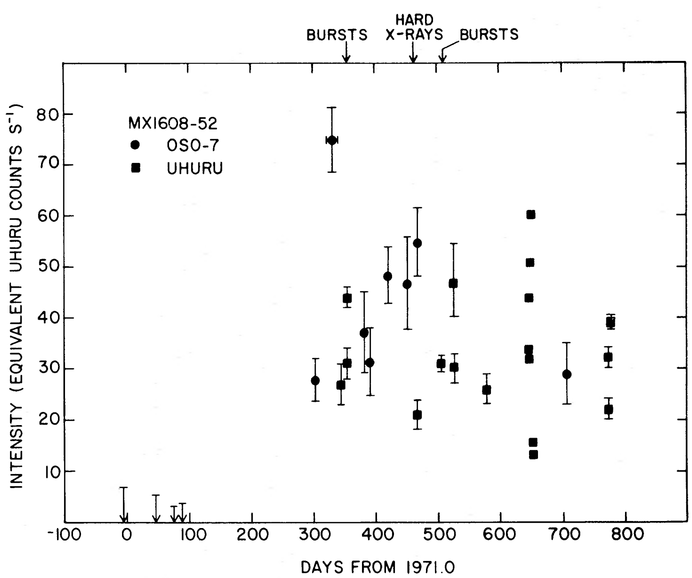


FIG. 3.—Light curve (2–6 keV) for MX 1608−52 (= 4U 1608−52) as observed by *Uhuru* (*squares*) and by MIT/OSO-7 (*circles*). The error bars for observations between days 640 and 660 are suppressed for clarity. The upper limits determined before day 100 are from *Uhuru* (Tananbaum *et al.* 1976). Also noted are times when bursts were detected from this region by *Uhuru* (Grindlay and Gursky 1976) and times when hard X-rays were observed by Ricker *et al.* (1973, 1976).

### *e) MX 1709−40*

This source was observed on eight different occasions with the 1° collimated detectors. The source position was also scanned several times with the 3° collimated detectors, but other strong, nearby sources confused the region considerably, so that the data from these observations are less useful. We saw no convincing evidence of variability from crossing to crossing, although variations in intensity of up to 50% could have been masked by the large statistical uncertainties in some of the observations.

We were able to fit the mean intensities for each counter to a thermal spectrum. We found the spectrum to be consistent with $kT \geqslant 4$ keV and a hydrogen column density less than $6 \times 10^{22}$ atoms $\mathrm{cm}^{-2}$ (90% confidence).

There were no stars or other objects found in the SAO catalog within the error box of MX 1709−40 (Table 1). A search of other catalogs of unusual objects (see references in Giacconi *et al.* 1974) was also unsuccessful.

### *f) Other Objects*

The OSO-7 sky survey was complete in the 3–10 keV (AR) range down to an intensity of about 1.0 counts $\mathrm{s}^{-1}$ (approximately 15 counts $\mathrm{s}^{-1}$ as measured by *Uhuru*). By this we mean that a source anywhere in the sky with an AR intensity averaged over a long period of time (tens of days) greater than 1.0 counts $\mathrm{s}^{-1}$ would have been detected in our survey at a level of significance 3 $\sigma$ or greater. This counting rate, therefore, is an upper limit on the time-averaged X-ray flux from any object not reported either here, in Markert *et al.* (1976), or in the *Uhuru* catalog (Giacconi *et al.* 1974). The only exceptions to this general upper limit would be objects close to strong X-ray sources, where an intensity greater than 1.0 counts $\mathrm{s}^{-1}$ might be masked by the "glare" of the brighter source.

Naturally, during the course of the 600 day survey, the sky was unevenly exposed. Therefore, for specific regions, it is possible to set more stringent upper limits. We have run our sky map intensity-fitting

TABLE 2

UPPER LIMITS TO X-RAY EMISSION FROM INTERESTING OBJECTS

| Object | Position (1950.0) ($l^{\mathrm{II}}$, $b^{\mathrm{II}}$) | | Intensity (cts $\mathrm{s}^{-1}$) 3 $\sigma$ Upper Limit: OSO-7 (3° AR) | Intensity (cts $\mathrm{s}^{-1}$) 3 $\sigma$ Upper Limit: ~ *Uhuru* (2–6 keV) | Comments |
|---|---|---|---|---|---|
| NGC 104 | 305°89 | −44°90 | 0.28 | 4.2 | Globular cluster, 47 Tuc |
| NGC 2808 | 282.18 | −11.26 | 0.36 | 5.4 | Globular cluster, $\omega$ Cen |
| NGC 5139 | 309.13 | +15.14 | 0.29 | 4.4 | Globular cluster |
| NGC 5824 | 332.55 | +22.00 | 0.19 | 2.9 | Globular cluster |
| NGC 6093 | 352.67 | +19.45 | 0.26 | 3.9 | Globular cluster, M80 |
| NGC 6266 | 353.58 | +7.30 | 0.40 | 6.0 | Globular cluster, M62 |
| NGC 6356 | 6.73 | +10.21 | 0.57 | 8.6 | Globular cluster |
| NGC 6522 | 1.03 | −3.93 | 1.05 | 15 | Globular cluster |
| NGC 6541 | 349.28 | −11.19 | 0.32 | 4.8 | Globular cluster |
| NGC 6569 | 0.49 | −6.68 | 0.53 | 8.0 | Globular cluster |
| NGC 6715 | 5.63 | −14.11 | 0.30 | 4.5 | Globular cluster, M54 |
| NGC 6752 | 336.49 | −25.62 | 0.30 | 4.5 | Globular cluster |
| NGC 6864 | 20.31 | −25.76 | 0.21 | 3.2 | Globular cluster, M75 |
| NGC 7089 | 53.37 | −35.78 | 0.19 | 2.9 | Globular cluster, M2 |
| NGC 7099 | 27.16 | −46.83 | 0.36 | 5.4 | Globular cluster, M30 |
| A0535+26 | 181.46 | −2.62 | 0.41 | 6.2 | Transient X-ray source prior to outburst |
| A0620−00 | 210.00 | −6.52 | 0.27 | 4.1 | Transient X-ray source prior to outburst |
| MX 0656−07 | 220.16 | −1.66 | 0.18 | 2.7 | Transient X-ray source prior to outburst |
| A1118−61 | 292.51 | −0.83 | 1.23 | 18 | Transient X-ray source prior to outburst |
| A1524−61 | 320.0 | −4.48 | 0.72 | 10.8 | Transient X-ray source prior to outburst |
| DQ Her | 70.98 | +25.98 | 0.24 | 3.6 | Old nova |
| CP Pup | 252.92 | −0.84 | 0.25 | 3.8 | Old nova |
| Nova Cygni 1975 | 89.82 | −0.08 | 0.48 | 7.2 | Recent nova prior to outburst |
| P Cygni | 75.82 | +1.31 | 0.69 | 10.4 | Early emission star |
| HD 66811 | 255.98 | −4.70 | 0.29 | 4.4 | Wolf-Rayet star |
| HD 68273 | 262.82 | −7.98 | 0.40 | 6.0 | Wolf-Rayet star, $\gamma^2$ Vel |
| WZ Sge | 57.54 | −7.94 | 0.30 | 4.5 | Recurrent nova |
| RS Oph | 19.79 | +10.37 | 0.27 | 4.1 | Recurrent nova |
| U Gem | 90.56 | −7.11 | 0.55 | 8.3 | U Gem star |
| SS Cyg | 199.22 | +23.40 | 0.25 | 3.8 | U Gem star |
| HD 188001 | 56.49 | −4.33 | 0.30 | 4.5 | 9 Sge, Of star |
| $\beta$ CMa | 226.05 | −14.26 | 0.22 | 3.3 | $\beta$ CMa star |

program on a number of interesting galactic objects, and we present the upper limits determined for these objects in Table 2. We note, in particular, the first 16 objects in Table 2, all of which are globular clusters with high central escape velocities and which have been suggested as possible candidate X-ray sources (Silk and Arons 1975; Bahcall and Ostriker 1975). Upper limits for many of these clusters have also been set from the *Uhuru* data (Ulmer *et al.* 1976). For the sources common to both sets of observations, the upper limits obtained are comparable.

## IV. SUMMARY OF RESULTS

We applied the computer program discussed in § II to the data which had been assembled in map form. With this program we determined the mean intensities of all the known X-ray sources in each of the TW, NE, AR, and KR counters in each counter bank. The XE counters were excluded, since our previous experience had shown very few sources with statistically significant XE counting rates.

Intensity fits were performed for each crossing of the satellite scan path over each source position. A crossing was typically a period of several days, and individual crossings were separated by weeks to months. Statistically more precise fits were also performed to the data from each source summed over the entire 600 days of analysis. Making use of these results, we are currently preparing a detailed history of the X-ray sky between 1971 and 1974 for presentation in catalog form. We present here a statistical summary of our findings which pertain to the galactic X-ray sources. As before, we take galactic sources to be those with $|b^{\rm II}| < 10°$ (except those usually associated with extragalactic objects) plus those high-latitude sources which are clearly associated with galactic objects.

In the following sections we have attempted to make general statements about the properties of various classes and populations of X-ray sources, e.g., supernova remnants, massive X-ray binaries and X-ray pulsars, globular cluster sources, galactic bulge sources, and galactic disk sources. We loosely define galactic bulge sources to be any sources with $|b^{\rm II}| < 10°$ and $|l^{\rm II}| < 20°$ and not known to be closer than about 5 kpc (this last criterion excludes 3U 1700−37, for example).

For the disk population, we take those sources with $|b^{\rm II}| < 10°$, $|l^{\rm II}| > 20°$, plus Her X-1 and 3U 1700−37. We exclude from both the disk and bulge groupings the supernova remnants, the globular clusters, and Sco X-1 and Cyg X-2 (the low-mass binaries), all of which we consider separately.

### *a*) *Number-Intensity Diagram*

In Figure 4 we show a standard log-log plot of the number of sources $N$ with observed intensity greater than or equal to $S$ versus $S$. For $S$ we chose the mean 3–10 keV (AR) counting rates because of the low background and high source counting rates for the AR detectors. The points in Figure 4 for which $S < 1.0$ counts s$^{-1}$ have been corrected for the incomplete sky coverage at these lower intensity levels.

Curve A of Figure 4 is the number-intensity curve obtained from our determinations of mean intensity for all of the galactic sources. It agrees well with the *Uhuru* results (Matilsky *et al.* 1973; Forman, Jones, and Tananbaum 1976), for sources with $|b^{\rm II}| < 20°$, including the location of the break in the slope.

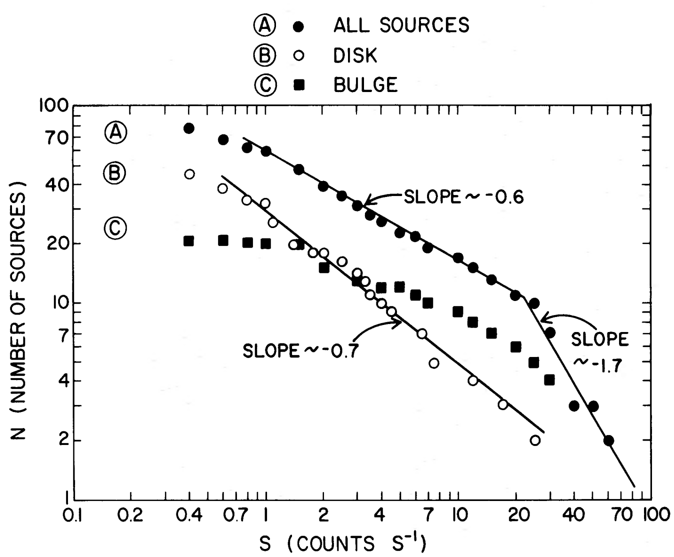


FIG. 4.—Number-intensity diagram for the OSO-7 galactic data. $N$ is the number of sources with counting rates greater than or equal to $S$. Curve A uses all data from galactic sources. Curve B uses just the data for sources in the galactic disk and Curve C just the data for sources in the galactic bulge. Data points for which $S < 1.0$ counts s$^{-1}$ have been corrected for incomplete sky exposure.

In curves B and C of Figure 4, we have separately plotted the number-intensity curves for disk sources (curve B) and the bulge sources (curve C). The points of curve B with $S \geq 1.0$ counts $s^{-1}$ (sources strong enough so that nearly every one has been detected) were fitted to a power law of the form $N \propto S^{-0.71}$ with a standard deviation in the exponent of $\pm 0.18$ (Crawford, Jauncey, and Murdock 1970). The number-intensity curve for a uniform distribution of sources in an infinite thin disk has a slope of $-1$, so that the observed curve is in reasonable agreement with such a distribution. The discrepancy between the observed slope and $-1$ may be due in part to the possible organization of sources along spiral arms. For an observer looking at a distribution of sources along a line, the slope of the log $N$–log $S$ curve is $-0.5$.

Note that the low-intensity points of curves A and B, although corrected for incomplete exposure, fall below the lines fitted to the higher intensity points. While this may reflect the actual distribution of sources, we feel that it is likely that several low-intensity sources may not have been detected because of confusion with stronger sources. Therefore, the low-intensity portion of the data probably lacks a number of sources which were not detected in crowded regions.

The bulge sources are all presumed to be about 10 kpc away, and the number-intensity diagram (curve C) should be nothing more than the integral of the luminosity function of these sources (see § IV*b*). Note that the low-intensity points on this curve are strongly affected by source confusion, so that the apparent flattening at $S < 2.0$ counts $s^{-1}$ is probably not real.

### *b*) *Luminosities*

Following the method of Margon and Ostriker (1973), we estimated the distances to a number of the sources in our sample and, using our measured counting rates, computed the luminosities of these sources (2–10 keV). The distances were assumed for two classes of sources. The first class was the set of sources with firmly established associations with optical objects whose distances had been well determined. The second class was the galactic bulge sources which we took to be at 9 kpc.

In order to determine the luminosity for a source, an intensity must be combined with the distance estimate. For intensity we chose the AR counting rate measured during that observation of the source position when the source was brightest. We converted from counting rate to energy flux according to the relationship 1 AR count $\approx 2.6 \times 10^{-10}$ ergs $cm^{-2}$ (2–10 keV). We estimate the typical error for this conversion to be less than about 30%.

The luminosities which we determined are displayed in histogram form in Figure 5. In this and the following figures we have indicated the values for several classes of objects, notably the bulge and disk sources. For comparison we have also included the Magellanic Cloud sources when the measurements were statistically useful.

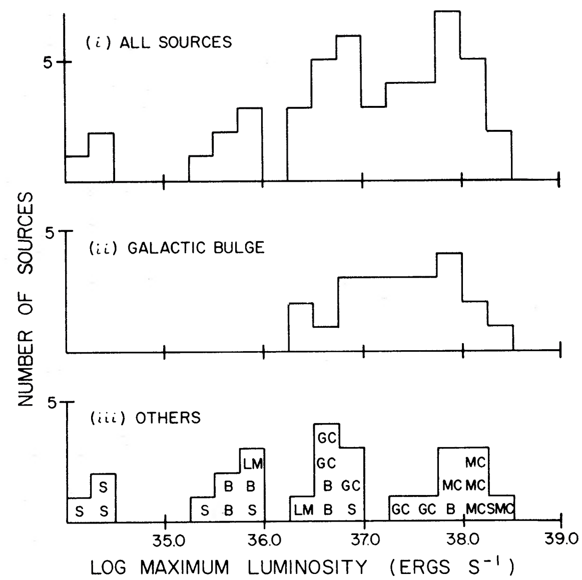


FIG. 5.—Luminosity histogram for galactic sources. The data are displayed separately for bulge sources, binaries (B), globular cluster sources (GC), sources in the Large Magellanic Cloud (MC), the Small Magellanic Cloud (SMC), the low-mass binaries (LM), supernova remnants (S), and others.

From Figure 5 we see confirmation of a number of familiar features of X-ray sources in general (see Seward *et al.* 1972; Gursky 1972; Setti and Woltjer 1972; Margon and Ostriker 1973; Giacconi and Gursky 1974): the upper limit on X-ray luminosity at $\sim 10^{38}$ ergs $s^{-1}$ (near the Eddington limit for a 1 $M_\odot$ object), the relatively low luminosity of the supernova remnants, the presence of a number of bright sources near the galactic bulge, etc. We see little evidence of the bimodal distribution in the X-ray luminosity function which has been suggested by some (Ryter 1970; Seward *et al.* 1972; Margon and Ostriker 1973). Because of the several sources of error and selection effects which are present, however, we cannot rule out a distribution with two peaks separated by as much as an order of magnitude.

### *c*) *Spectra*

Figure 6 summarizes the spectral data obtained from our study of galactic sources. The data are presented in the form of color-color diagrams—scatter plots in which the axes are the ratios of the counting rates in each of the counters with respect to the AR counter. Each of the ratios provides some information about source spectra. Recalling the relative energy responses of the counters, one can approximate that a high TW/AR rate implies a very soft or low-temperature source, that low TW/AR and/or NE/AR ratios imply a highly absorbed source, and that a large KR/AR value corresponds to a very hard or high-temperature source.

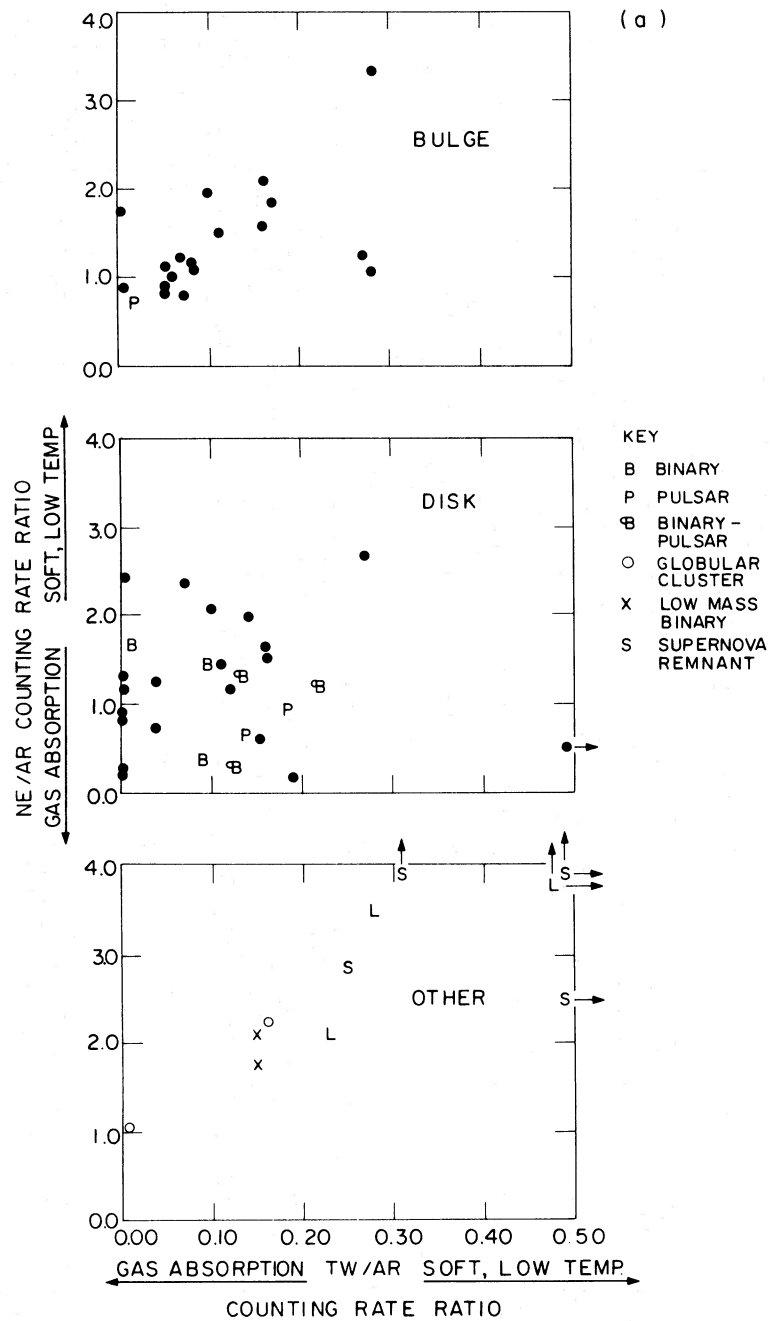


FIG. 6*a*

FIG. 6.—Color-color diagrams of galactic source observations. The axes are the ratios of the counting rates in each of the TW (1–1.5 keV), NE (1–6 keV), and KR (15–40 keV) counters with respect to the AR counters. The TW/AR versus NE/AR plot is Fig. 6*a* while the KR/AR versus NE/AR is Fig. 6*b*. Those ratios with very poor statistical significance are not shown. Simple interpretations of the ratios are given beneath the axes. The data are displayed separately for the bulge sources, the disk sources and for each of several source groupings: binaries (B), pulsars (P), sources which have been shown to be both binaries and pulsars (Ꞵ), globular clusters (O), low-mass binaries Cyg X-2 and Sco X-1 (X), supernova remnants (S), and sources in the Large Magellanic Cloud (L).

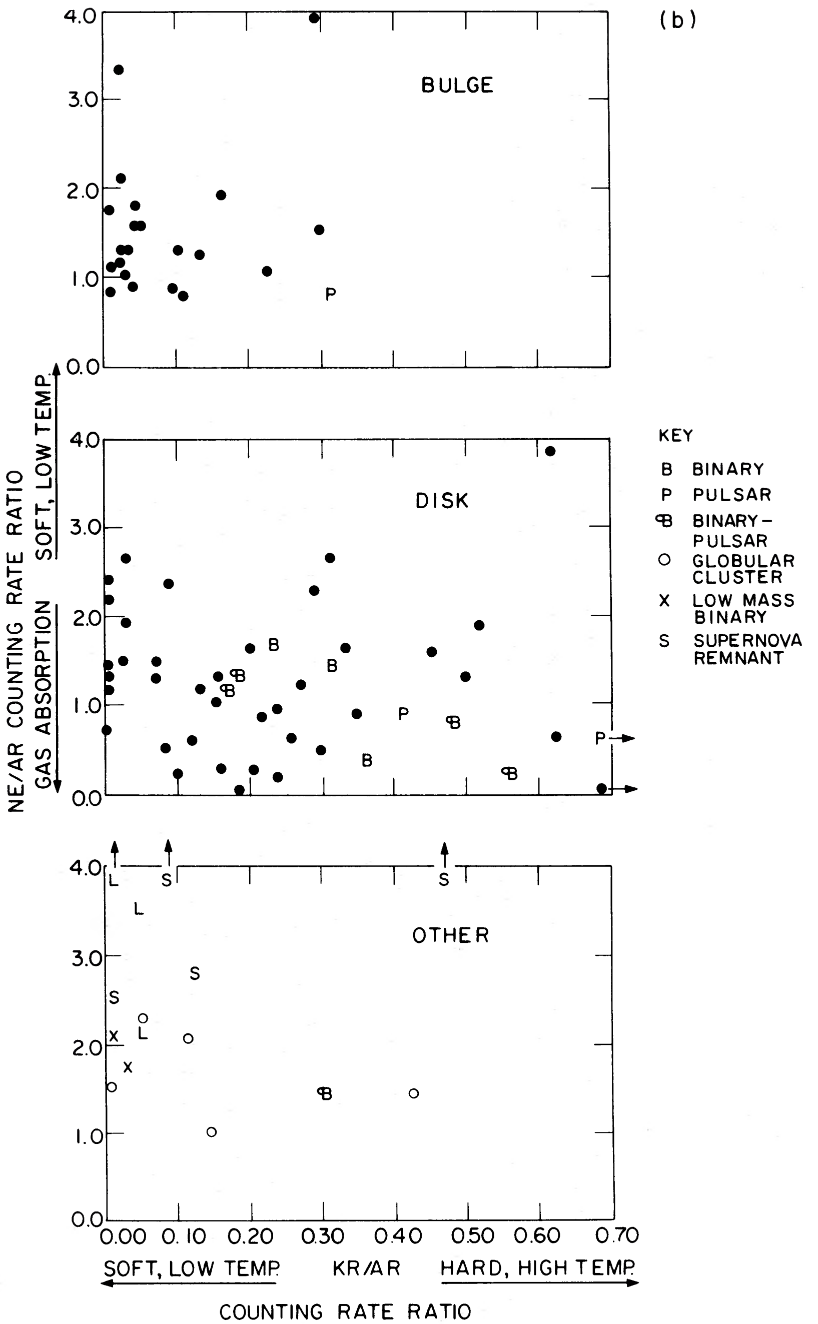


FIG. 6*b*

FIG. 6.—*Continued*

One can draw some general conclusions concerning X-ray source spectra from Figure 6. For example, Figure 6*a* displays the well-known spectral softness of most supernova remnants (Gorenstein and Tucker 1976) whose ratios are all at the upper right or "soft" region of the TW/AR–NE/AR plot. Figure 6*a* is apparently a fairly good indicator of the amount of gas between the Earth and an X-ray source. The relatively nearby sources (Cyg X-2, Sco X-1, and the supernova remnants) are only slightly absorbed and have relatively large TW/AR and NE/AR ratios. Similarly, the Large Magellanic Cloud sources, while quite distant, are at high galactic latitude where very little interstellar gas intervenes—again they are found in the "soft" region of the color-color diagrams. Most of the galactic bulge and disk sources, on the other hand, are more highly absorbed and are found, for the most part, in the lower left corner of the diagrams. It is interesting to note the apparent correlation of the TW/AR and NE/AR ratios for the bulge sources. Such a correlation is consistent with the existence of a collection of sources with identical inherent spectra which are modified at low energies by interstellar absorption caused by varying amounts of intervening gas.

Perhaps the most striking result of this study of spectra is shown in Figure 6*b*, the KR/AR–NE/AR diagram. Here we see that the galactic bulge sources are considerably softer than the massive binaries, the pulsars, and many of the other disk sources. This division in the hardness-ratio distribution is quite well delineated—nearly all of the bulge population (17 of 22 sources) have KR/AR ratios less than 0.15, while only 16 of 49 disk sources do. This division is even more marked for the class of pulsars and massive binaries; each[1] of these, including GX 1+4 in the bulge and SMC X-1, has a KR/AR ratio in excess of 0.15. This property of X-ray pulsars has been noted by others (Jones 1977).

Table 3 summarizes the data of Figure 6. Here we have computed the mean ratios (unweighted) for each of the source groupings. No account has been taken of the relative precisions of the ratios for the individual sources; i.e., the weak sources, with larger uncertainties, contribute as much as strong sources to the computed mean values.

[1] GX 17+2 and Cir X-1 may be exceptions. GX 17+2 (KR/AR = 0.04 ± 0.01) has been reported to be weakly modulated (5%) with a period of ~32 minutes (White *et al.* 1976). The probability of any period occurring at random was estimated at 0.04. A 16.6 day modulation has been reported from Cir X-1 (Kaluzienski *et al.* 1976), which has a counting rate ratio KR/AR = 0.08 ± 0.05.

## V. X-RAY SOURCE POPULATIONS

As discussed in § IV, X-ray stars[2] seem to fall naturally into two classes which may be termed the bulge and disk populations (see Canizares 1975 and references therein). Many of the members of the disk population are clearly identified as collapsed stars (neutron stars or black holes) in close binary systems with young, massive, nuclear-burning companions. Furthermore, it has been argued (e.g., Blumenthal and Tucker 1974) that nearly all of the disk population are members of such systems.

The X-ray stars in the bulge are much more poorly understood. There are few optical candidates for the bulge sources; it is unlikely, however, that they can be similar to the disk systems because young, massive stars are rarely found in the central regions of galaxies such as our own. (Johnson [1967, 1975], however, has proposed that the bulge sources are relatively young objects which form in the expanding rings of dense matter which encircle the galactic center.)

The X-ray properties of the two populations contrast strongly (Seward *et al.* 1972; Margon and Ostriker 1973; Dilworth, Maraschi, and Reina 1973; Jones 1977). As discussed earlier, the number-intensity and luminosity diagrams (Figs. 4–5) reveal important differences between the two classes. Most striking, however, are the differences in spectra, in particular the marked deficiency of X-rays of energy greater than 15 keV from the bulge group (Fig. 6).

It is clear, in short, that there are at least two populations of X-ray stars. It is natural to ask, therefore, whether all X-ray stars belong to one or the other of these sets. One subclass which has been considered

[2] Here we shall refer to compact X-ray sources as X-ray stars. The nebular supernova remnants, which clearly form a class of their own, will not be discussed in this section.

TABLE 3

MEAN* COUNTING RATE RATIOS

| Source Class | TW/AR | NE/AR | KR/AR |
|---|---|---|---|
| Galactic bulge | 0.09 (−0.12, 0.28) | 1.50 (+0.80, 3.93) | 0.09 (+0.01, 0.03) |
| Globular clusters | 0.03 (−0.10, 0.16) | 1.63 (+1.02, 2.23) | 0.14 (+0.00, 0.42) |
| Disk† | 0.07 (−0.24, 0.55) | 1.26 (−0.35, 3.90) | 0.24 (−0.02, 0.78) |
| Massive binaries | 0.07 (+0.01, 0.10) | 1.17 (+0.39, 1.69) | 0.31 (+0.25, 0.36) |
| Pulsars‡ | 0.11 (+0.01, 0.18) | 0.77 (+0.61, 0.92) | 0.48 (+0.31, 0.71) |
| Binary pulsars§ | 0.16 (+0.12, 0.22) | 1.03 (+0.26, 1.47) | 0.34 (+0.17, 0.56) |
| Low-mass binaries‖ | 0.15 (+0.15, 0.15) | 1.92 (+1.75, 2.08) | 0.03 (+0.02, 0.03) |
| Supernova remnants | 1.90 (+0.25, 7.29) | 9.83 (+2.47, 30.16) | 0.15 (−0.08, 0.47) |
| Large Magellanic Cloud | 0.38 (+0.23, 0.63) | 3.63 (+2.14, 4.55) | 0.02 (−0.02, 0.05) |

* Ratios from each source were equally weighted, although editing was performed to remove values with extremely large uncertainties. The numbers in parentheses adjacent to each mean are the extremes of the range of values making up the mean.

† Includes binaries and pulsars lying in the disk.

‡ Includes GX 1+4 in the bulge.

§ Includes SMC X-1.

‖ Sco X-1 and Cyg X-2.

TABLE 4

PROPERTIES OF PERSISTENT SOURCES ASSOCIATED WITH X-RAY BURST SOURCES

| No. | Burst Source(s) | Associated Persistent Source | $l^{II}$ | $b^{II}$ | Peak Steady Flux (AR) Counts s$^{-1}$ | Mean Ratios TW/AR | NE/AR | KR/AR | References |
|---|---|---|---|---|---|---|---|---|---|
| 1 | MX 0513−40 | MX 0513−40 | 245° | −35° | 0.65 ± 0.05 | +0.37 ± 0.32 | 2.05 ± 0.25 | 0.11 ± 0.10 | 1,2,3 |
| 2 | XB 1608−52 | MX 1608−52 = 4U 1608−52 | 331 | −1 | 9.67 ± 1.16 | −0.03 ± 0.14 | 0.87 ± 0.23 | 0.22 ± 0.06 | 4,5,6,7 |
| 3 | MXB 1637−53 | 3U 1636−53 | 333 | −5 | 18.27 ± 1.54 | +0.10 ± 0.03 | 2.06 ± 0.14 | 0.02 ± 0.01 | 8 |
| 4 | MXB 1728−34 | MX 1728−33 = 4U 1728−33 = 3U 1727−33 | 354 | 0 | 12.65 ± 1.05 | +0.05 ± 0.03 | 1.32 ± 0.10 | 0.10 ± 0.01 | 9,10,11 |
| 5 | MXB 1742−29, MXB 1743−28, MXB 1743−29 | GCX, 3U 1743−29 | 0 | 0 | 11.77 ± 1.69 | +0.05 ± 0.10 | 0.62 ± 0.17 | 0.16 ± 0.04 | 12 |
| 6 | 3U 1820−30 | 3U 1820−30 | 3 | −8 | 17.56 ± 0.71 | +0.16 ± 0.02 | 2.23 ± 0.12 | 0.05 ± 0.01 | 13,14,15,16 |
| 7 | MXB 1837+05 | Ser X-1 | 36 | +5 | 13.52 ± 0.56 | +0.14 ± 0.01 | 1.96 ± 0.10 | 0.03 ± 0.01 | 17,18 |
| Average | | | | | | +0.12 ± 0.13 | 1.59 ± 0.65 | 0.10 ± 0.07 | |

NOTES.—Source (1) Identification not firmly established. MX 0513−40 associated with globular cluster NGC 1851. (2) Identification not firmly established. (4) Identification with 3U 1727−33 not firmly established. If two different sources are present, MIT observations may include contributions from either or both or from MXB 1728−335 as well. (5) Extended source at galactic center may be several unresolved sources, some of which may be associated with some of the burst sources. X-ray data obtained from 1° field-of-view detectors. (6) Associated with globular cluster NGC 6624.

REFERENCES.—1) Clark, Markert, and Li 1975; 2) Forman and Jones 1976; 3) Hoffman 1977; 4) Belian, Conner, and Evans 1976; 5) Grindlay and Gursky 1976; 6) Li 1976; 7) Tananbaum *et al.* 1976; 8) Hoffman, Doty, and Lewin 1977; 9) Hoffman *et al.* 1976; 10) Hoffman, Lewin, and Doty 1977; 11) Carpenter *et al.* 1976; 12) Lewin *et al.* 1976; 13) Grindlay *et al.* 1976; 14) Clark *et al.* 1977; 15) Clark *et al.* 1977; 16) Canizares and Neighbours 1975; 17) Swank *et al.* 1976; 18) Li *et al.* 1977.

is the set of globular cluster X-ray sources. As noted by Canizares (1975), these objects have much in common with the bulge sources. Both sets are associated with populations of old, low-mass stars; both are found in regions of high stellar density. The X-ray properties of both groups are consistent (e.g., high luminosity, deficiency of hard X-rays), although the small sample of globular cluster X-ray sources (five) makes such comparisons difficult. It appears that the cluster sources are related to the bulge sources, but too little is known about both populations to determine how close this relationship may be.

A subset of the galactic X-ray sources which has generated much recent interest is the class of X-ray bursters (Lewin 1976 and references therein). The MIT OSO-7 detectors were not useful for observing bursts because of their long accumulation times ($\sim$190 s). However, a number of burst sources have been associated with persistent X-ray sources, most of which were observed by OSO-7. Table 4 lists these objects and their relevant X-ray characteristics.

Are the burst sources associated with the bulge or disk populations? Like the bulge sources, they are concentrated toward the galactic center (Lewin *et al.* 1977). Two or three of the burst sources have been associated with globular clusters (two in Table 4 and MXB 1730$-$335, Liller 1976). Lewin (1976), however, has emphasized that many of the burst sources are almost certainly not in globular clusters.

The above discussion suggests that the burst sources may be a subset of the bulge and globular cluster family. The X-ray data for the persistent sources support this suggestion. The mean spectra of the two classes (Tables 3 and 4) are quite similar, and some of the sources in Table 4 are quite luminous. In contrast, there are clearly a number of burst sources with quite underluminous counterparts—namely, those which have not been observed. Low-luminosity bulge sources are uncommon, although, as discussed earlier, this may be due in part to extensive source confusion near the galactic center.

In light of the evidence linking the bulge, globular cluster, and burst sources, and considering our ignorance of the true nature of these objects, there have been some efforts in recent years to create models for the bulge and related families of sources. For example, Ostriker (1976) has suggested that the bulge sources may be massive black holes in obscured or dissipated globular clusters, which accrete gas from the interstellar medium to produce X-rays. Several authors have suggested modified versions of the binary X-ray star model to explain the bulge population. (Such theories are handicapped by the fact that binary behavior has never been observed for any of the bulge sources.) As mentioned above, Johnson (1967, 1975) has proposed that the bulge sources are relatively young objects, probably quite similar to the disk sources, which are born in the expanding rings of dense matter centered on the galactic nucleus. Jones (1977) has remarked that the different spectra of X-ray stars can be due to variations in the mass or the inclination angle of the binary system. This latter characteristic evidently cannot explain the general softness of the bulge sources (although it may well explain the distribution of spectra in the disk), since the orientation of orbits within the bulge would presumably be random.

We note that within the standard binary model there are other parameters, such as the magnetic field strength and the rotation period of the collapsed objects, which might be varied to explain the properties of the bulge sources. For example, a weaker magnetic field would decrease the high-energy cutoff in the spectrum due to modifications in the Thomson scattering of photons by a magnetized plasma (Boldt *et al.* 1976). If the bulge sources are as old as their association with Population II objects in the bulge suggests, then they may well have very different masses, magnetic field strengths, and rotation periods.

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*Note added in proof.*—At least two additional burst sources have been firmly identified with persistent X-ray sources since this paper was submitted. We have reexamined the OSO-7 observations of these objects and determined their counting rate ratios. The sources 3U 1735−44 (= MXB 1735−44) and 3U 1915−05 (= MXB 1916−05) had a mean NE/AR value of $1.62 \pm 0.27$ and KR/AR value of $0.02 \pm 0.04$, consistent with the ratios of the other persistent sources listed in Table 4. The precision of the observations of these sources with the TW detectors was significantly inferior to those sources listed in Table 4.

Also, since this paper was submitted, 3U 1626−67 and 3U 1538−52 have been shown to be X-ray pulsars. The counting rate ratios derived from the OSO-7 data for these sources are in fair agreement with those for other pulsars listed in Table 3. In particular, the mean KR/AR ratio for 3U 1626−67 is $0.67 \pm 0.09$ and for 3U 1538−52 is $0.15 \pm 0.14$.

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