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# WIDE-FIELD HIGH-RESOLUTION 327 MHz RADIO OBSERVATIONS OF X-RAY GLOBULAR CLUSTER FIELDS

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## ABSTRACT

A radio survey of X-ray emitting globular clusters selected from the *Einstein X-Ray Observatory* survey has been conducted at 327 MHz using the Ooty Synthesis Radio Telescope and the results are presented in this paper. We have detected 14 radio sources within the total area encompassed by one tidal radius of the clusters. Statistically, there is no excess of radio sources in these fields, but, however, we have detected two radio sources which, based on thermal nature or positional coincidence with the core, may be associated with the globular clusters NGC 5272 (M3) and NGC 6656 (M22). Significant differences in terms of positional coincidence, radio flux density, and size of the radio sources have been found with some of the earlier radio observations of similar nature. An important result of the present study is the double-lobed radio structure detected for the X-ray source 1E 1339.9+28 lying toward the field of the globular cluster NGC 5272. Further observations made recently with the Very Large Array indicate highly linearly polarized radio emission from one of the lobes associated with this X-ray object. If this source is Galactic, it could belong to the class of the objects like SS 433 or Sco X-1; or else, if indeed associated with the globular cluster, its radio morphology and properties resemble sources wherein millisecond pulsars are being searched. If extragalactic, it is more likely to be an unusual low radio luminosity quasar showing double-lobed radio structure.

*Subject headings:* clusters: globular — stars: radio radiation — X-rays: sources

## I. INTRODUCTION

The number of X-ray emitting globular clusters in the Galaxy has increased to 18 after the recent X-ray survey of 71 galactic globular clusters using the *Einstein X-Ray Observatory* by Hertz and Grindlay (1983; referred hereafter as HG). Among these, the globular clusters NGC 5139 ($\omega$ Cen) and NGC 6656 (M22) have multiple X-ray sources in their fields separated in their positions by as much as 10′. Searches for radio sources in X-ray emitting globular clusters had earlier been conducted by Johnson (1976), Geldzahler (1983), Hamilton *et al.* (1985), and very recently by Grindlay and Seaquist (1986). In the earlier high-resolution observations of Johnson (1976), no direct association of radio sources with X-ray sources was found. However, observations of NGC 6440 first by Johnson (1976) and later by Gopal-Krishna and Steppe (1980) suggested association of a radio source with the globular cluster. Based on their observations with the Arecibo radio telescope, Terzian and Conklin (1977) suggested variability and universal spectra for sources associated with globular clusters. These suggestions were further examined by Birkinshaw and Downes (1982; hereafter referred to as BD) who found long-term variability for only one source. BD also concluded that the number of sources in the fields of X-ray globular clusters would be consistent with the cosmic field source counts of extragalactic sources. But, nevertheless, the question is still left wide open whether some of the detected radio sources are indeed associated with the globular clusters. The recent detection of a radio source in NGC 6624 by Grindlay and Seaquist (1986) encourages further searches for radio sources in globular cluster fields. They have suggested that since the brightest X-ray sources are variable, increased sensitivity and repeated observations might show most of the X-ray bursters in globular clusters to be detectable radio sources. The difficulties associated with the earlier observations are twofold. As demonstrated by Gopal-Krishna and Steppe (1980), some of the interferometric measurements have missed a significant fraction of the total flux densities and hence the variability associated with few sources is not certain. Also, not a wide enough field has been covered to map with adequate resolution all the sources which may be lying within a few tidal radii of the clusters. On the other hand, the single-dish measurements made at 1.4, 2.7, and 4.8 GHz on the globular clusters by Gopal-Krishna and Steppe (1980) and BD did not have adequate resolution to clearly identify the association of any of the radio sources with the clusters. Our measurements at 327 MHz are mainly aimed at mapping a large region ($0\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$) centered on the globular clusters with sufficiently good resolution of 40″ to enable us to identify multiple components and radio lobes, if any, of the radio sources already reported. Besides, the spectra of these sources could also be examined to detect unambiguously any nonthermal emission associated with these radio sources.

## II. OBSERVATIONS

The observations were made during 1986 March–June using the Ooty Synthesis Radio Telescope (OSRT). The telescope and its operation are described by Swarup (1984). The OSRT operates at 327 MHz having 12 antennas situated over an area of 4 km × 2 km yielding a resolution of 30″ × 60″ (depending upon the declination of the source) and rms sensitivity of 4.5 mJy over 9 hr observations. A limited dynamic range of about 15 is available for the preliminary maps which in some cases

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can be improved by a factor 2 to 5 if special calibration methods like infield calibration (Sukumar 1986) and self-calibration are adopted. The astronomical parameters of the X-ray globular clusters selected for our observations are listed in Table 1. These parameters have been obtained from the compilations of Harris and Racine (1979), Bradt *et al.* (1979), Webbink (1985), and HG. Typically, each globular cluster field was observed for 9 hr covering a hour angle range of $-4^{h}.0$ to $+5^{h}.0$.

For each field, a calibrating source preferably located close to the cluster was chosen from the standard list of sources. The flux densities of these calibration sources at 327 MHz were extrapolated from the high-frequency values using Baar *et al.*'s (1977) scale. Typically, the strength of the calibration sources ranged from 8 to 15 Jy. The calibration sources were observed once in 20 minutes to reduce phase variations resulting from the changing conditions of the ionosphere. The data were carefully edited for interference and ionospheric scintillations and later calibrated. In certain fields, discrete sources of strength $\sim$300–800 mJy lying within the field of view, but situated away from the cluster center were used as infield calibrators to improve phase stability of the observed visibility data. The data thus calibrated were analyzed using the standard Astronomical Image Processing Software (AIPS) of the NRAO.[1] Large size maps covering about $2° \times 2°$ sky area centered on the observed phase centers were initially made to identify any strong point sources lying outside the primary beam area, but producing sidelobe responses on the sources within one tidal radius of the clusters. Such sources were first CLEANed and afterward the inner $1° \times 1°$ area centered on the cluster center was CLEANED until the residuals reached the noise limits. Since most of the fields contained sources with peak flux densities between 200 and 400 mJy only, the limited dynamic range did not restrict the map sensitivity except in a few cases. The CLEAN components were restored with appropriate beams depending on the declination of the fields. The radio maps have been corrected for the primary beam pattern of OSRT which has a FWHM of $170' \times 42'$ in the east-west and north-south directions, respectively. The map parameters such as rms sensitivity, synthesized beam widths, and the radio source positions are compiled in Table 2 along with observed X-ray parameters obtained from HG. The radio source positions have a rms error of $\sim 5''$.

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

## III. RESULTS

The radio maps of the globular clusters at 327 MHz are shown in Figure 1*a* to 1*i*. The fields shown include the area within one tidal radius of the clusters in all cases except in the case of M22, for which the tidal radius stretches beyond the primary beam width of OSRT. The contour levels scale up by −2, −1, 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, and 30 times the lowest contour which is 20 mJy beam$^{-1}$ for all the maps except that of M22. In the case of M22, the rms noise is limited by the dynamic range of OSRT and hence the lowest contour is restricted to 30 mJy beam$^{-1}$. The flux densities measured for the discrete sources detected within one tidal radius of each cluster are also listed in Table 2. These values have a maximum error of 15% contributed mainly due to uncertainties in the flux densities of calibration sources. We briefly describe our results on each source below and it may be noted that nondetection of a radio source at an X-ray source position implies the upper limit for radio flux to be 22 mJy, which is 5 times the rms sensitivity of our observations.

*NGC 1904* (*M79*).—The dim X-ray source associated with M79 is situated $8'' \pm 60''$ (HG) from the center of the cluster. Our 327 MHz observations do not show any radio source coincident with the cluster center or the X-ray source position. However, we detect a radio source within one tidal radius of the cluster with a total flux density of 300 mJy at 327 MHz. In the absence of any spectral information no conclusive association could be established and it could be an extragalactic background source.

*NGC 5272* (*M3*).—Our observations reveal very interesting details on the radio sources seen within this cluster. The high-frequency observations of Rood, Turner, and Goldstein (1978)

TABLE 1

ASTRONOMICAL PARAMETERS OF X-RAY GLOBULAR CLUSTERS

| Cluster | Distance (kpc) | R.A. (1950) Decl. (1950) | Core Radius (″) | Tidal Radius (′) |
|---|---|---|---|---|
| NGC 1904 (M79) ........ | 13.3 | 05$^h$22$^m$ 7$^s$.4<br>−24°34′ 8″ | 16 | 10.7 |
| NGC 5272 (M3) ......... | 10.0 | 13 39 54.1<br>28 37 52 | 29 | 16.2 |
| NGC 5824 ............... | 23.5 | 15 0 53.8<br>−32 52 27 | 4 | 20.0 |
| Terzan 2 ................. | 10.5 | 17 24 20.0<br>−30 45 37 | 7 | 3.1 |
| Grindlay 1 ............... | 10.0 | 17 28 39.2<br>−33 47 55 | 32 | 8.7 |
| Liller 1 ................... | 10.0 | 17 30 6.6<br>−33 21 20 | 4 | 3.3 |
| NGC 6440 ............... | 3.5 | 17 45 54.2<br>−20 20 40 | 12 | 7.9 |
| NGC 6624 ............... | 8.7 | 18 20 27.6<br>−30 23 16 | 5 | 6.3 |
| NGC 6656 (M22) ........ | 3.0 | 18 33 20.4<br>−23 56 56 | 144 | 33.1 |
| NGC 7078 (M15) ........ | 9.4 | 21 27 33.4<br>11 56 49 | 6 | 20.9 |

TABLE 2

SOURCES IN THE X-RAY GLOBULAR CLUSTER FIELDS

| | | | PARAMETERS OF RADIO OBSERVATIONS AND SOURCES DETECTED AT 327 MHz WITHIN ONE TIDAL RADIUS OF CLUSTER | | | | |
|---|---|---|---|---|---|---|---|
| CLUSTER NAME | X-RAY SOURCE POSITION | X-RAY BURSTER? | Synthesized Beam Width | rms Noise (mJy) | Source Name | R.A. (1950)<br>Decl. (1950) | Integrated Flux Density (mJy) |
| NGC 1094 (M79) ........ | 05ʰ22ᵐ 7ˢ.7<br>−24°33′55″ | ... | 70″ × 30″<br>at PA = −5° | 5.1 | N1904 A | 05ʰ22ᵐ32ˢ.7 ± 5″<br>−24°42′22″ ± 5″ | 300 ± 15 |
| NGC 5272 (M3) ......... | 13 39 51.4<br>28 37 52 | ... | 59 × 29<br>at PA = −11° | 4.5 | N5272 A | 13 38 56.3<br>28 31 30 | 126 ± 15 |
| | 13 39 56.6<br>+28 44 12 | | | | N5272 Bi | 13 39 53.8<br>28 44 50 | 298 ± 15 |
| | (1E 1339.9 + 28) | | | | N5272 Bii | 13 39 51.9<br>28 43 34 | 227 ± 15 |
| | | | | | N5272 C | 13 40 6.4<br>28 42 0 | 80 ± 15 |
| | | | | | N5272 D | 13 40 36.2<br>28 43 21 | 335 ± 15 |
| NGC 5824 ............... | 15 0 49.4<br>−32 52 7 | ... | 59 × 31<br>at PA = 4° | 5.7 | N5824 A | 15 01 0<br>−32 48 36 | 159 ± 23 |
| Terzan 2 ................. | 17 24 20.1<br>−30 45 39 | Yes | 66 × 27<br>at PA = 8° | 4.2 | Terz2 A | 17 23 56.8<br>−30 44 54 | 57 ± 13 |
| | | | | | Terz2 B | 17 24 22.8<br>−30 52 40 | 72 ± 14 |
| | | | | | Terz2 C | 17 24 28.9<br>−30 45 43 | 79 ± 14 |
| | | | | | Terz2 D | 17 24 54.5<br>−30 43 23 | 130 ± 15 |
| Grindlay 1 .............. | 17 28 39.2<br>−33 47 55 | Yes | 58 × 29<br>at PA = 2° | 4.4 | | ... | ... |
| Liller 1 ................... | 17 30 6.6<br>−33 21 13 | Yes | 58 × 29<br>at PA = 22° | 4.4 | | ... | ... |
| NGC 6440 ............... | 17 45 55.0<br>−20 21 7 | Transient | 72 × 27<br>at PA = 8° | 3.9 | N6440 A | 17 45 24.0<br>−20 28 24 | 64 ± 11 |
| | | | | | N6440 B | 17 45 58.1<br>−20 17 37 | 125 ± 14 |
| NGC 6624 ............... | 18 20 27.8<br>−30 23 17 | Yes | 63 × 27<br>at PA = −9° | 5.3 | | ... | ... |
| NGC 6656<br>(M22) A ............... | 18 32 49.1<br>−23 50 5 | ... | 72 × 29<br>at PA = −4° | 8.6 | | ... | ... |
| B .............. | 18 33 21.7<br>−23 57 18 | ... | | | N6656 A | 18 33 12.9<br>−23 56 22 | 63 ± 17 |
| C .............. | 18 33 43.6<br>−23 38 59 | ... | | | | ... | ... |
| D .............. | 18 34 12.2<br>−23 50 8 | ... | | | | ... | ... |
| NGC 7078 (M15) ........ | 21 27 33.1<br>11 56 51 | ... | 102 × 32<br>at PA = 10° | 3.9 | | ... | ... |

show four radio sources within one tidal radius of the cluster which are all seen at 327 MHz. In addition, our observations resolve the radio source B2.2 1339+28 into two components (marked as Bi and Bii in Fig. 1*b*) which may be associated with the serendipitous X-ray source 1E 1339.9+2844, listed by HG. The single-dish measurements of Gopal-Krishna and Steppe (1980) and BD could not have resolved these sources at 2.7 GHz due to poor resolution ($\sim 4'.5$). Also, the 5 GHz interferometric observations of BD with a synthesised beam of 2″ does not cover a large enough field to see the southern component, Bii. As seen from our observations, the two components are lying almost at the same right ascension (separation 22″) and separated by $\sim 1'.5$ in declination. The total flux density of both these components is $\sim$450 mJy which very well fits with the nonthermal spectral index of 0.7 ($S \propto \nu^{-\alpha}$) expected from the measurements of Gopal-Krishna and Steppe (1980) and BD. However, the interferometric measurements at 2.7 GHz by Rood, Turner, and Goldstein (1978) indicate much lower flux ($\sim$60 mJy) implying either the large-scale structures greater than 20″ are not seen or the source is time-variable. Rood, Turner, and Goldstein (1978) rule out any possibility of missing flux and assuming the flux density quoted by them at 2.7 GHz and no variability of the radio flux, we compute the spectral index as 0.4 over the frequency range of 327 MHz to 10.7 GHz suggesting the source may not be extragalactic. In any case, our observations of a double-lobed radio structure coincident with an intense X-ray source brings out interesting questions about the nature of the source for further study irrespective of whether it is Galactic or extragalactic. Recently, we observed this object with the Very Large Array at 90, 20, and 6 cm, and the preliminary analysis showed that approximately 25% of the radio emission from the northern lobe is linearly polarized. It also seems more likely that the X-ray source is located closer to the northern lobe. Even though the X-ray and radio positions differ by $\sim$38″, they are still located within the large X-ray error of $\sim \pm 1'$ (Paul Hertz, personal communication). More details on these observations and the probable nature of this source will be discussed elsewhere.

The other X-ray source close to the cluster center does not seem to be associated with any radio source. However, other than M3 B, three more radio sources (M3 A, M3 C, and M3 D) are located within one tidal radius of the cluster. The source M3 A is perhaps quite unusual. BD suggest 15% variability for this source over a long time period of 1 yr based on their measurements at 2695 MHz. Comparing our measurements with high-frequency ones, we find that the flux density increases with frequency with a flat spectral index of $\sim 0.02$. This indicates thermal nature for the radio source thus confirming the suggestion of Rood, Turner, and Goldstein (1978) that the source could be a planetary nebula associated with the globular cluster. Also, our observations indicate a turnover frequency less than 300 MHz in contrast to 1500 MHz suggested by Gopal-Krishna and Steppe (1980). The sources M3 C and M3 D are likely to be extragalactic background sources having a spectral index of $\sim 0.7$. Of these, Gopal-Krishna and Steppe (1980) report association of a blue object with M3 D at a redshift of 1.02. For M3 C, they suggest flattening of the integrated flux density spectrum below 2 GHz, for which we find no evidence.

*NGC 5824*.—Our observations do not indicate presence of any radio source at the position of the dim X-ray source IE 1500.7−3251 located 59″ ± 12″ from the center of this globular cluster. However, we find an extended source (> 2′) situated 4′ north of the cluster center. In the absence of any spectral information, it is difficult to confirm association of this radio source with the globular cluster.

*Terzan 2*.—This globular cluster is identified with an X-ray burster 4U 1722−30 (Swank *et al.* 1977; Grindlay *et al.* 1980) categorized as a bright burster source and if any radio emission is associated with it one might expect variability in its radio intensity, too. No high-frequency radio observations have so far been reported for this source. Our observations provisionally indicate presence of a weak radio emitter in proximity to the position of the X-ray burster, but outside the error circle of the X-ray source.

*Liller 1 and Grindlay 1*.—These are the X-ray identified globular clusters found after the detection of the rapid burster source MXB 1730−335 and 4U 1728−34 (Liller 1977; Lewin and Joss 1981; Grindlay and Hertz 1981). Our observations do not show evidence for any association of radio sources with these clusters.

*NGC 6440*.—This globular cluster having the transient X-ray burster source MX 1746−20 was reported by Johnson (1976) to contain two radio sources close to the cluster center. Later observations of Gopal-Krishna and Steppe (1980) and BD confirmed the existence of a broad radio source whose centroid was located within 1′ of the center of the cluster. Our observations show existence of two radio sources within one tidal radius of the globular cluster, but we do not find a large-scale structure (10′.3 as reported by BD) associated with any of the radio sources. In our map, the two sources are approximately separated by 12′ and it is possible that BD have interpreted this separation as a large-scale structure. The association of any of the two radio sources with the X-ray source is rather remote. Also, the radio spectral index (0.61) of source A suggests extragalactic nature.

*NGC 6624*.—This globular cluster has been subjected to numerous investigations due to the bright X-ray burster source 4U 1820−30 displaying type I bursts and quasi-periodic oscillations (Stella, White, and Priedhorsky 1985). Recently, Grindlay and Seaquist (1986) reported provisional detection with the VLA, of a radio source (0.49 mJy) at 20 cm. Our observations do not indicate any radio source at the X-ray position, but an upper limit of 22 mJy of our observations is consistent with the VLA detection and this source may be a probable candidate for future radio detection.

*NGC 6656* (*M22*).—The X-ray survey (HG) of this globular cluster having a large core radius of 114″ and a tidal radius of about 33′ revealed four X-ray sources in its field of which, based on probability, at least three are associated with it. Since the tidal radius is very large, we could not cover the entire cluster field in our observations and we only observed a limited field containing the four X-ray sources. Due to the presence of a strong extragalactic background source within this field, the rms noise in our map has been dynamic range limited to 10 mJy. Our observations do not suggest direct association of any radio source with any of the four X-ray sources within the 4 $\sigma$ upper limit of $\sim 40$ mJy. However we may cautiously mention that a radio source of strength $\sim 60$ mJy located within the core radius of the cluster, but outside the X-ray error circle (marked as A in Fig. 1*h*) may have some association with the cluster. Statistically, we expect only 0.1 background radio source to fall within any of the cluster cores and since the total area inside cores is dominated by the area in M22's core, there is about 90% probability that the source is associated with this cluster.

*NGC 7078* (*M15*).—The bright X-ray source 4U 2131+11 associated with this globular cluster exhibits variable spectrum (HG) and in the observations of Johnson (1976), Gopal-

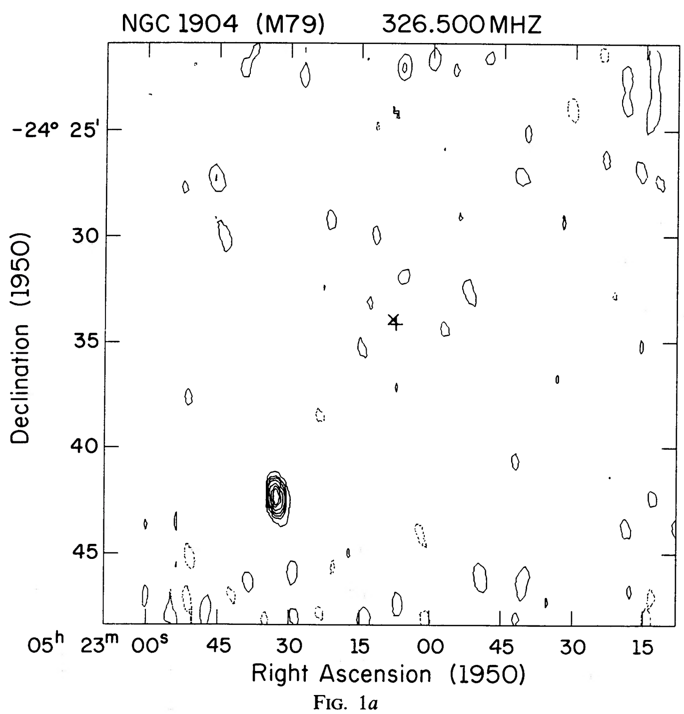


FIG. 1*a*

FIG. 1.—(*a*–*i*) Radio emission at 327 MHz observed toward the X-ray globular cluster fields M79, M3, …, M15 and sequentially arranged as in Table 1. The cluster centers are marked by "+" and the X-ray source positions are indicated by "×." The fields of Grindlay 1 and Liller 1 have been combined in Fig. 1*e*. The contours scale up as −2, −1, 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30 of the lowest positive contour level, 20 mJy beam$^{-1}$, for all fields except M22 for which it is 30 mJy beam$^{-1}$. The synthesized beam widths used to restore the CLEANed maps are listed in Table 2.

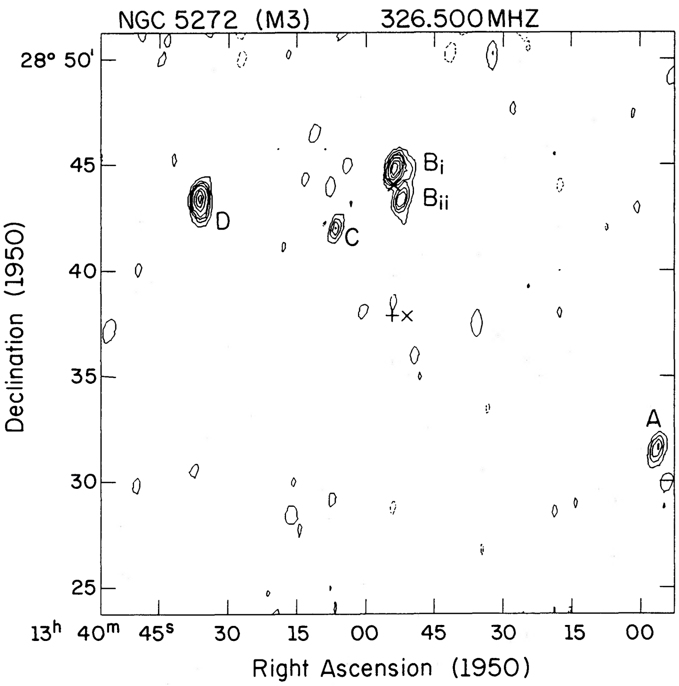


FIG. 1b

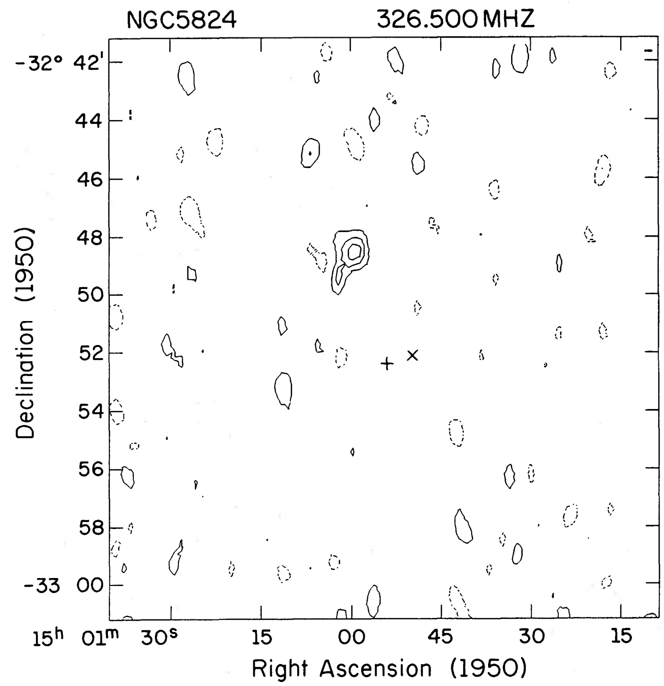


FIG. 1c

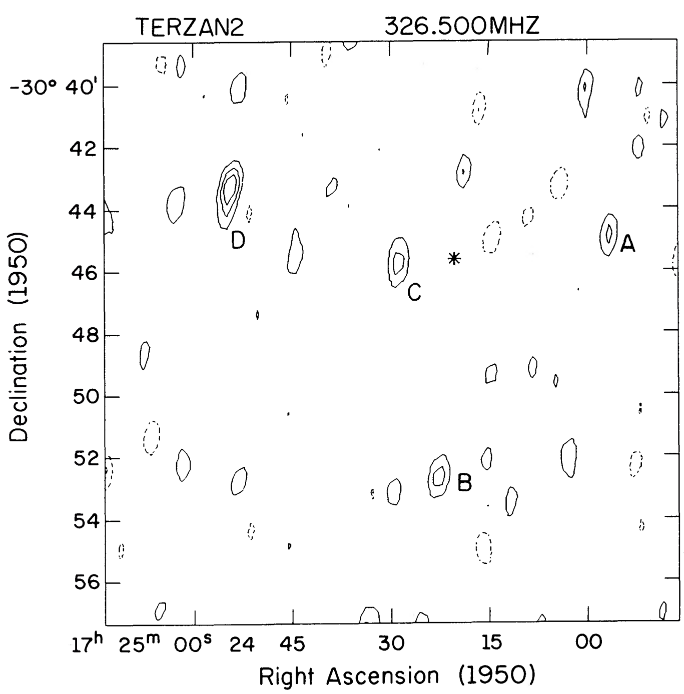


FIG. 1d

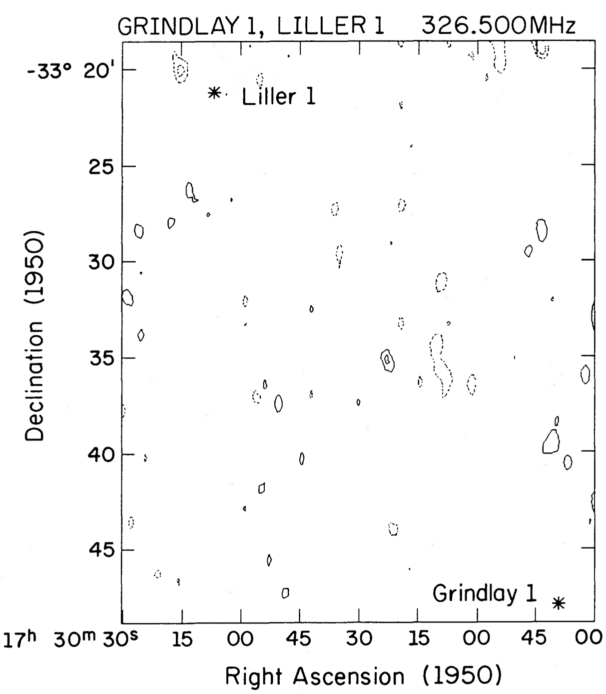


FIG. 1e

FIG. 1—*Continued*

Krishna and Steppe (1980) and BD, a radio source and the planetary nebula K648 have been detected within one tidal radius. We do not find any evidence for radio emission at 327 MHz at the positions reported by them implying that the sources may have thermal emission characteristics with turn over frequencies around 1 GHz. In our map we also find a weak radio source of strength ~50 mJy at 327 MHz lying almost at the tidal edge of the cluster and the probability of this source being an extragalactic background source is quite high.

## IV. DISCUSSION

Some of the radio sources detected in the fields of the globular clusters are noteworthy. In particular, we draw attention to the radio source M3 B associated with the serendipitous X-ray source 1E 1339+2844, for which we have detected a double-

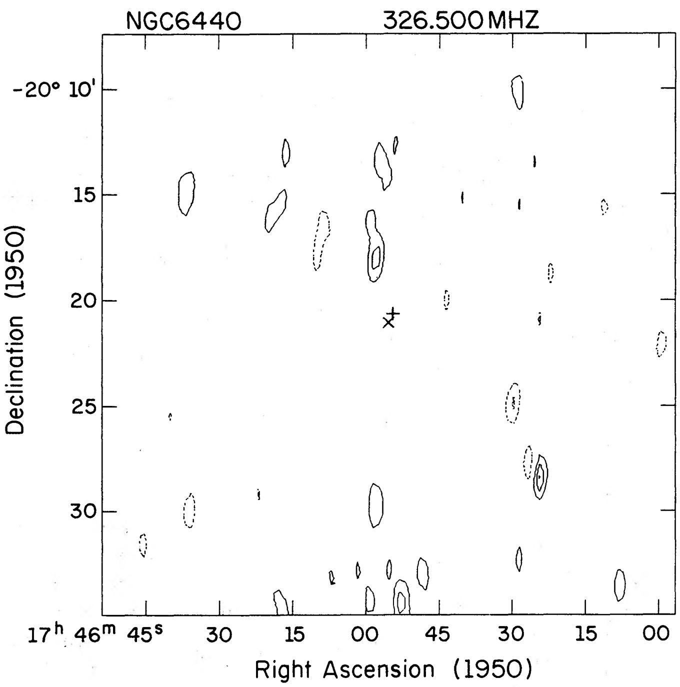


FIG. 1*f*

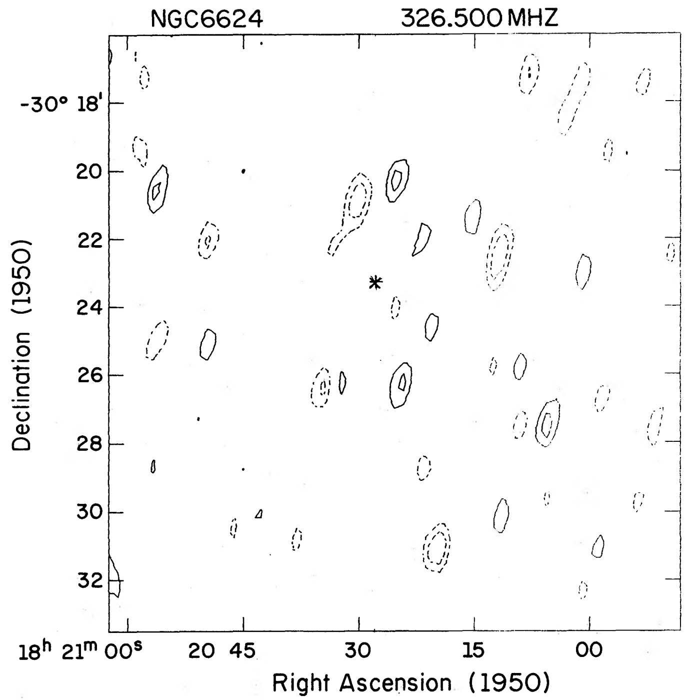


FIG. 1*g*

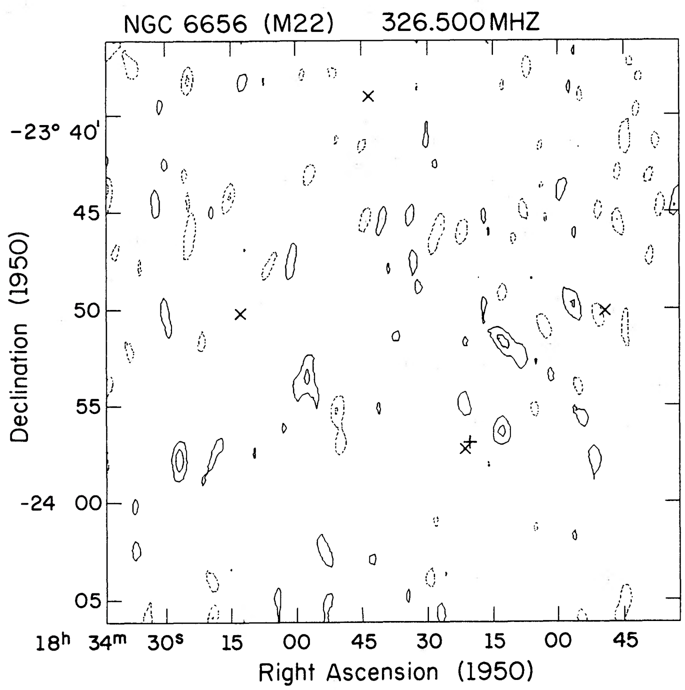


FIG. 1*h*

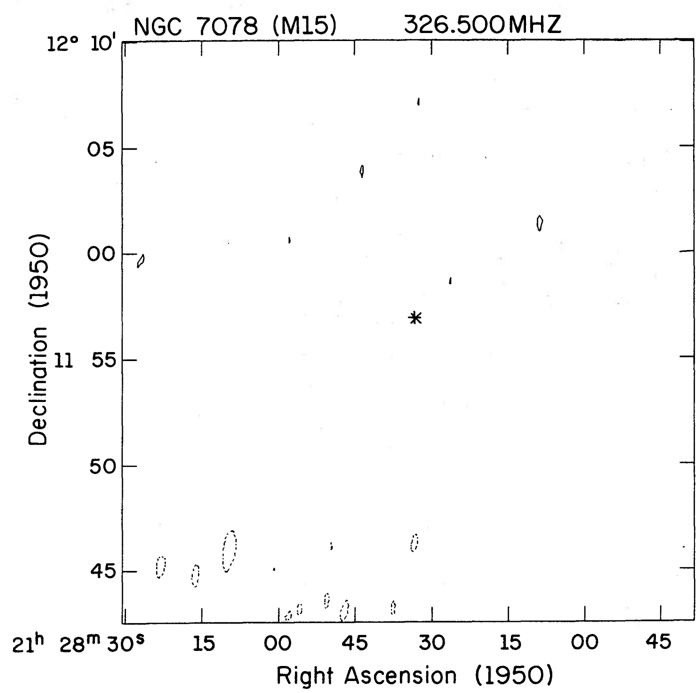


FIG. 1*i*

FIG. 1—*Continued*

lobed structure. This source, cataloged as B2.2 1339+28 in the low-resolution radio surveys at 408 MHz (Colla *et al.* 1972), is rather unusual. In discussing the possible physical mechanisms operating in the source, it may be noted that its X-ray luminosity is $\sim 10^{33}$ ergs $s^{-1}$ and the radio luminosity is $\sim 1.5 \times 10^{32}$ ergs $s^{-1}$ over the frequency range 0.327 to 10.7 GHz, for an assumed distance of $\sim 10$ kpc for M3. This indicates a spectral index slightly flatter than 1 and extending over a very large range of frequencies. In the absence of any optical identification and redshift measurement the exact nature of the source cannot be easily understood. If this source is a Galactic object, it is quite unusual and might bear some similarity to Sco X-1 or SS 433. Based on the radio/X-ray spectral index, HG conclude that 1E 1339.9+2844 is extragalactic and not physically related to the globular cluster NGC 5272. On the basis of color indices, variability, radio flux, and optical appearance, Carney (1976) judged it to be a quasi-stellar source, but in the absence of optical spectrograms the extragalactic identification was not affirmative. If the object is extragalactic, one might invoke the similarity of its radio spectrum with that of quasars or BL Lac objects; however, for typical redshifts observed for confirmed quasars, the observed flux density at 90 cm would indicate the object to be a low radio luminosity quasar in which case the double-lobed radio structure would again make it unusual (see, for example, Machalski and Condon 1986; Bridle and Perley 1984). In fact, there exists no definitive clue at the moment to indicate whether the object is Galactic or extragalactic. The suggested variability for this source is worth investigating further. The high percentage of linearly polarized radio emission from the northern lobe of the radio source associated with 1E 1339.9+2844 makes it a probable candidate for searching a millisecond pulsar within this source. We feel this source is a good candidate for further study at various radio frequencies which should aim at detecting variability.

The detection of radio source in the globular cluster NGC 6656 is provisional and needs to be confirmed by further observations. From the integral source count distribution at 408 MHz (Ryle 1968) and radio source count distribution at 327 MHz (Oort 1987) we expect to detect approximately 0.1 sources exceeding 40 mJy within the area encompassed by one core radius of NGC 6656. However, we have detected a 60 mJy source within the core radius which makes it likely that the radio source is indeed associated with the cluster. Assuming random distribution of radio sources, there is only 10% chance that the source could be a background radio source. The diffuse and dim X-ray source 1E 1833.3−2357 in the core of NGC 6656 is located well outside the X-ray error circle and there seems to be no direct association of the radio source with the X-ray source. The thermal radio source M3 A in the globular cluster NGC 5272 is more likely to be a planetary nebula with a turnover frequency of less than 300 MHz.

Considering the question for the presence of any excess radio sources in the globular cluster fields, we compute the expected number of radio sources with flux density greater than 22 mJy within the total area encompassed by one tidal radius of the globular clusters in our search. We expect to detect at least 58 radio sources over the entire field, whereas we have actually detected only 14, and thus there seems to be no excess of radio sources toward the globular cluster fields.

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