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RADIO OBSERVATIONS OF GALACTIC BULGE AND GLOBULAR CLUSTER X-RAY SOURCES

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ABSTRACT

A program of VLA[1] observations of luminous X-ray sources in the galactic bulge and globular clusters has been initiated. Short observations were made at either λ6 cm or λ20 cm (with the A-configuration) at the precise X-ray positions obtained with the *Einstein X-ray Observatory* for 14 galactic bulge and seven globular cluster sources. Three of the X-ray sources surveyed were detected at λ6 cm (including the discovery of the radio counterpart of the source GX 13+1), and two were probably detected at λ20 cm. Significant differences were found for several of the sources previously observed at the VLA by Geldzahler, implying that the sources are highly variable. Implications of our results for the emission region and the physical nature of the galactic bulge sources are discussed.

Subject headings: clusters: globular — galaxies: stellar content — radio sources: variable — X-rays: sources

I. INTRODUCTION

In an effort to investigate the nature of galactic bulge X-ray sources (the "GX sources") as well as the closely related bright X-ray sources found in some globular clusters, we have begun a program of VLA studies of these objects. Preliminary results of this program were reported by Grindlay and Seaquist (1982). A related program has been reported by Geldzahler (1983), although both our objectives and results have important differences, as is evident below. Several of the GX sources have been detected as weak (and variable) radio sources in previous studies (e.g., Braes and Miley 1971; Wade and Hjellming 1971). In particular, the prototype (but relatively nearby) GX source Sco X-1 was detected (Wade and Hjellming 1971) as a variable point source with flux densities at 3.7 cm typically 10–60 mJy. Recent VLA observations of Geldzahler and Fomalont (1985) have shown that the surrounding two compact and nearly colinear radio lobes at 1'.2 separation have detectable proper motion (36 km s^{-1} for an assumed 500 pc source distance).

Precise X-ray positions (3".2 radius for 90% confidence error circle; Grindlay *et al.* 1984; Grindlay, Hertz, and Tokarz 1986) are now available from the reprocessed HRI data from the *Einstein X-ray Observatory*. With the high sensitivity and resolution of the VLA, it is therefore possible to search for much fainter radio counterparts for many bright galactic bulge X-ray sources. Many of these sources are as yet unidentified (see review by Bradt and McClintock 1983), although their X-ray properties (and where identified, optical properties) make it clear that they are probably compact binaries containing a neutron star accreting from a low-mass binary companion (see Lewin and Joss 1983 and references therein). Our goals are (i) to detect sources and thereby obtain source positions accurate to 1" or smaller to assist in source identification, (ii) to search for evidence of nonthermal emission processes in compact X-ray binaries, and (iii) to search for surrounding lobes (as in Sco X-1).

I. OBSERVATIONS

Observations were made of 21 X-ray source fields with the VLA in the A configuration on 1982 June 21–22. One source (GX 17+2) was also observed in 1982 February. Preliminary X-ray positions were known from the initial processing of the *Einstein* high resolution imager (HRI) data and precise positions from the improved reprocessing of the HRI data are now available for each source (Grindlay, Hertz, and Tokarz 1986). All fields were observed at λ6 cm for (typically) 15 minute integration times. Several sources (NGC 6624, GX 5−1, and GX 17+2) were also observed at λ20 cm. All 27 antennas were used and the observed system noise levels were nominal, such that the 3 σ sensitivities were $\sim$0.3 mJy at λ6 cm annd λ20 cm, respectively. Special attention was given to the calibration sources used so that precise source positions could be obtained. An absolute flux calibration was carried out using 3C 286. Standard data processing was carried out at the VLA, and CLEANed maps were derived for the detected sources in follow-up processing.

III. RESULTS

Results of the observations are summarized in the tables below. In Table 1 we give the flux densities and positions derived for the sources detected at $\sim$5 σ or greater. The two objects in Table 2, with statistical significance of 3.5 σ or greater, are very likely detections (although their formal significance is marginal) since they are within the 90% confidence radius error circle positions for the X-ray sources and are unlikely to be background sources (see discussion below). All of the sources listed in Tables 1 and 2 were observed with the same calibration source, 1748−253, so that the source positions are all subject to the same $\sim$0".1 uncertainty in this calibrator (see Table 1, footnote b). The remaining observations

[1] The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

DEFINITE DETECTIONS[a]

Source	Wavelength (cm)	Flux[b] (mJy)	R.A. (1950.0)	Decl. (1950.0)	Formal Error[c]	X-ray Offset[d]
GX 5−1	6	1.07 ± 0.12	17^h58^m 3.182	−25° 4′40″.2	0″.02	2″.7 ± 1″.6
	20	1.33 ± 0.17	17 58 3.268	−25 4 40.4	0.13	2.6 ± 1.6
GX 13+1	6	1.80 ± 0.15	18 11 36.688	−17 10 22.9	0.01	2.9 ± 1.6
GX 17+2	6	0.98 ± 0.08	18 13 10.928	−14 3 14.5	0.01	1.9 ± 1.6

[a] Greater than 5 σ.

[b] Fluxes in Tables 1–3 refer to values measured in 1982 June, *except* for the λ6 cm detection of GX 17+2, which was in 1982 February.

[c] The formal error In Tables 1 and 3 in source position is that derived from centroiding the source peak in the reconstructed map; actual positional errors are larger due to the uncertainty (~0″.1) in the position of the calibration source (1748−253) used for all the sources in Tables 1 and 2.

[d] The X-ray offset in Tables 1 and 2 is based on the HRI position and error for each source as given by Grindlay, Hertz, and Tokarz 1986.

TABLE 2

POSSIBLE DETECTIONS[a]

Source	Wavelength (cm)	Flux (mJy)	R.A. (1950.0)	Decl. (1950.0)	Formal Error	X-ray Offset
GX 17+2	20	0.57 ± 0.15	18^h13^m10.91	−14° 3′14″.9	0″.15	1″.9 ± 1″.6
NGC 6624	20	0.49 ± 0.12	18 20 27.718	−30 23 15.2	0.12	2.4 ± 0.9

[a] Approximately 3.5 σ or greater.

yielded the upper limits (3 σ) given in Table 3. In the following paragraphs we describe our results obtained for the four sources detected: GX 5−1, GX 13+1, GX 17+2, and NGC 6624.

a) GX 5−1

The previously known radio counterpart of GX 5−1 was detected at both λ20 cm and λ6 cm with an implied spectral index of −0.27 ± 0.11. The λ20 cm flux (1.33 ± 0.17 mJy) is consistent with that measured by Geldzahler (1983) in 1981, February, although comparison with flux densities reported by Braes, Miley, and Schoenmaker (1972) suggest the source is variable.

TABLE 3

λ6 cm UPPER LIMITS[a]

Source	Coordinate Name	Flux Upper Limit (mJy)
GX Sources		
GX 340+0	4U 1642−45	0.53
4U 1702−41	4U 1702−42	0.36
Sco X-2	4U 1703−36	0.34
MXB 1735−44	4U 1735−44	0.26
GX 3+1	4U 1744−26	0.25
GX 9+1	4U 1758−20	0.33
4U 1822−00	4U 1822−00	0.40
Ser X-1	4U 1837+04	0.41
4U 1905+00	4U 1905+00	0.32
4U 1916−05	4U 1916−05	0.35
Globular Clusters		
Grindlay 1	4U 1728−34	0.32
Terzan 2	4U 1724−30	0.28
NGC 6441	4U 1756−37	0.42
NGC 6712	4U 1850−08	0.31
M15	4U 2127+11	0.50
Liller 1	MXB 1730−335	0.38

[a] 3 σ.

b) GX 13+1

A relatively bright (1.9 mJy at λ6 cm) source was discovered in the HRI error circle for GX 13+1. In follow-up optical observations of this field with the CCD at the Whipple Observatory (in 1982 June), we found a faint reddened stellar object near the VLA radio position (Grindlay, Hertz, and Schild 1982). Deeper CCD observations of the field were carried out in 1985 May at CTIO (Grindlay *et al.* 1986) and show that the stellar object mentioned above is significantly displaced from the VLA position; no optical counterpart brighter than $m_v \approx 22$ was detected at the radio position. However, follow-up IR observations at the MMT reveal a relatively bright object consistent with the VLA position (Garcia and Grindlay 1986). Follow-up radio observations of this source have now also been carried out at the VLA to measure the source spectrum and variability simultaneous with X-ray observations from *EXOSAT*; these results will be reported by Garcia *et al.* (1986).

c) GX 17+2

GX 17+2, which is a known variable radio source (Hjellming and Wade 1971), was detected only marginally at λ20 cm: it was not detected (upper limit of 0.34 mJy) at λ6 cm in our June observations. In our earlier observations of this source in 1982 February, however, it was detected with a flux of 0.98 mJy at λ6 cm, implying variability by a factor of ~3 or greater, or more than previously observed by Hjellming (1978). Our confidence in the λ20 cm detection is supported by the excellent agreement in position between the (nearly) 4 σ feature and our earlier 1982 February detection. The variability and nonsimultaneity of our λ20 cm and λ6 cm measurements prevent us from determining a spectral index.

Our position for GX 17+2 is within 0″.5 of "Star 28" noted by Tarenghi and Reina (1972) to be a possible optical counterpart on the basis of the initial ~1′ radio position. Davidsen (1975) and Margon (1980) showed this star was of spectral type G and without obvious continuum or emission line features to associate it with the ~2″ × 5″ radio position obtained by Hjellming (1978) for the X-ray source. However, our present much improved VLA position (~0″.1 uncertainty) and an improved optical position for Star 28 kindly derived by H. Ables from astrograph plates at the USNO indicate that the radio and optical positions are coincident to within the 0″.5 optical measurement errors.

Although the lack of emission lines and (variable) blue continuum component make it most unlikely that the G star (probably a late G or early K subgiant; see Grindlay 1984) is the binary companion of GX 17+2, its apparent spatial coincidence argues that it may nevertheless be physically associated with the compact binary source. Grindlay (1985) and Bailyn and Grindlay (1987) have in fact suggested that the G star may be a triple companion of the compact X-ray binary.

d) NGC 6624

The provisional λ20 cm detection at 0.49 mJy of the X-ray burster in NGC 6624 is based on a 4 σ feature within the 95% X-ray source confidence radius, which is 2″.5 for this source (Grindlay *et al.* 1984). The probability of a receiver noise fluctuation at this level or greater within the error circle is less than 3%. In addition, the probability of a chance coincidence with an extragalactic source at this level or greater is less than 0.1%, as determined from the radio source counts of Condon and Mitchell (1982).

IV. DISCUSSION

Several significant discrepancies with Geldzahler's (1983) results emerge from this work. First, our position for GX 5−1, which is consistent with Geldzahler's, is *not* consistent with Star 22 in the finding chart of Hoffman, Davison, and Morrison (1973) as stated by Geldzahler. Rather, the optical astrometry (~0″.7 accuracy) we have carried out of this field indicates that Star 22 is 7″.3 east and 1″.6 north of the radio position.

Second, Geldzahler's position of the source in the globular cluster NGC 6624 is not consistent with either the X-ray position (Grindlay *et al.* 1984) or the radio position given here (which is consistent with the X-ray position). No radio source is detected in our observations at the position given by Geldzahler with a (3 σ) upper limit of ~0.3 mJy, or a factor of ~8 below that given by Geldzahler. Thus either the ±0″.4 positional accuracy of the radio position given by Geldzahler is in error (our radio position is 4″.2 west and 0″.9 north of Geldzahler's) or there are two variable radio sources in the core of NGC 6624. Although we regard the second possibility as much less likely, it is interesting that Geldzahler's source, while not apparently associated with the X-ray source, is nevertheless consistent (i.e., within 2 σ of the 0″.7 combined errors quoted) with the position given by Grindlay *et al.* (1984) and Hertz and Grindlay (1985) for the cluster center. It is therefore consistent with being in the central cusp (Grindlay 1983; Djorgovski and King 1984; Hertz and Grindlay 1985) which might contain an enhanced number of compact binaries (expected to include both white dwarf and neutron star companions), some of which may be radio emitters.

The third discrepancy with Geldzahler's results is for the burster 4U 1916−05, where again no source was detected (see Table 3) at or near the position given by Geldzahler. We note further that the optical position of "Star 2" given by Geldzahler is also apparently in error (by ~2″) but that Star 2 is consistent with the preliminary *Einstein* X-ray position given by Walter *et al.* (1982). Nevertheless, Geldzahler's source detected near Star 3 may indeed be the correct counterpart since the final HRI processing yields an X-ray image which could be consistent with Star 3 (see Grindlay, Hertz, and Tokarz 1986, for a complete discussion) and a faint UV optical candidate has been found near Star 3 in our CCD photometry from CTIO (Grindlay *et al.* 1986).

From the measured flux densities (at λ6 cm) and the source distances (generally known only for the globular cluster sources) we may derive lower limits on the source diameters assuming the sources are due to either thermal bremsstrahlung or nonthermal synchrotron emission. For thermal emission, the limit on surface brightness is set by assuming that the source is optically thick at the observing wavelength. In the nonthermal case, two limits are possible. The first corresponds to a maximum brightness temperature of 10^{12} K, above which inverse Compton (IC) cooling will dominate while the other limit is set by synchrotron self-absorption for an assumed value of the magnetic field in the source. Results of these estimates as well as their dependences on assumed parameters are given in Table 4.

V. CONCLUSIONS

Faint radio sources have been found as the counterparts of several galactic bulge X-ray sources. Discovery of a relatively bright radio counterpart for GX 13+1 has allowed a much more precise source position to be obtained and a likely IR identification (Garcia and Grindlay 1986) to be made. The X-ray burster in the core of the globular cluster NGC 6624 is a provisional detection and needs to be confirmed by further observations. Comparison of our results for NGC 6624 with those obtained by Geldzahler (1983) indicates that both the X-ray source and the (spatially separated) central cusp in the cluster may have been detected.

Our present results suggest that the radio emission may be

TABLE 4

LOWER LIMITS ON RADIO SOURCE DIAMETERS[a]

Object	Frequency[b]	Thermal[c]	Nonthermal (IC Limit)[d]	Nonthermal (SSA Limit)[e]
GX 5−1	1.4	4.8×10^{16}	4.6×10^{12}	3.5×10^{13}
GX 13+1	4.9	1.6×10^{16}	1.6×10^{12}	0.9×10^{13}
GX 17+2	4.9	1.3×10^{16}	1.3×10^{12}	6.6×10^{12}
NGC 6624	1.4	2.4×10^{16}	2.4×10^{12}	1.7×10^{13}

[a] Diameters (limits) are in cm units and scale directly with source distance, which is assumed to be 10 kpc for GX 5−1, GX 13−1, and GX 17+2, and 8 kpc for NGC 6624 (Webbink 1985).

[b] Frequency, in GHz, at which observed flux density is used to estimate source diameters.

[c] Thermal limits assumes emission is bremsstrahlung, and source is just optically thick at observed frequency. The source diameter is for an assumed electron temperature of $T_e = 10^4$ K, and the diameter scales as $T_e^{-1/2}$.

[d] Nonthermal limit for synchrotron emission and surface brightness limited to brightness temperatures $T_B < 10^{12}$ K above which inverse Compton (IC) losses would dominate.

[e] Nonthermal limit for synchrotron emission and source just optically thick to synchrotron self-absorption (SSA) at observed frequency. The source diameter is for an assumed magnetic field of $B = 1$ G and scales as $B^{1/4}$.

nonthermal, since the approximate source sizes may then be reasonably compact (~ 10 binary radii) and since the spectrum of at least one source (GX $5-1$) appears to have a spectral index steeper than a thermal spectrum would allow. Comparison of our results with those of Geldzahler (1983) and earlier workers shows that the radio emission from galactic bulge X-ray sources is *highly variable* by factors of at least 3 (and probably ~ 10). The fact that the radio sources are variable further suggests they are compact and probably nonthermal and that periodic flaring, possibly due to particle acceleration in or near the accretion disk during enhanced mass transfer at a particular binary phase, might be observed as has recently been found for Cyg X-3 (Molnar, Reid, and Grindlay 1984). If so, extended radio monitoring could yield the long-sought binary periods for these objects.

It is possible, therefore, that compact X-ray binaries as a class include nonthermal processes and particle acceleration in at least the accretion disk coronae which probably surround the systems, since the radio source sizes are apparently at least an order of magnitude larger than the expected binary separations. The minimum radio source sizes of $\sim 10^{12}$ cm for galactic bulge sources at ~ 10 kpc (see Table 4) are essentially the same as those derived by Molnar, Reid, and Grindlay (1984) for the quiescent radio source (composed of low-level flares) in Cyg X-3. Since Cyg X-3 may represent a high mass transfer (and therefore brief) phase of an otherwise typical galactic bulge source, the recent suggestions that Cyg X-3 is a significant source of galactic cosmic rays (e.g., Hillas 1984) may also apply to other much more numerous galactic bulge and globular cluster sources. Similar conclusions have recently been reached by Fabbiano and Trinchieri (1985) from the observed correlation of X-ray versus radio flux and surface brightness profiles in the bulges of external galaxies.

VLA detections of GX sources, which are largely unidentified, enable them to be located with uncertainties much smaller than the current X-ray positions (or indeed those expected with further X-ray observatories). Since the brightest sources are known to be time variable, increased sensitivity and repeated observations might show that most of the X-ray bursters in globular clusters and galactic bulge X-ray sources are detectable as radio sources. Searches for optical counterparts may then be carried out with much greater precision and sensitivity (i.e., fainter confusion limits) than in our previous studies using the HRI X-ray positions alone. Follow-up optical/IR searches of this kind have in fact yielded candidates for 4U $1916-05$ and GX $13+1$, as discussed above. For compact X-ray sources in globular clusters, this will allow both improved measurements of the source mass and studies of the gravitational potential in the cluster core (see Grindlay *et al.* 1984). Given the ratio of flux densities in the central source to the surrounding lobes in Sco X-1, it is also possible that the GX sources (at a factor of ~ 10 greater distance) would show surrounding lobes. Higher sensitivity follow-up studies are planned to search for lobes and measure source spectra and variability.

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