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Radio Images of the Globular Cluster 47 Tucanae

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Abstract: We present deep ATCA radio images of the globular cluster 47 Tucanae made at 1.4 and 1.7 GHz and identify 9 compact sources in the cluster core with 11 pulsars. At present there are several pulsars for which pulse timing analyses have not yet yielded precise positions. We examine other sources in the image, and on the basis of their spectral index find two that would possibly correspond to the pulsars with undetermined positions.

Keywords: pulsars: general — globular clusters: individual (47 Tucanae) — radio continuum: stars

1 Introduction

Previously we imaged the globular cluster 47 Tucanae with the Australia Telescope Compact Array (ATCA) at 1.4 and 1.7 GHz (McConnell & Ables 2000: MA2000) with the aim of identifying radio sources corresponding to the pulsars known to exist in the cluster. We were able to report the detection of pulsars 47 Tuc C and D and identified several compact sources which had spectral indices and time variability characteristic of pulsars. One of these was later identified with pulsar 47 Tuc J. (See also Fruchter & Goss 2000.) Here we describe more sensitive images of the cluster derived from ~170 hours of integration.

47 Tuc is known to contain at least 22 millisecond pulsars (Manchester 2000). Many of the pulsars show period variations characteristic of motion in binary orbits. This, and the pulsars' intermittent detectability, have made difficult the use of pulse timing analyses to determine pulsar positions. Pulse timing has so far yielded positions for only 15 of the 22 pulsars (Manchester 2000; Freire et al. 2000).

2 Observations and Data Reduction

Observations of 47 Tuc were made with the ATCA, as described in MA2000, over two 128 MHz bands centred at 1.408 GHz and 1.708 GHz in a number of array configurations. Several reference positions close to the cluster centre were used to minimise the effects of artefacts at the phase reference centre and to flatten the sensitivity profile over the cluster. Table 1 lists the details of each observation.

The MIRIAD data reduction package was used to calibrate the data and form images. The antenna gains were calibrated using brief observations of the source B2353-686 ($S_{1.4} = 1.05$ Jy, $S_{1.7} = 1.00$ Jy) and B0252-712 ($S_{1.4} = 5.5$ Jy, $S_{1.7} = 4.6$ Jy). The flux scale was referred to the ATCA primary flux calibrator B1934-638 ($S_{1.4} = 14.9$ Jy, $S_{1.7} = 14.0$ Jy).

The image we present here is derived from all datasets listed in Table 1 combined with Compact Array data from 1992. Before combination, separate images corresponding to each dataset were made to assist in the identification of data affected by radiofrequency interference or instrumental faults. The MIRIAD software supports the reduction of data collected from a mosaic of pointing centres, and tasks INVERT and MOSMEM were used to produce and deconvolve images at each observing frequency. Both images have reference (tangent) point at $\alpha(2000) = 00{:}24{:}05.3''$, $\delta(2000) = -72{:}04{:}52.7''$, the nominal cluster centre (De Marchi et al. 1996). An imaging cell size of $2''$ was used to provide adequate sampling of the synthesized beam which is $8.3'' \times 7.2''$ at 1.4 GHz and $8.6'' \times 5.7''$ at 1.7 GHz. The size of each image is 2755×2820 pixels (91.8×94 arcmin^2).

The final image analysis was performed over a region of approximate diameter $53'$ within which the sensitivity varied by less than a factor of ~3.5. Within this region the variation of sensitivity was modelled taking account of both primary beam attenuation towards the field edges and the increased fluctuations close to strong sources. The sensitivity model allowed uniform discrimination of sources across the entire analysed field. Sources with peak flux density greater than 5 times the local *rms* brightness fluctuation were selected.

We note that from the analysis of the earlier ATCA image of 47 Tuc, two sources were reported (numbered 9 and 11 in Table 2 of MA2000) with fluxes of ~200 μJy or 4.8 times the image *rms* brightness fluctuation. Neither source is detected in the more sensitive image reported here, whereas all sources with flux $S > 5\sigma$ in the original report are detected with the new data.

3 Image Analysis and Results

We describe the analysis and results from the 1.4 GHz image. (The same reduction procedure was used for the

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Table 1. Summary of new observations

The pointing and phase reference position and Compact Array configuration for each observation is tabulated. The data listed here were combined with data obtained from the Compact Array in 1992 (McConnell & Ables 2000). The total effective integration time on the cluster core, including the 1992 observations, is 170 hours.

Date (UT)	Time (UT)	Integration (hours)	α (J2000)	δ (J2000)	Array
1998 Oct 16	13:36	1.5	00:24:06	−72:05:00	1.5D
1998 Nov 13	10:30	7.5	00:24:06	−72:05:00	6D
1998 Nov 24	02:21	3.9	00:24:06	−72:05:00	6D
1999 Jan 25	23:23	9.9	00:24:06	−72:03:00	0.75B
1999 Feb 12	01:40	1.9	00:24:06	−72:03:00	6C
1999 Mar 23	00:29	6.2	00:24:06	−72:03:00	1.5B
1999 May 04	16:40	10.3	00:24:06	−72:03:00	6A
1999 May 08	21:59	4.5	00:24:06	−72:03:00	6A
1999 Jun 03	16:31	9.5	00:24:06	−72:03:00	6A
1999 Aug 17	11:30	11.1	00:24:06	−72:03:00	6D
1999 Aug 18	08:25	11.0	00:24:06	−72:03:00	6D
1999 Aug 30	07:37	12.9	00:23:44	−72:03:15	6D
1999 Sep 02	22:45	8.1	00:23:49	−72:03:15	6D
1999 Sep 11	20:28	1.4	00:23:49	−72:03:15	6A
1999 Sep 22	17:41	2.1	00:23:49	−72:03:15	6A
1999 Oct 04	16:30	5.2	00:23:49	−72:03:15	6A
1999 Dec 26	04:31	7.1	00:23:49	−72:03:15	1.5A
1999 Dec 31	02:21	24.8	00:24:06	−72:03:00	1.5A

Table 2. Flux measurements at 1.4 GHz and 1.7 GHz and spectral indices of the sources in Figure 1

The fluxes of pulsars L and O were estimated by modelling the associated extended source with two point sources constrained to lie at their timing positions. Although pulsars O and U are not detected at 1.7 GHz the table gives meaningful (but broad) limits to their spectral indices. Column (2) gives the source numbers from Table 2 of MA2000. Sources 9 and 11 from MA2000 are not detected (see text). Other sources reported in MA2000 were outside the area analysed here.

(1) Source	(2)	(3) $S_{1.4}$ (μJy)	(4) $S_{1.7}$ (μJy)	(5) α
C	4	243	122	-3.6 ± 0.8
D	8	369	200	-3.2 ± 0.5
E		84	61	-1.7 ± 2.1
F		176	50	-6.5 ± 2.2
G/I		102	65	-2.3 ± 1.9
J	5	330	202	-2.5 ± 0.5
L		95	79	-1.0 ± 1.7
O		77	(22)	(-6.4 ± 7)
Q		116	59	-3.5 ± 2.3
U		114	(28)	(-7.3 ± 5.4)
142	3	727	628	-0.8 ± 0.2
176	7	202	201	0.0 ± 0.7
178		92	116	1.2 ± 1.4
183		108	36	-5.7 ± 5.5
186		101	59	-2.8 ± 2.2

1.7 GHz image and its relevance in this paper is restricted to the measurement of spectral indices of sources in the cluster centre.) Over the 53′ field (2208 arcmin^2) the image noise fluctuations range from $\sigma_{1.4} \simeq 18\,\mu$Jy over the cluster centre to ~60 μJy at the field edge. Within this area 305 sources were detected above the 5σ threshold. After correction for the varying sensitivity across the field we found a mean density of sources with $S_{1.4} > 90\,\mu$Jy of 0.25 ± 0.01 arcmin^{-2}.

The sensitivity to radio sources is limited by image fluctuations originating from thermal noise in the receiving equipment and radiation from the sky and ground. The detectability of weak sources is also limited by the extent to which corrections can be made for the sidelobe response to strong sources in the field. While image fluctuations are dominated by sources of random noise the sensitivity σ is expected to improve with integration time T as $\sigma \propto T^{-1/2}$. The image formed from the 1992 observations had an effective integration time on the cluster core of 33 hours and at 1.4 GHz the image *rms* was 42 μJy. The new image has $T = 170$ hours and $\sigma_{1.4} \simeq 18\,\mu$Jy close to the value expected from the $\sigma \propto T^{-1/2}$ relation. Note that this is well above the *rms* value of ~10 μJy expected from considering only the thermal contributions to noise.

Figure 1 shows the centre of the 1.4 GHz image — within 2′ of the cluster centre. The positions of pulsars with known timing positions are indicated and labelled with their alphabetic names. Sources not coincident with known pulsar locations are labelled with their respective numbers from our list of 305 sources.

Table 2 gives, for each source in Figure 3, measured values of flux at 1.4 GHz and 1.7 GHz and their spectral indices. The relatively large uncertainties in spectral index result from the small frequency separation of the flux measurements and the low signal-to-noise ratio for most sources.

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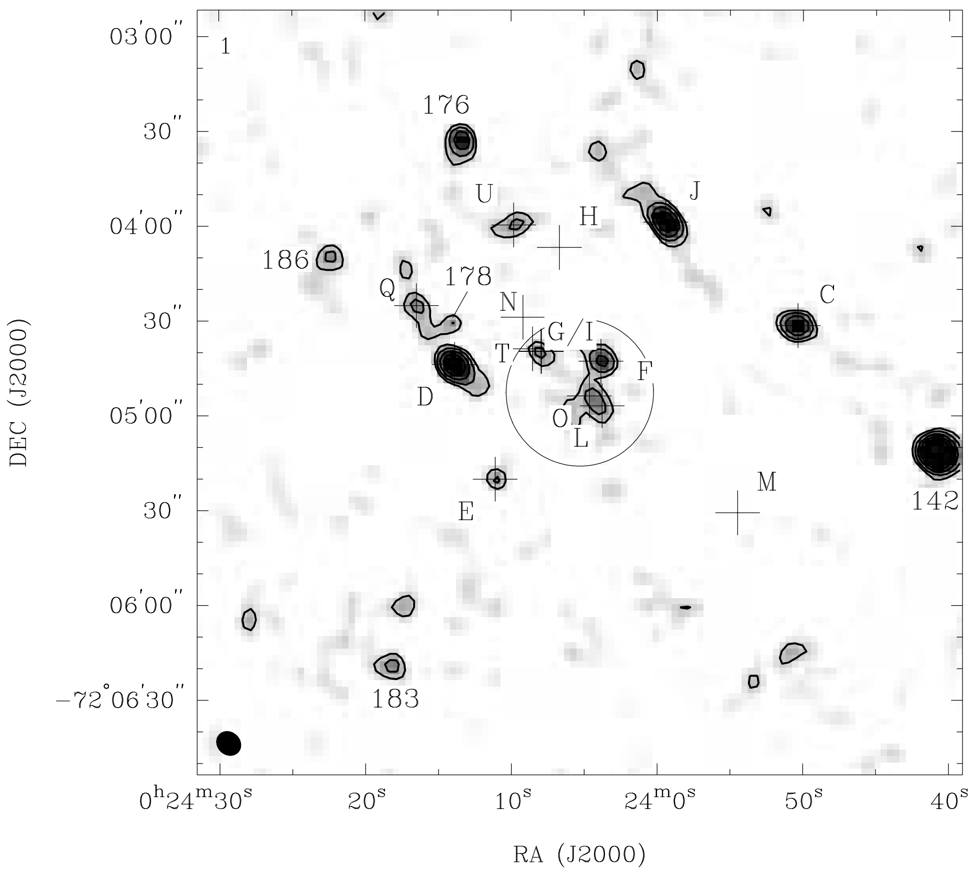

Figure 1 The inner part of the imaged field. The radio emission is shown as the 1.4 GHz brightness contours at 54, 90, 144, 216, 306 µJy/beam (that is $\sigma \times 3$, $\times 5$, $\times 8$, $\times 12$, $\times 17$). The size of the synthesized beam at 1.4 GHz is indicated at lower left. The central circle marks the position (De Marchi et al. 1996) and size ($r_c \simeq 23''$, Howell, Guhathakurta & Gilliland 2000) of the cluster core. The positions of pulsars with known timing positions are indicated by crosses and labelled with their alphabetic names. Other 1.4 GHz sources are numbered as described in the text.

4 Discussion

Of the 15 pulsars with positions well determined by pulsar timing (Freire et al. 2000), 11 correspond to nine sources in the ATCA image at 1.4 GHz. Pulsars G and I are separated by less than 0.2″ and appear as a single point source. Pulsar T lies 2.8″ from the G/I pair. Pulsars L and O are separated by ~5″ and appear as a single extended source. Thus nine discrete sources in the image account for 11 of the pulsars. Pulsars M, H and N correspond to no emission above the 3σ level of 54 µJy and are reported by Camilo et al. (2000) to be faint — 70 ± 20 µJy, 90 ± 20 µJy and 30 ± 10 µJy respectively.

The core region of the cluster (Figure 3) shows five sources in addition to the nine identified with pulsars. Based on the source density discussed in section 3 above we expect 3.1 ± 1.8 sources above the 5σ detection threshold, consistent with all five being unrelated to the globular cluster.

As noted in Section 3, the spectral index measurements in many cases have large uncertainties. However, they are consistent with all pulsar related sources having spectral index $-3 < \alpha < -2$, typical of pulsar emission. Three of the numbered sources (142, 176, and 178) have spectral index range $-0.8 < \alpha < 1.2$, characteristic of extragalactic radio sources. The remaining two (183, 186) have steeper spectra and may correspond to any of the seven pulsars yet to be *located* with pulse timing.

Two sources, numbered 2 and 5 of Table 2 (MA2000), were identified as possible pulsars based on their spectral index (-2.4 ± 2.0 and -2.4 ± 0.7 respectively) and their apparent variability. Source 2 lies 248″ (~10 core radii) from the cluster centre. The improved sensitivity of the new image gives a more precisely determined spectral index of -0.1 ± 0.9, weakening the case for it being a pulsar. Source 5 can now be identified with the pulsar 47 Tuc J.

A remarkable feature of the 47 Tuc pulsars is their strong scintillation. Camilo et al. (2000) quote estimates of the flux density of 14 pulsars; only two have mean flux greater than the sensitivity (nominally ~ 300 µJy at 1.4 GHz) of the observing system used for their discovery. Intensity enhancements have allowed pulsars with mean flux $\lesssim$ 30 µJy to be detected — a factor of 10 below the nominal threshold. The Compact Array image reported here has a 5σ detection limit of 90 µJy, and so only half of the pulsars detectable with the Parkes telescope are

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visible in the image. Future improvements to the image sensitivity may come in two ways. Additional integration time is expected to continue reducing the fluctuation level in the image. Secondly, as noted above, the sensitivity of the image reported here is considerably poorer than expected from formal noise estimates. Some improvement may be gained from understanding the origin of this degradation.

Finally we note that the pulsars already detected in 47 Tuc probably represent the brightest set of a larger population. Camilo et al. (2000) have estimated that as many as 200 potentially observable pulsars may exist in the cluster. Such a population of pulsars may be visible with the Compact Array as an extended radio source in the cluster core. The luminosity function of pulsars (Lyne, Manchester & Taylor 1985) is well described by $dN = -L^{-1}d(\log L)$ down to a minimum luminosity at 400 MHz of ~ 0.3 mJy kpc^2, equivalent to 0.024 mJy kpc^2 at 1.4 GHz, assuming a spectral index of -2. This relation was used by Camilo et al. (2000) to estimate the size of the pulsar population. We use the same relation to estimate the total flux density from the whole population to be $\sim$4 mJy, with about half of this from pulsars below the ATCA detection limit and appearing in the extended component. The detection of an extended radio source in the cluster core, and a measurement of its angular extent would give an interesting alternative estimate of the pulsar population and its distribution within the cluster core.

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