

# DEEP RADIO IMAGING OF GLOBULAR CLUSTERS AND THE CLUSTER PULSAR POPULATION

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## ABSTRACT

We have obtained deep multifrequency radio observations of seven globular clusters using the Very Large Array and the Australia Telescope Compact Array. Five of these, NGC 6440, NGC 6539, NGC 6544, NGC 6624, and Terzan 5, had previously been detected by Fruchter & Goss in a shallower survey for steep-spectrum radio sources in globular clusters. The sixth, the rich globular cluster Liller 1, had heretofore been undetected in the radio, and the seventh, 47 Tucanae, was not included in our original survey. High-resolution 6 and 20 cm images of three of the clusters, NGC 6440, NGC 6539, and NGC 6624, reveal only point sources coincident with pulsars which have been discovered subsequent to our first imaging survey; 21 and 18 cm images reveal several point sources within a few core radii of the center of 47 Tuc. Two of these are identified pulsars, and a third, which is variable and has a steep spectrum, is also most likely a pulsar previously identified by a pulsed survey. However, the 6, 20, and 90 cm images of NGC 6544, Liller 1, and Terzan 5 display strong steep-spectrum emission which cannot be associated with known pulsars. The 90 cm flux densities of Terzan 5, Liller 1, and NGC 6544 are 35, 9, and 6 mJy, respectively, implying that a number of bright pulsars in these clusters have been hidden from pulsed searches.

The image of the rich cluster Terzan 5 displays numerous point sources within 30", or 4 core radii, of the cluster center. The density of these objects rises rapidly toward the core, where an elongated region of emission is found. This feature may be due to the presence of a higher density of point sources than can be resolved by the 1" resolution of our data. The brightest individual sources, as well as the extended emission, possess the steep spectra expected of pulsars. Furthermore, the flux distribution of the sources agrees well with the standard pulsar luminosity function. The total luminosity and number of objects observed suggest that Terzan 5 contains more pulsars than any other Galactic globular cluster.

*Subject headings:* globular clusters: general — radio continuum: stars

## 1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) announce themselves from across the galaxy to telescopes with effective areas measured in square centimeters, but some of their descendants, binary millisecond pulsars (MSPs), are far less vocal. The majority of MSPs are difficult for even the largest radio telescopes to detect at a distance of a few kiloparsecs, and the pulses from even the bright MSPs can be obscured by the dispersion of the interstellar medium or by Doppler smearing resulting from the gravitational tug of a binary companion. These latter difficulties, however, can be overcome by radio interferometric imaging. The flux density measured in a radio image is not affected by dispersion or Doppler broadening. Furthermore, one can generally distinguish between pulsars and background sources by the steep spectra of pulsars and their occasional polarization. Indeed, the first pulsar found in a globular cluster was located in a Very Large Array (VLA) image (Hamilton, Helfand, & Becker 1985).

As discussed in Fruchter & Goss (1990), henceforth FG90, interferometric imaging has another, subtle, but equally important advantage. If the synthesized beam of the interferometer is comparable in diameter to the core of the cluster, then the flux density one observes will frequently be the sum of the emission from many pulsars in the cluster. If the number of pulsars in a clusters is large, this sum can substantially exceed the flux density from the single bright-

est pulsar in the cluster. The luminosity function of pulsars, as measured in the field, has the form

$$\frac{dn}{dl} = \frac{1}{l^p}, \quad (1)$$

where  $L$ , the pulsar luminosity, is bounded below by a minimum luminosity,  $L_{\min}$ , of order  $\sim 0.3$  mJy kpc<sup>2</sup> at 20 cm (1400 MHz), and the power,  $p$ , is approximately 2 (Manchester & Taylor 1977; Dewey et al. 1985; Stollman 1987). Limited observational evidence has so far suggested that the luminosity function of pulsars in globular clusters agrees with that of the field (Anderson 1992). Although with this luminosity law the expected luminosity of a pulsar (and thus a cluster) diverges logarithmically, it can be shown that for a given observed cluster luminosity, if  $L_{\text{tot}} \gg L_{\min}$ , the expected number of pulsars in the cluster beaming toward Earth is

$$N_{\text{puls}} = \frac{L_{\text{tot}}}{L_{\min} \ln(L_{\text{tot}}/L_{\min})}. \quad (2)$$

Thus, by observing a cluster with a large beam, we not only gain the advantage of the increased flux density, but also obtain an estimator of the number of pulsars in the cluster.

In FG90 we described a search of 17 globular clusters for radio emission at 20 cm. Resolutions comparable to the core diameters were employed to maximize the sensitivity to the integrated emission from a population of pulsars in

the clusters. New sources were detected in NGC 6440, NGC 6539, NGC 6544, and Terzan 5, and we confirmed the existence of a controversial source in NGC 6624. As reported in FG90, repeat observations of these sources at 20 cm, and observations of many of them at 6 cm, suggested that, with the possible exception of the source in NGC 6624, all of the sources were due to radiation from pulsars, as a result of their observed variability or steep spectrum. Later, pulsed searches from Parkes and Jodrell revealed individual pulsars with flux densities comparable to those we observed in three of the clusters, NGC 6440, NGC 6539, and NGC 6624. In addition, a source visible on our image of Terzan 5, but well outside the cluster core, was found to be an eclipsing millisecond pulsar.

In order to better study the pulsar population in these clusters, we have reobserved these clusters with the VLA but using a substantially smaller beam size. Observations were taken at 20 and 6 cm, and particular attention was paid to the two optically richest clusters in our survey, Terzan 5 and NGC 6440. Further observations were taken at 90 cm of NGC 6544 and Terzan 5 in order to better characterize the emission from clusters where emission was seen but no pulsar found. Finally, we have expanded our study to include two other rich clusters, Liller 1 and 47 Tuc, which had substantial unpublished data in the archives of the VLA and Australia Telescope Compact Array (ATCA), respectively. Early versions of some of the results reported here were presented in Fruchter & Goss (1991, 1995).

## 2. OBSERVATIONS AND RESULTS

### 2.1. Terzan 5

The globular cluster Terzan 5 was observed at 20 cm in the A, BnA, B, and CnB configurations of the Very Large Array (VLA).<sup>1</sup> In each case, approximately 4 hr of data were obtained. All observations were done in continuum mode, using two 50 MHz bandpasses, centered on the sky frequencies of 1465 and 1515 MHz. Both right- and left-circular polarizations were observed. Terzan 5 was also observed at 6 cm in the B and C configurations. In both cases, the observations were done in continuum mode, employing two orthogonal polarizations in each of two 50

MHz bandpasses, centered at the sky frequencies of 4835 and 4885 MHz. Here we discuss the 6 cm C-configuration data, as its beam size ( $\sim 4''$ ) closely approximates that which we used to measure the extended emission observed at 20 cm. About 6 hr of data were taken on source in the C configuration during two 4 hr observing sessions separated by about 1 week. Finally, Terzan 5 was reobserved on 3 successive days in the A/B configuration. During these observing sessions we rapidly switched between 20 and 90 cm. The 20 cm observations were done as described above. At 90 cm we observed across two 3.125 MHz bandpasses centered at 327.5 and 333 MHz. Both linear polarizations were observed. These dual-frequency observations were designed to allow us to study both the emission from the center of the cluster as well as the low-frequency eclipse behavior of the 11 ms pulsar 1744–24A.

Figure 1 shows the contours of the 20 cm image of Terzan 5 superposed on an *I*-band image of the cluster taken by Taft Armandorff with the Cerro Tololo Inter-American Observatory (CTIO) 1 m telescope. The VLA image was made using uniform weighting and a 40 k $\lambda$  taper. This weighting produces a small beam size ( $2''.9 \times 2''.9$ ) which sharpens the details of the image with the loss of some sensitivity to extended structure. The bright radio source about  $30''$  to the west of the cluster is the eclipsing pulsar, PSR 1744–24A (Lyne et al. 1990; Nice et al. 1990; Nice & Thorsett 1992). The “sidelobes” and apparent elongation of this source are due to its time variability caused primarily by the obscuration of the pulsar by a wind off its companion. Two other point sources, a northern and southern source, can be seen on either side of the central cluster emission (the positions and flux densities *per beam* of the sources in Fig. 1 are displayed in Table 1). Perhaps the most striking feature of the radio image, however, is the diffuse radiation centered on the optical cluster, which can be better viewed in the image shown in Figure 2, which has a beam of  $5''.9 \times 4''.1$ . This image was created using a “robust weight” of  $R = 1$  (Briggs 1995); this is a weighting roughly intermediate between uniform weighting, which emphasizes resolution, and natural weighting, which emphasizes sensitivity.

The flux density of the diffuse component is  $\sim 2$  mJy at 20 cm—stronger than the two prominent point sources in the image. Even when only the highest resolution data is retained and an image with a  $1''$  beam is produced (with a consequent loss of signal-to-noise ratio), the center of the cluster remains a continuous, elongated resolved source. If,

TABLE 1  
TERZAN 5 SOURCE POSITIONS AND FLUX DENSITIES

Source	$\alpha$ (1950)	Error	$\delta$ (1950)	Error	Flux Density <sup>a</sup> ( $\mu$ Jy)
N'	17 45 00.50	0''09	–24 45 21.1	0''8	7500
N	17 44 59.985	0''005	–24 45 35.58	0''05	1420
A (PSR 1744–24A)	17 44 57.710	0''005	–24 45 38.20	0''05	1340
C	17 45 00.41	0''012	–24 45 46.0	0''18	230
S	17 45 00.13	0''015	–24 45 51.8	0''20	230

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

<sup>a</sup> Flux densities are given per beam. All flux densities, with the exception of that for the source N', are for the  $2''.9$  beam of the 20 cm image shown in Fig. 1. These sources have an error of  $28 \mu$ Jy beam<sup>–1</sup>. Source N' is visible only in the 90 cm image, and the flux density given is for that image (Fig. 4). The 90 cm flux density error is  $1.3$  mJy beam<sup>–1</sup>.

<sup>1</sup> The A configuration of the VLA is its largest. Each successive configuration (B, C, D) is approximately a factor of 3 smaller than its predecessor. Hybrid configurations (e.g., BnA), have the northern arm in the larger configuration to provide a more circular beam for southern sources.

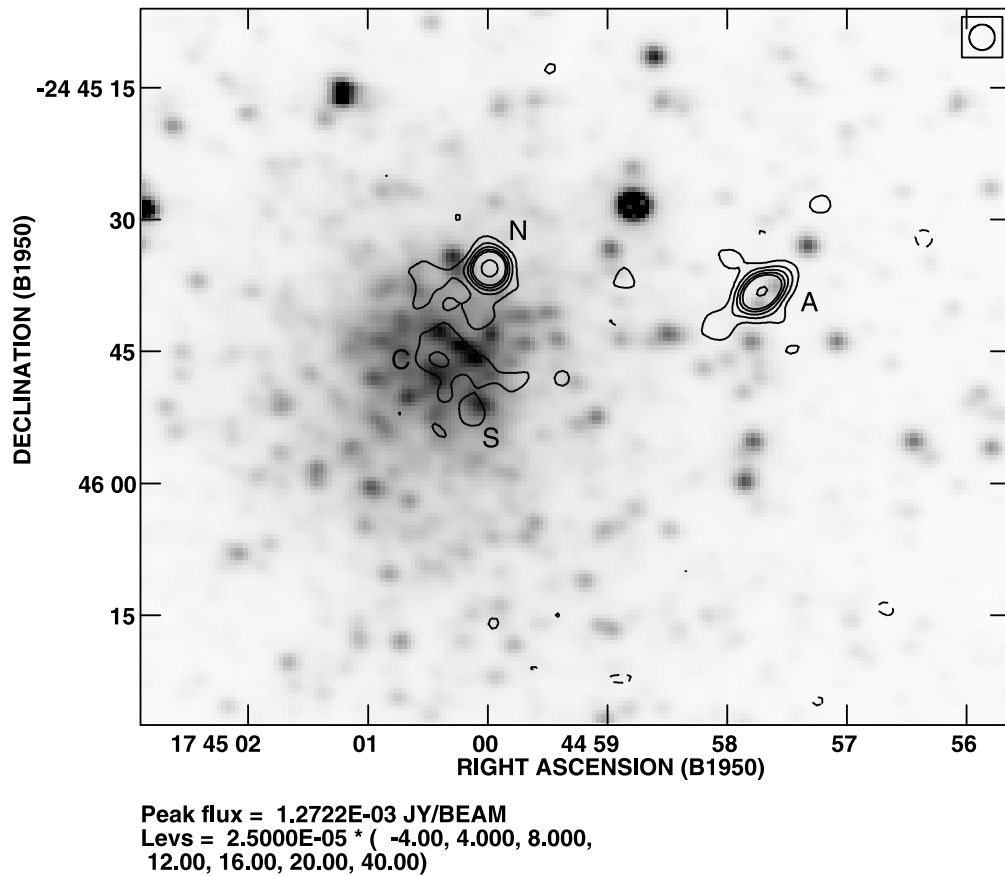


FIG. 1.—Radio contours are shown superposed on an *I*-band image of the rich cluster Terzan 5. The 20 cm radio image combines data taken with several different VLA configurations and has a beam size of  $2''.9 \times 2''.9$ . Contour levels are  $-100, 100, 200, 300, 400, 500$ , and  $1000 \mu\text{Jy beam}^{-1}$ . The rms noise level in the image is  $28 \mu\text{Jy}$ .

as we suspect, the source of this emission is pulsars, their central density is too large for them to be individually distinguished in our data.

The alignment of the radio and optical images is based on the astrometric solutions for a number of stars in the *I*-band image which are also found in the *Hubble Space Telescope* (*HST*) Guide Star Catalog (Russell et al. 1990), which has an astrometric accuracy somewhat better than  $1''$ . As a number of stars in that catalog were in the *I*-band image, and as the positions of the peaks of the diffuse radio and optical flux densities are indistinguishable with this astrometry, we believe we have accurately identified the center of the Terzan 5 cluster. The position derived for the center of the diffuse emission,  $\alpha(1950) = 17^{\text{h}}45^{\text{m}}0^{\text{s}}.4$ ,  $\delta(1950) = -24^{\circ}45'45''.9$ , agrees well with that measured by the discoverer of the cluster, Terzan (1971); however, this position disagrees with that of Picard & Johnston (1995) by about  $6''$ . (The Picard & Johnston position is also inconsistent with that of Terzan.) We believe the position and association proposed here are correct.

In Figure 3 we have superposed the 6 cm images as contours upon the 20 cm image, which is shown in gray scale. Comparison of these images shows that the  $\approx 1.5 \text{ mJy}$  20 cm source about  $10''$  to the northwest of the cluster center (labeled “N” in both Table 1 and Fig. 1) possesses a spectral index,  $\alpha$ , of 2, and the central diffuse emission (source C) has an index greater than 1.4 [to determine the spectral index it is assumed that the flux density of the object,  $f(\nu)$ ,

scales as  $f(\nu) \propto \nu^{-\alpha}$  between the observed frequencies]. The only astrophysical sources likely to possess spectra this steep are pulsars. Indeed, it is worth noting that the spectrum of PSR 1744–24A is completely undetected in the 6 cm image.

The 6 cm image also reveals the  $\sim 200 \mu\text{Jy}$  source to the southeast of the cluster (source S) to be highly variable (undetectable in one image, its flux density increased by at least a factor of several in the other taken days later). Furthermore, in the 20 cm BnA-configuration image obtained simultaneously with our 90 cm data (but which is not included in the 20 cm image shown here), this source has brightened considerably to become a  $\sim 1 \text{ mJy}$  source. While the rapid 6 cm variability can be ascribed to diffractive scintillation, the cause of the long-term 20 cm variation is less clear. The expected diffractive scintillation bandwidth at 20 cm (assuming a dispersion measure of  $\sim 200 \text{ pc cm}^{-3}$ ) is of order 1 MHz (Cordes, Weisberg, & Boriakoff 1985), significantly smaller than the 100 MHz bandpass of the observations, and refractive scintillation is usually limited to changes in flux density of a factor of 2 (Kaspi & Stinebring 1992). Scattering by caustics in the interstellar medium, while relatively rare, can cause such strong variability (Goodman et al. 1987). Nonetheless, there can be little doubt that the object is a pulsar—the simultaneous 90 and 20 cm observations imply a spectral index of  $\sim 1.75$ , far steeper than typical background sources (Condon 1984).

Indeed, both the northern and southern point sources

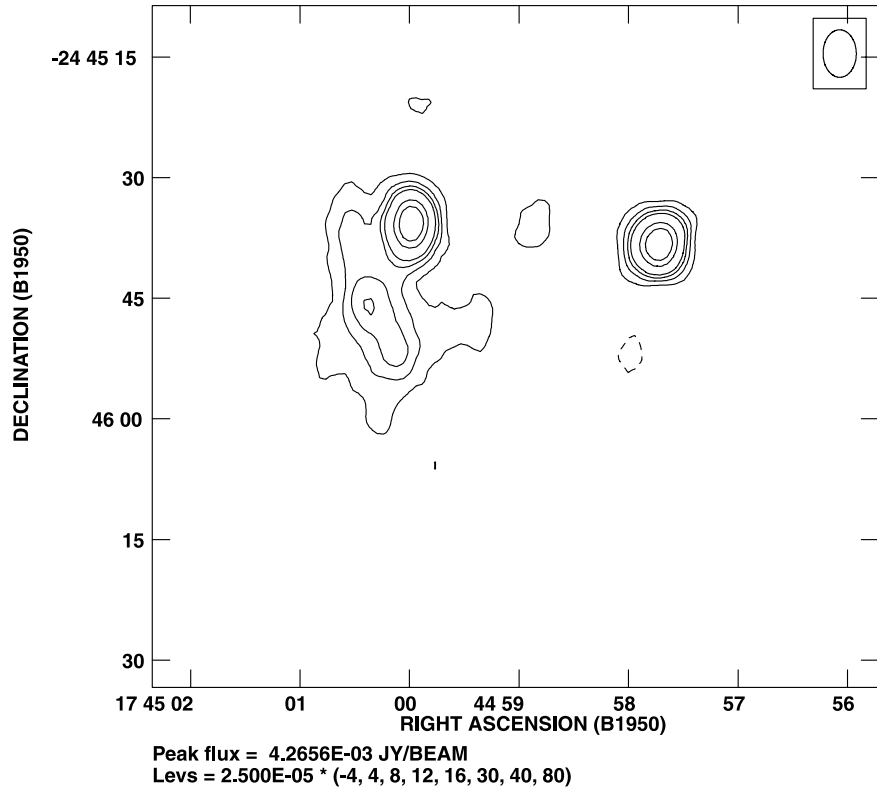


FIG. 2.—20 cm image of Terzan 5 using a larger synthesized beam (robust weight  $R = 1$ ) than in Fig. 1. This image shows the large extent of the diffuse radio emission centered on the core of the globular cluster. The beam is  $6''.3 \times 4''.4$  and the image has an rms noise of  $23 \mu\text{Jy beam}^{-1}$ . Contour levels are  $-100, 100, 200, 300, 400, 750, 1000$ , and  $2000 \mu\text{Jy beam}^{-1}$ .

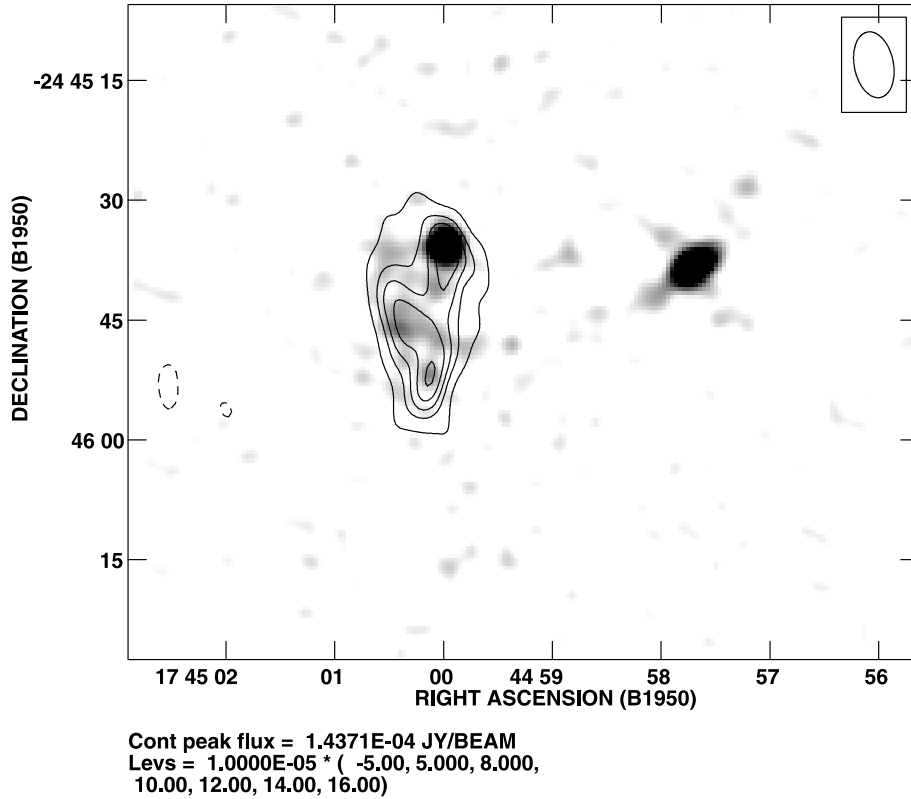


FIG. 3.—6 cm radio contours (beam size  $8'' \times 5''$ , P.A. =  $6^\circ$ ) are shown superposed on a 20 cm image (*gray scale*) of the cluster Terzan 5. The rms noise of the image is  $25 \mu\text{Jy beam}^{-1}$ . The radio contours are  $-50, 50, 80, 100, 120, 140$ , and  $160 \mu\text{Jy beam}^{-1}$ .

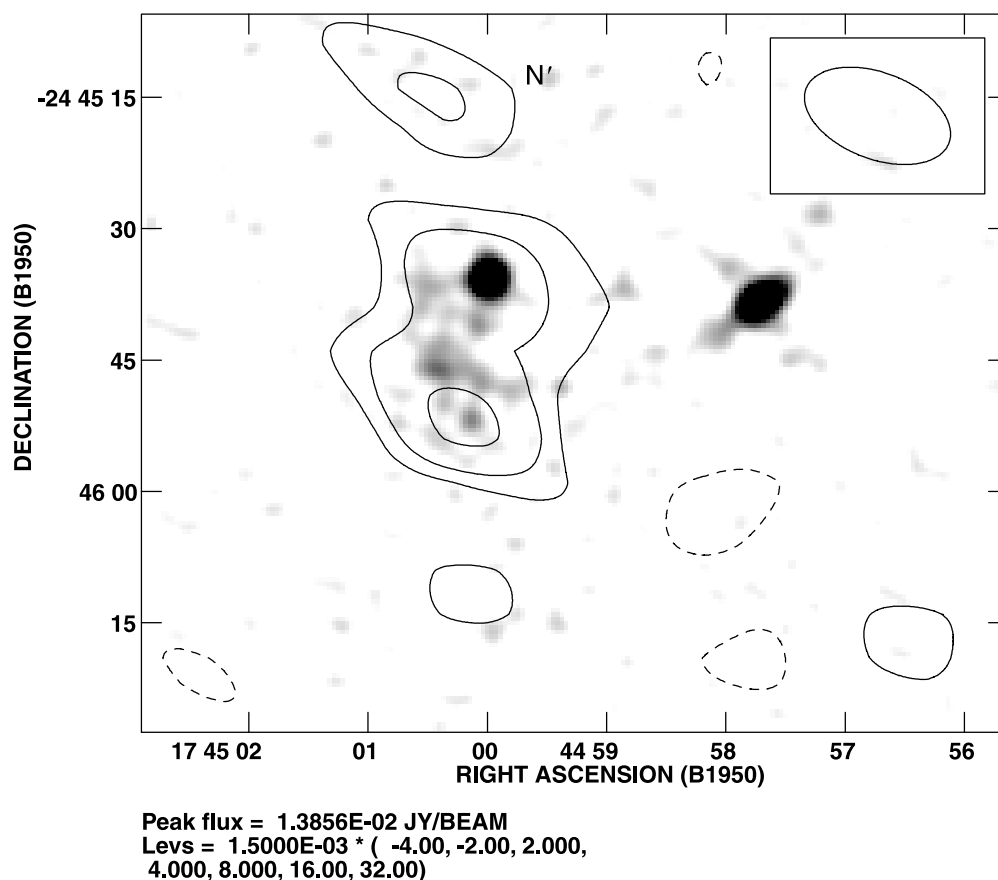


FIG. 4.—90 cm radio contours (beam size  $18'' \times 12''$ , P.A. =  $67^\circ$ ) are shown superposed on a 20 cm image of the cluster Terzan 5 (Fig. 1, now shown in gray scale). While the central emission displays a steep spectral index characteristic of pulsars, the one identified pulsar in the field, PSR 1744–24A is not detected, even though it was a strong source in the simultaneous 20 cm observations. This pulsar appears to be continuously eclipsed at 90 cm. The source N' is undetected in either the 20 or 6 cm images of this cluster, implying a spectral index  $\alpha > 2.5$  between 90 and 20 cm. The radio contours are  $-6, -3, 3, 6, 12, 24$ , and  $48 \text{ mJy beam}^{-1}$ ; the rms noise of the image is  $1.3 \text{ mJy beam}^{-1}$ .

show up strongly in our 90 cm image. Each contributes about  $\sim 13 \text{ mJy}$  to the total flux density of the cluster, with another  $\sim 10 \text{ mJy}$  apparently due to the cluster as a whole. As our 90 cm beam size is  $9''$  across, the division of the flux density into these components must be regarded as approximate. Unfortunately, a beam size this large was required in order to make the necessary three-dimensional imaging of the 90 cm data computationally feasible. In Figure 4, we display the 90 cm radio contours superposed on a gray-scale image of the 20 cm data displayed in Figure 1. The rms noise in the 90 cm image is approximately  $1.3 \text{ mJy}$ . Note that the only 20 cm source not also observed at 90 cm is the one identified pulsar in the cluster, PSR 1744–24A. Our data provides strong evidence that this pulsar is continuously enshrouded by material lost from the companion. However, there is a strong 90 cm source, which we have labeled N' (see Fig. 4 and Table 1), that is not visible at all in the 20 cm image. This source must either have a spectral index  $\alpha > 2.5$  between 90 and 20 cm or vary dramatically with time. This argues strongly for the identification of N' as a pulsar. It is worth noting that neither N' nor any of the other point radio sources found in Terzan 5 has a position which agrees with either of the two known X-ray sources in that cluster (Johnston, Verbunt, & Hasinger 1995); thus, radio emission from X-ray binaries is unlikely to be the cause of any of the point sources reported in this cluster.

## 2.2. Liller 1

The strong central emission observed in Terzan 5 made the nondetection (Johnston, Kulkarni, & Goss 1991) of the nearly equally dense and equidistant cluster Liller 1 particularly surprising. While the 20 cm observations of Johnston et al. (1991) reached the deep limit of  $180 \mu\text{Jy}$ , the data were taken in the A configuration which has a beam size of  $\sim 1''.5$  and thus greatly overresolve the  $\sim 7''$  core radius of the cluster (Djorgovski 1993). If the cluster were to contain a number of sources, a lower resolution image would be more sensitive. We therefore observed Liller 1 at 20 cm in the CnB configuration, which, at this wavelength, has a beamwidth of approximately  $10''$  at the declination of Liller 1. This observation revealed a  $280 \pm 50 \mu\text{Jy}$  source. In order to determine the spectral index of this emission we observed Liller 1 at 6 cm in the DnC configuration and rereduced 90 cm B-configuration archival observations made by Johnston & Kulkarni using three-dimensional imaging. We find a 90 cm (330 MHz) flux density of  $9 \pm 1 \text{ mJy}$  and a 6 cm (4885 MHz) flux density of  $95 \pm 14 \mu\text{Jy}$ .

## 2.3. NGC 6544

Although NGC 6544 has been searched extensively for pulsed radio sources (Biggs & Lyne 1996), even after our discovery of a radio source in this cluster (FG90) no pulsar

TABLE 2  
SOURCES IN CLUSTERS DOMINATED BY KNOWN PULSARS

Cluster	Band	$\alpha$ (J2000)	$\delta$ (J2000)	Flux Density ( $\mu$ Jy)
NGC 6539.....	20 cm	18 04 49.87 $\pm$ 0.01	-07 35 24.7 $\pm$ 0.1	485 $\pm$ 85
	6 cm	...	...	<100
	Pulsar <sup>a</sup>	18 04 49.89 $\pm$ 0.01	-07 35 24.7 $\pm$ 0.1	500 $\pm$ 200
	Optical <sup>b</sup>	18 04 49.72	-07 35 09.1	...
NGC 6624.....	20 cm	18 23 40.46 $\pm$ 0.01	-30 21 39.6 $\pm$ 0.1	420 $\pm$ 45
	6 cm	...	...	116 $\pm$ 26
	Pulsar <sup>c</sup>	18 23 41.46 $\pm$ 0.02	-30 21 40.1 $\pm$ 0.4	400 $\pm$ 100
	Optical <sup>b</sup>	18 23 40.66	-30 21 38.8	...
NGC 6440.....	20 cm	17 48 52.66 $\pm$ 0.01	-20 21 39.3 $\pm$ 0.1	750 $\pm$ 100
	6 cm	...	...	90 $\pm$ 30
	Pulsar <sup>d</sup>	17 48 52.6 $\pm$ 0.1	-20 22 30 $\pm$ 30	1500 $\pm$ 500
	Optical <sup>b</sup>	17 48 52.65	-20 21 34.5	...

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

<sup>a</sup> D'Amico et al. 1993.

<sup>b</sup> Shawl & White 1986.

<sup>c</sup> Biggs et al. 1994.

<sup>d</sup> Manchester et al. 1989.

has been found. Nonetheless, we followed up our low-resolution imaging of this cluster with deep A-configuration 20 cm imaging and B-configuration 6 cm observations. In addition, the cluster was observed by Helen Johnston and colleagues at 90 cm in the B configuration. We have also reduced these archival data. A source of  $6.5 \pm 0.8$  mJy is found at 90 cm. At 20 cm, the flux density is  $1.2 \pm 0.1$  mJy. No source was detected at 6 cm, with a  $3\sigma$  upper limit to the flux density of  $75 \mu$ Jy. The 20 cm position  $\alpha(\text{J2000}) = 18^{\text{h}}07^{\text{m}}20^{\text{s}}.24 \pm 0^{\text{s}}.01$ ,  $\delta(\text{J2000}) = -24^{\circ}59'25''.3 \pm 0''.1$ , agrees within the rather large ( $7''$ ) errors with the 90 cm source and is within  $2''$  of the position found by Shawl & White (1986) for the optical center of the cluster. There is no evidence of an extended emission in any of the images. Although the spectral index of the source between 90 and 20 cm is only 1.1, between 90 cm and 6 cm it is greater than 2.5, strongly implying that the radio emission from this cluster is produced by one or more pulsars.

#### 2.4. NGC 6440, NGC 6539, NGC 6624

As noted previously, after our detection of strong 20 cm emission from a number of southern clusters, deep pulsed surveys were undertaken at Jodrell and Parkes to locate these objects as pulsars. In three cases, NGC 6440 (Manchester et al. 1989), NGC 6539 (D'Amico et al. 1993), and NGC 6624 (Biggs et al. 1994), these surveys detected pulsars coincident with the 20 cm emission. All three of these clusters were reobserved by us at 20 cm using the A configuration of the VLA and at 6 cm in the B configuration. In addition, NGC 6440, one of the two richest clusters in our sample, was also reobserved in the BnA, B, and CnB configurations at 20 cm. All observations were done in continuum mode, employing two orthogonal polarizations in each of two 50 MHz bandpasses, typically centered on the sky frequencies of 1465 and 1515 MHz at 20 cm and 4835 and 4885 MHz at 6 cm. NGC 6539 and NGC 6624 were each observed for 2 hr at 20 cm in the A configuration and 2.2 hr at 6 cm in the B configuration. NGC 6440 was

observed at 20 cm for 4.7 hr in the A configuration and 3 hr in each of the BnA, B, and CnB configurations. NGC 6440 was also observed at 6 cm for 3.5 hr in the B configuration. All of the resulting observations are consistent with a single point source dominating the flux density from each of the clusters, and each of these point sources is consistent with the position of a known pulsar in a cluster. In the case of NGC 6440, a small variation in flux density ( $\sim 25\%$ ) was seen between images taken in the different VLA configurations; however, the size of the variability is comparable to that expected from the scintillation of the known pulsar, and there is no evidence that the flux density of the cluster increases with lower resolution, as would be the case were a diffuse population of pulsars contributing significantly to the total flux density. In Table 2 the source positions and flux densities are compared with those of the known pulsars in the cluster cores. The agreement of the positions and flux densities is excellent.

#### 2.5. 47 Tucanae

All of the observations so far discussed were performed with the VLA. However, the rich and relatively nearby globular cluster 47 Tuc is too far south to be observed from New Mexico and was therefore not included in our original survey. As 47 Tuc has more detected pulsars than any other cluster, this was a particularly unfortunate omission. Since FG90, however, archival observations of 47 Tucanae taken by David McConnell and Jon Ables using the 6 km ATCA have become public. We therefore have reduced these data. Two orthogonal linear polarizations in each of two bandpasses centered on 1408 and 1708 MHz were used. Each bandpass was divided into 4 MHz channels, and a total effective bandwidth of 104 MHz was obtained. The data were taken 1992 January 24–25 (13 hr) and 1992 April 23–25 1992 (48 hr). The final image is shown in Figure 5. The image has noise of  $32 \mu\text{Jy beam}^{-1}$ , where the beam is essentially circular with a  $6''$  FWHM.

Five objects with flux density greater than  $200 \mu\text{Jy}$  are

visible in our radio image in a radius of about  $1'.5$  about the center of 47 Tucanae; their positions and flux densities are listed in Table 3. Based upon positional coincidence, two of these sources can clearly be associated with the two of the brightest pulsars yet discovered in the cluster, 47 TucC and 47 TucD (Manchester et al. 1991; Robinson et al. 1995). Furthermore, when our position for source 2 is used as a starting position for the pulsar timing data of 47 Tuc, a timing solution is found for the eclipsing pulsar 47 TucJ (F. Camilo 1999, personal communication). Source 2 is highly variable and has a steep spectrum; over the course of the ATCA observations the flux density of this source varied by more than a factor of 2 and its average flux densities at 1408 and 1708 MHz are  $714 \pm 30 \mu\text{Jy}$  and  $454 \pm 50 \mu\text{Jy}$ , respectively, corresponding to a spectral index of  $\alpha = -2.3 \pm 0.6$ . Therefore, it is highly likely that source 2 is 47 TucJ.

TABLE 3  
POSITIONS AND FLUX DENSITIES OF 47 TUCANAE SOURCES

Source	$\alpha$ (J2000)	$\delta$ (J2000)	Flux Density (mJy)
C .....	00 23 50.34 $\pm$ 0.07	-72 04 31.5 $\pm$ 0.3	0.33 $\pm$ 0.03
D .....	00 24 13.78 $\pm$ 0.04	-72 04 44.9 $\pm$ 0.3	0.40 $\pm$ 0.05
1 .....	00 23 40.80 $\pm$ 0.03	-72 05 12.2 $\pm$ 0.1	0.78 $\pm$ 0.03
2 .....	00 23 59.33 $\pm$ 0.03	-72 03 59.1 $\pm$ 0.2	0.65 $\pm$ 0.03
3 .....	00 24 13.36 $\pm$ 0.07	-72 03 32.6 $\pm$ 0.4	0.30 $\pm$ 0.03

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Based on number counts of faint field radio sources, we would expect, by chance, to detect about  $\sim 0.7$  sources brighter than  $200 \mu\text{Jy}$  within our search radius (Condon 1984). Thus, there is no strong statistical reason to believe that either source 1 or 3 is a pulsar. In addition, we find no evidence of extended diffuse emission in the cluster. After convolution of the image with both a  $25''$  and a  $40''$  beam we find  $3\sigma$  limits on emission from the center of the cluster of  $0.9$  and  $1.5 \text{ mJy beam}^{-1}$ , respectively. Although these beams are large enough to encompass the most recent measurement of the core radius of 47 Tucanae,  $12''.2$  (De Marchi et al. 1996), we note that none of the identified pulsars lie within  $45''$  of the cluster center. If the observed pulsars, rather than the reported core radius, provide the best estimate of the distribution of fainter pulsars in the cluster, then one would need perhaps as many as 10 beams to properly cover the cluster, and the limit on extended emission would be, at a minimum, several mJy.

### 3. DISCUSSION

Our observations of Terzan 5, Liller 1, and NGC 6544 have revealed steep-spectrum radio emission even though these clusters do not possess known pulsars (or, in the case of Terzan 5, known pulsars coincident with the sources of most of the observed radiation). In this section, we show that this emission is almost certainly produced by a significant population of pulsars so far undetected by pulsed searches.

We have used a Monte Carlo simulation to determine whether our observations of the total radio emission of

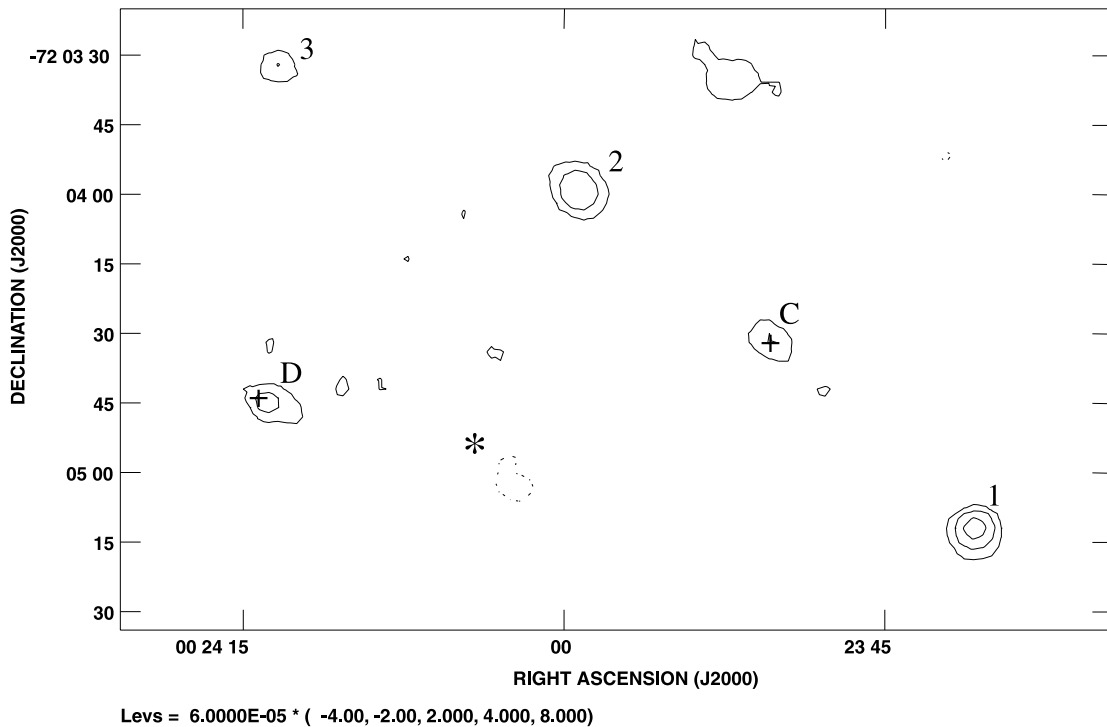


FIG. 5.—The ATCA image of the rich globular cluster 47 Tucanae. The center of the cluster is marked with an asterisk, and the radio timing positions of pulsars 47 TucC and 47 TucD are marked with crosses. Two of the sources are identified, based on their positions, as being pulsars C and D from this cluster, and, as discussed in the text, source 2 is most likely pulsar 47 TucJ. Sources 1 and 3 remain unidentified. The observations were obtained at a wavelength of approximately 20 cm, and the beam is nearly circular with a  $6''$  FWHM. Contours shown are  $-120, 120, 240,$  and  $480 \mu\text{Jy beam}^{-1}$ ; the rms noise of the image is  $32 \mu\text{Jy beam}^{-1}$ .

Terzan 5 are consistent with the standard luminosity function (as shown in eq. [1]). Pulsar populations were created to simulate Terzan 5 using a range of  $L_{\min}$ ,  $p$  (the power-law exponent, see eq. [1]), and total pulsar population. For each set of parameters, we determined the probability of creating a population whose brightest two pulsars were within a factor of 2 of the two brightest point sources in our Terzan 5 image (the eclipsing pulsar and the steep-spectrum source north of the cluster center) and whose remaining total luminosity agreed, again within a factor of 2, with the observed total luminosity of the central region of the cluster. As was found in FG90, the ability to fit the data is largely independent of the assumed  $L_{\min}$ . However, the quality of our fits depends strongly on  $p$ . The 90% confidence interval is found to be  $1.6 < p < 2.4$ , with the best fit at  $p = 1.85$ . This striking agreement with the well-observed field luminosity function and the M15 pulsar luminosity function derived by Anderson (1992) makes it appear highly probable that all of the radio emission observed from Terzan 5 is produced by pulsars.

Our observations of Liller 1 and NGC 6544 are, however, significantly less informative. All of our detections of Liller 1 are with beam sizes *larger* than the cluster core radius. Thus, our inability to resolve the emission and study its luminosity function is not surprising. Nonetheless, the signal-to-noise ratios of our detections are good enough to allow us to obtain an accurate radio position in spite of our large beam. In Table 4, we compare the position of the radio emission with that of the optical cluster and the X-ray source in Liller 1. All radio positions agree; therefore, we have reported only the 6 cm position, which has the smallest error ellipse.

Although the reported position of the rapid X-ray burster in Liller 1 (Grindlay et al. 1984) is offset from the radio position by about  $8''$ , or about  $4.5 \sigma$ , evidence has recently been growing of a correlation between the 6 cm flux density of Liller 1 and the X-ray strength of MXB 1730–335 (Guerriero et al. 1998; Fox et al. 1998; Rutledge et al. 1998). The agreement between the radio source and the position of the center of the globular cluster reported by Liller 1977 is good; however, the position of the optical center of the cluster is controversial. Grindlay et al. (1984) report a position which disagrees by several arcseconds with that of Liller. However, Grindlay et al. used *U*-band plates for their work whereas Liller worked in the *R* and *I* bands. As the visual extinction to this object is estimated at  $\sim 10$  mag (Djorgovski 1993), we have used Liller's position in the table.

Although the astrometric situation remains uncertain, an identification of our 6 cm source with MXB 1730–335 could help explain the radio spectrum of Liller 1. Figure 6

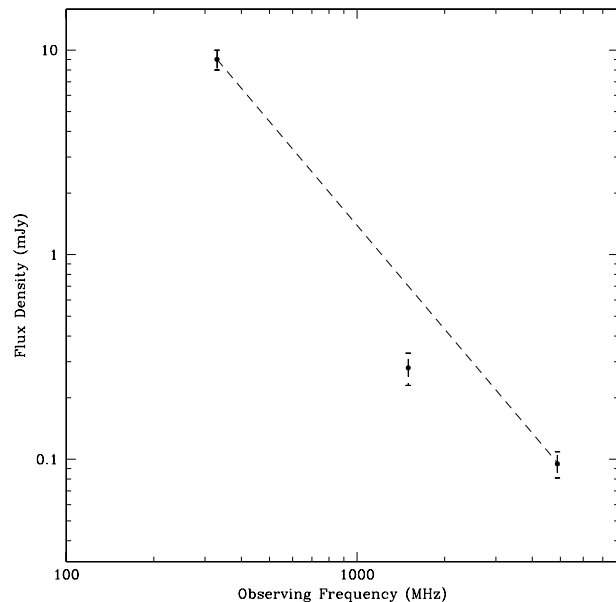


FIG. 6.—Flux density of the radio emission from Liller 1 as a function of observing frequency. As discussed in the text, the flux densities at 330 MHz (90 cm) and 1400 MHz (20 cm) are most likely dominated by emission from one or more pulsars, while some or most of the 4860 MHz (6 cm) emission may arise from an X-ray binary in the cluster. The line connecting the 90 and 6 cm flux densities is used only to guide the eye and emphasizes the particularly sharp drop in flux density between 90 and 20 cm.

shows a plot of the radio data versus observing frequency. Pulsar spectra are usually steeper at shorter rather than longer wavelengths (Manchester & Taylor 1977). The object in Liller 1, however, shows the opposite trend. Indeed, our 20 cm flux density is 100  $\mu$ Jy greater than the  $4 \sigma$  A-configuration limit of Johnston et al. (1991). Averaging our 20 cm data with theirs would make this spectral break even more evident. We think it probable then that we may indeed be seeing flux from the Liller 1 X-ray source in our 6 cm data; given that our 20 and 90 cm observations have flux densities significantly brighter than the 6 cm flux densities observed at X-ray outburst (the 90 cm flux density is more than a factor of  $\sim 40$  brighter than outburst levels), we doubt this object contributes significantly to our 90 or 20 cm images. Indeed, observations of X-ray binaries have typically found centimeter radio spectra that are inverted or flat rather than steeply declining, as seen here (Hjellming 1998).

Given that our Terzan 5 observations confirm that the standard field pulsar luminosity function can be applied to cluster MSPs, we can use our Monte Carlo simulations to estimate the number of pulsars in these clusters. Assuming that the minimum 20 cm pulsar luminosity is  $0.3 \text{ mJy kpc}^2$  (see FG90 for a discussion of this assumption), we estimate that there are between 60 and 200 pulsars in Terzan 5. Similarly, using equation (2), we can use the total luminosity of Liller 1 to estimate a population of  $\sim 15$  pulsars. A similar number is indicated for the other cluster with an apparent undetected pulsar in our VLA sample, NGC 6544. While these estimates of total numbers depend upon the assumed (and not well-known) minimum pulsar luminosity,  $L_{\min}$ , it should be noted that the relative expected number of pulsars in different clusters is independent of the assumed

TABLE 4  
LILLER 1 SOURCE POSITIONS

Band	$\alpha$ (J2000)	Error	$\delta$ (J2000)	Error
Radio .....	17 33 24.56	0 $^{\circ}$ 03	–33 23 19.8	0 $^{\circ}$ 5
Optical <sup>1</sup> .....	17 33 24.47	0 $^{\circ}$ 08	–33 23 20.2	1 $^{\circ}$ 0
X-ray <sup>2</sup> .....	17 33 24.09	0 $^{\circ}$ 08	–33 23 16.4	1 $^{\circ}$ 0

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

<sup>1</sup> Liller 1977.

<sup>2</sup> Grindlay et al. 1984.



$L_{\min}$ . Furthermore, the absolute numbers derived from this method will, in general, underestimate the total number of pulsars. As noted earlier, all of the identified sources in 47 Tuc lie outside a core radius from the center of the cluster, and similarly, the bright sources in Terzan 5 are more than a core radius from the cluster center. This, however, is not entirely unexpected: a large fraction of MSPs are thought to be produced as a result of a collision of a binary with a third star (quite possibly the neutron star) and this interaction can scatter the binary into the outskirts (or indeed out) of the binary. Depending on the mass distribution of the cluster, this may produce a significant enhancement of the pulsar density at large radii (Sigurdsson & Phinney 1995). Thus, the measurement of the diffuse radio emission within a core radius of the cluster will underestimate the number of weak pulsars in the cluster.

Yet, if the radio spectra and luminosities of these sources are consistent with their being pulsars, why have a substantial fraction of the bright sources been missed by pulsed searches? There are two obvious possibilities: (1) binary pulsars may be lost to pulsed surveys due to Doppler smearing, even though their radio emission remains detectable by interferometric observations (FG90; Kulkarni, Narayan, & Romani 1990, Johnston et al. 1991); and (2) the pulses may be smeared beyond detectability by interstellar dispersion and scattering. Indeed, all three clusters found in this survey to have substantial emission unassociated with known pulsars are located in the direction of the Galactic center at uncertain but great ( $\sim 10$  kpc) distances. The resulting expected dispersion measures are large. Indeed, the 11 ms pulsar in Terzan 5, PSR 1744–24A, has a dispersion measure of  $230 \text{ cm}^{-3} \text{ pc}$ , making searches for pulsars with periods close to 1 ms extremely difficult. Searches are presently underway at Parkes that incorporate software capable of detecting accelerated pulsars or that coherently dedisperse the radio signal, thus largely eliminating the effect of dispersion (although not scattering) on the pulsed signal. One may hope that these searches will find the pulsed signals associated with the pulsars apparent in our data.

Yet, one of the largest puzzles of these observations may come from the clusters where pulsars were detected. Our results imply that the flux density of NGC 6440, NGC 6539, and NGC 6624 are all dominated by a single pulsar. In FG90 we used the total integrated flux density of pulsars in globular clusters to estimate the total number of pulsars in the Galactic globular cluster system. We estimated the number to lie between 500 and 2000. The fact that so many of our clusters are dominated by a single pulsar would tend to push the best estimate down to the lower end of this range. Thus, our latest result only compounds a problem pointed out in FG90. While 10% of Galactic LMXBs are in clusters, only 1% of their proposed descendants live there. Is this, as we noted in FG90, related to the apparent lower luminosity of globular LMXBs—do they spin-up their pulsars more slowly? Or, is it just that objects in binaries are occasionally expelled from the clusters (either with or without their companion, depending upon the interaction), and as the lifetime of an MSP is longer than that of an LMXB, there is a greater chance that it will be expelled during its lifetime? Or are the LMXBs formed by collision in clusters somehow less fecund than the native-born binaries of the disk? In these discrepant statistics may lie an important clue to understanding the evolution of cluster binaries and the formation of MSPs.

We would like to thank Tim Cornwell, whose programs and assistance were invaluable to our 90 cm imaging, and David McConnell, Shri Kulkarni, and Helen Johnston for supporting our use of their archival data. Taft Armandroff graciously provided an *I*-band image of Terzan 5 obtained at the CTIO 1 m telescope. We also thank an anonymous referee for a very careful reading of our manuscript and many helpful comments. The radio observations presented here were done at the Very Large Array of the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc., and at the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a national facility by CSIRO.

## REFERENCES

- Anderson, S. J. 1992, Ph.D. thesis, Caltech  
 Biggs, J., Bailes, M., Lyne, A., Goss, W., & Fruchter, A. 1994, *MNRAS*, 267, 125  
 Biggs, J. D., & Lyne, A. G. 1996, *MNRAS*, 282, 691  
 Briggs, D. S. 1995, Ph.D. thesis, NM Inst. Mines Technology  
 Condon, J. J. 1984, *ApJ*, 287, 461  
 Cordes, J. M., Weisberg, J. M., & Boriakoff, V. 1985, *ApJ*, 288, 221  
 D'Amico, N., Bailes, M., Lyne, A. G., Manchester, R. N., Johnston, S., Fruchter, A. S., & Goss, W. M. 1993, *MNRAS*, 260, L7  
 De Marchi, G., Paresce, F., Stratta, M. G., Gilliland, R. L., & Bohlin, R. C. 1996, *ApJ*, 468, L51  
 Dewey, R. J., Taylor, J. H., Weisberg, J. M., & Stokes, G. H. 1985, *ApJ*, 294, L25  
 Djorgovski, S. 1993, in ASP Conf. Ser. 50, Physical Parameters of Galactic Globular Clusters (San Francisco: ASP), 373  
 Fox, D., Guerriero, R., Lewin, W., Rutledge, R., Moore, C., Van Der Klis, M., & Van Paradijs, J. 1998, *The Astronomer's Telegram*, 1  
 Fruchter, A. S., & Goss, W. M. 1990, *ApJ*, 365, L63  
 ———, 1991, in *X-Ray Binaries and Recycled Pulsar* (Dordrecht: Kluwer), 105  
 ———, 1995, *J. Astrophys. Astron.*, 16, 245  
 Goodman, J. J., Romani, R. W., Blandford, R. D., & Narayan, R. 1987, *MNRAS*, 229, 73  
 Grindlay, J. E., Hertz, P., Steiner, J. E., Murray, S. S., & Lightman, A. P. 1984, *ApJ*, 282, L13  
 Guerriero, R., Fox, D., Lewin, W., Rutledge, R., Moore, C., Van Der Klis, M., & Van Paradijs, J. 1998, *IAU Circ.*, 6815, 2  
 Hamilton, T. T., Helfand, D. J., & Becker, R. H. 1985, *AJ*, 90, 606  
 Hjellming, R. M. 1998, in *Galactic and Extragalactic Radio Astronomy*, ed. G. L. Verschuur & K. I. Kellermann (2d ed.; New York: Springer), 381  
 Johnston, H., Kulkarni, S., & Goss, W. 1991, *ApJ*, 382, L89  
 Johnston, H. M., Verbunt, F., & Hasinger, G. 1995, *A&A*, 298, 21  
 Kaspi, V. M., & Stinebring, D. R. 1992, *ApJ*, 392, 530  
 Kulkarni, S. R., Narayan, R., & Romani, R. 1990, *ApJ*, 356, 174  
 Liller, W. 1977, *ApJ*, 213, L21  
 Lyne, A. G., et al. 1990, *Nature*, 347, 650  
 Manchester, R. N., Lyne, A. G., Johnston, S., D'Amico, N., Lim, J., Kniffen, D. A., Fruchter, A. S., & Goss, W. M. 1989, *IAU Circ.*, 4905, 2  
 Manchester, R. N., Lyne, A. G., Robinson, C., Bailes, M., & D'Amico, N. 1991, *Nature*, 352, 219  
 Manchester, R. N., & Taylor, J. H. 1977, *Pulsars* (San Francisco: Freeman)  
 Nice, D. J., & Thorsett, S. E. 1992, *ApJ*, 397, 249  
 Nice, D. J., Thorsett, S. E., Taylor, J. H., & Fruchter, A. S. 1990, *ApJ*, 361, L61  
 Picard, A., & Johnston, H. 1995, *A&AS*, 112, 89  
 Robinson, C., Lyne, A. G., Manchester, R. N., Bailes, M., D'Amico, N., & Johnston, S. 1995, *MNRAS*, 274, 547  
 Russell, J. L., Lasker, B. M., McLean, B. J., Sturch, C. R., & Jenkner, H. 1990, *AJ*, 99, 2059  
 Rutledge, R., Moore, C., Fox, D., Lewin, W., & Van Paradijs, J. 1998, *The Astronomer's Telegram*, 8, 1  
 Shawl, S. J., & White, R. E. 1986, *AJ*, 91, 312  
 Sigurdsson, S., & Phinney, E. S. 1995, *ApJS*, 99, 609  
 Stollman, G. M. 1987, *A&A*, 171, 152  
 Terzan, A. 1971, *A&A*, 12, 477

*Note added in proof.*—Since the acceptance of our paper site, McConnell & Ables have submitted their own analysis of the 47 Tucanae data to the Monthly Notices of the Royal Astronomical Society. They report two sources close to the center of the cluster, their sources 9 and 11, which we did not detect. In both these cases they find significant emission in only the 1408 MHz image. We have therefore reexamined our data to search for these sources. We also find no emission from either of these possible sources in the 1706 MHz image. We do find a flux density of  $158 \pm 48 \mu\text{Jy}$  at the position of source 9 in the 1408 MHz image; however, this is only marginally above  $3 \sigma$  and less than we would consider sufficient to support the identification of a source without a priori knowledge of its existence.

We also note that the results on Liller 1 cited here from telegrams by Guerriero et al. and Rutledge et al. can now be found in Moore et al. (ApJ, 532, 1181 [2000]).