Detection of extended component of 47 Tuc, due to unresolved pulsar emission

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Abstract

We present a method for statistically detecting an amount of pulsars in a cluster (47 Tucanae) that can not be individually resolved because of their low flux. The method involves forming a low resolution image of the core of a cluster, that has a beam that is matched with the expected spatial distribution of pulsars, and so will see unresolved pulsars as an extended component, and subtracting those pulsars that are in the process of scintillating. From this, we find typically $\sim 500\mu$Jy contributed from easily resolved pulsars, and another ~ 400 from unresolved pulsars, suggesting there are 10 times as many pulsars 10 times less luminous than the 4 visible on most days - ie, at least 40 more pulsars in 47 Tuc.

1 Introduction

Timing solutions have given the position[2] and flux[1] of 15 pulsars in 47 Tuc (all millisecond pulsars), out of the 20 pulsars listed in those papers, and this represents the current level of sensitivity, with all of the pulsars being only visible during periods of interstellar scintillation (5 more are occasionally visible but are not yet located because of their rare appearance or binary orbit). We can expect perhaps 200 more pulsars[1] in 47 Tuc, if the luminosity distribution is similar to the galactic distribution of millisecond pulsars, which is given by

$$dN = L^{-1} d \log L \tag{1}$$

From this, for every lower decade of flux, there will be 10 times more pulsars, up to a cutoff (since the integral of pulsar count diverges for no cutoff). We should expect that they are spatially distributed in the same way, independent of luminosity.

Camilo et al[1] gave mean fluxes for the 15 located pulsars, using timing measurements from the 64m Parkes telescope, and the flux totals to 2.06 mJy. We assume that the flux of the 5 other unlocated pulsars are going to be small compared to this, and so if there are 200 pulsars, there will be about 4 mJy in the extended component, and 2 mJy from the as yet undetected pulsars.

We suggest that imaging the core of the cluster with the ATCA, with a suitably compact array (for a large synthesised beam), we should be able to see the group of pulsars as a single extended component, and be able to remove the effects of background sources and those bright pulsars that may be in a process of scintillating.

2 Observations and data analysis

All data analysis was performed using the Miriad package. The observations were done at 1408 and 1708 MHz, with a bandwidth of 128MHz using the usual ATCA setup, although only the 1408 MHz data is used here. All data was collected from the ATCA, with the timing positions presented by Camilo et. al.[2] from the Parkes 64m telescope being used to identify the pulsars that we remove later.

The cluster was imaged in a number of different configurations (table 1), over many days. The 1.5 and 6km array data, that are not sensitive to the extended component of the unresolved pulsars, were mosaiced together to form a sensitive high resolution image of the core[3]. The 375 and 750m arrays were combined to form a low resolution image of the core and was well matched with the spatial distribution of the known pulsars.

Table 1: Observing configurations. Field centre 0:24:06.00,-72:03:00.00 (J2000)

Observation date	99-Feb-12 — 99-Dec-31	99-Jan-25	00-May-08	00-Dec-23	00-Dec-25	00-Dec-27
Configuration	many: 1.5A, 1.5B, 6A, 6C, 6D	750B	375	750C	750C	750C
Image type	Large array for high res image	5 antennae for extended sources, 6th for removal of bright pulsars				
Comments	Many days combined to make a very high res image with very high S/N of $28\mu Jy$	Because of maintenance, 3rd antenna missing for most of day, and many faults during observing ⇒ only 4 antennae left. Data unused currently				Loss of several hours because of error and thunderstorm

An attempt was made to verify, using UVGEN, that a source with characteristic size of the pulsar distribution half width of 70"[2] would not be attenuated appreciably by the $\sim$ 60" beam size of the 375/750 data. This work is incomplete.

A self-calibration of the low resolution image using itself as a model would be extremely difficult, since there are only 5 antennae that are used to form the small baselines. The individual small array images were self calibrated (for amplitude and phase) using GPSCAL, with the model being McConnell and Ables' (2000) 6km mosaic. This might have the side-effect of decreasing the amplitude of anything that does not appear in the 6km mosaic - which would include the extended flux we are searching for.

Subtracting the point sources in the high resolution image should leave us with the extended component we are looking for in the low resolution image (as well as some sources that vary between the observations). Because McConnell and Ables' (2000) 6km mosaic has modelled the point sources well, we can subtract them from the UV data, removing both the sources and their sidelobes from the image. We do this by forming the UV data for the smaller arrays individually, and subtracting the clean components of McConnell and Ables' (2000) mosaic formed by using the 1.5 and 6km arrays, using UVMODEL. Because this will remove the pulsars that appear in McConnell and Ables' (2000) high resolution mosaic (ie, those ones that are bright enough for a few of the observations), we mask the clean image first, using MATHS, to exclude the pulsars (and anything else within 130" of the core), and assume that anything that appears within this mask and is similar in all the days observations is a background source, so remove those manually from the low resolution data.

Each of the pulsars scintillate, and some are quite dramatic - if one happens to be bright on any one day, then we may falsely conclude that we have found the extended flux, when the extra flux really belongs to a single pulsar, and not 200 of them. Hence, we form an image using just the antenna 6 baselines (hence the UV coverage is poor, with only $\sim$ 6km baselines) for each day, and IMFIT to each of the sources that are both above 3σ, and that correspond to one of the already known and located pulsars. The sources were both modelled as point sources, and Gaussian (since they may vary within the day's observation, due to scintillation), but the difference between the two was minimal, so the point source method was chosen for simplicity. We assume that the pulsars we do not know about never get bright enough to skew our extended flux measurements significantly. Since the 6km baseline image is hard to calibrate because of the lack of good UV coverage, we assume that the two background sources near the core are reasonably constant, and scale the pulsars by an amount that scales the brightest of these 'calibrators' to the level obtained in the McConnell and Ables' (2000) 1.5/6km mosaic. The scaled fluxes from the pulsars are then subtracted from the UV data from each individual day, again with UVMODEL, and a combined image is again formed. This image should now only contain the extended component due to the unresolved pulsars in the centre, with the main sources of noise being low level confusion.

3 Results

The two sets of data (high resolution 1.5/6km arrays, and low resolution 375/750m arrays) were combined and imaged, and appear on the same scale in figures 1 and 2. It is apparent already that there are some extended sources in the field of the core, in particular the two bright sources near the top left corner, and these do not become subtracted completely, later on.

From each day, the 6km only baselines were individually imaged, and one (2000-Dec-27) appears in figure 3. Evident are the two constant sources (labelled 142 and 178), and 4 pulsars. The only contour is at 3σ, so most of the random points are noise, but some may be scintillating pulsars. The central circle (radius 23") is the size of the core of the cluster.

Table 2 lists each of the pulsars, and the two constant sources (source 142 and 178) fluxes, and the scaled value. Since source 142 is 643μJy in the high resolution map, we scale it to be 643μJy on all days, and all the others as appropriate. Source 178 is similarly always left (ie, not scaled) as the 226μJy that is was in the high resolution map.

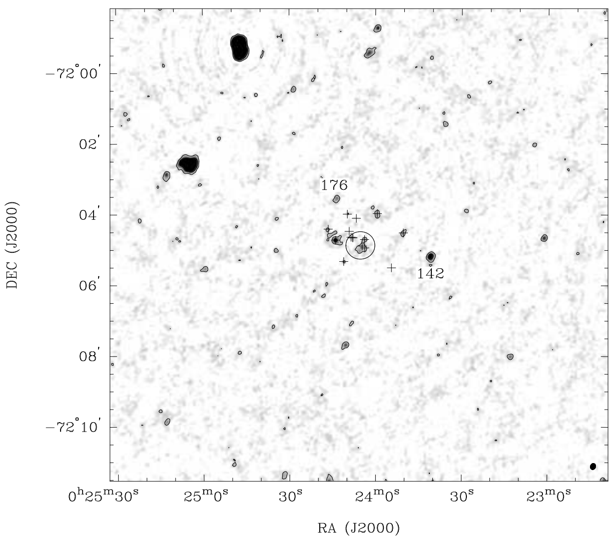

Figure 1: McConnell and Ables' (2000) 1.5 and 6km array image, at 1408MHz, with a 8×10" synthesised beam. The RMS noise level is 28μJy, the contours are at 3, 12 and 48σ, and the range is from 0 - 0.4 mJy. The central circle is the size of the core at 23".

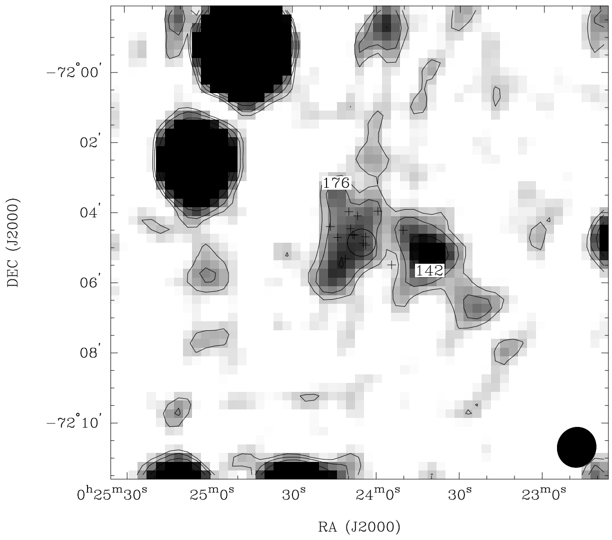

Figure 2: A mosaiced 375 and 750m array image, at 1408MHz, with an approximate 63×68" beam, and a RMS noise level of 35μJy. The contours are at the same level as figure 1, so are at ~ 2.5, 10, 40σ, and the range is from 0 - 0.4 mJy.

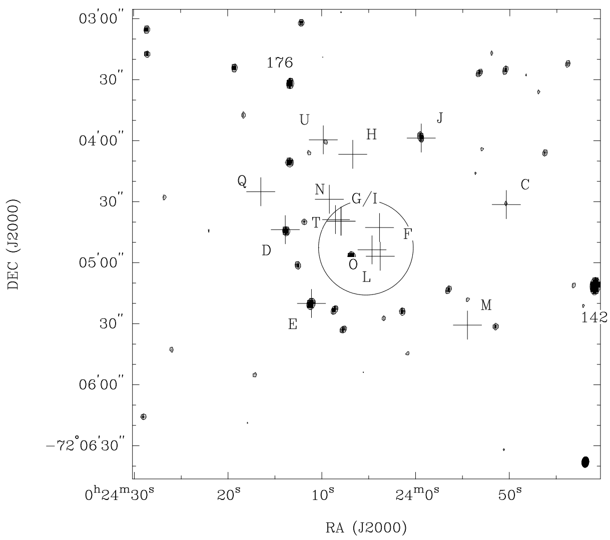

Figure 3: Image constructed using only antenna 6 baselines from the 750C configuration on the 2000-Dec-27. The RMS in the image was 50μJy, but the image quality was quite poor because of the lack of UV coverage, and poorly calibrated. The only contour is at 3σ, and the range is from 150 to 200μJy. Most of the points above the contour are noise, but those points that corresponded to a known pulsar (within a small proportion of the synthesised beam) that were above 3σ were modelled by point sources.

Due to persistent problems during the 1999-Jan-25 observation, culminating in the loss of one antenna for most of the day, this data had to be discarded.

It is seen in table 2, that some of the mean fluxes from the antenna 6 baselines are a lot lower than Camilo et. al.[1] claim (particlularly pulsar J), and this is as yet unexplained.

Subtracting the point sources in the masked high resolution image, the two constant sources manually, and the 4 significant pulsars from the 2000-Dec-27 data yields the image in figure 4. The process was repeated for the other days, and the result was combined to yield figure 6. The combined image was also produced without subtracting the pulsars in figure 5 - only subtracting the two constant sources. The integrated flux within the core of figure 5 is only $810 \pm 60\mu$Jy, which is much lower than the expected 4mJy. Similarly, after subtracting the pulsars to give figure 6, we are left with much lower than the 2mJy expected - only $415 \pm 60\mu$Jy. The errors quoted are the image RMS (fitted using IMSAD from the region surrounding the core). Note that this error is typically 3 times larger, for all the images created in this analysis, than the theoretical RMS quoted by INVERT, and the difference is attributed to image confusion.

Table 2: Fluxes of each resolved pulsar. The lack of data for the 2000-Dec-25 is because of observing problems - this data is as yet unused. The column labelled "Only 6km" is the raw fitted (for a point source) flux from the individual 6km baseline map, and "Rescaled" is after the source 142 is scaled to be the same as in McConnell and Ables' (2000) 6km mosaic (643μJy)

	Source/ Pulsar name	**Camilo et. al.[1] flux**	**Observation Date**									
			99-Jan-25		**00-May-05**		**00-Dec-23**		**00-Dec-25**		**00-Dec-27**	
			Only 6km	Rescaled	Only 6km	Rescaled	Only 6km	Rescaled	Only 6km	Rescaled	Only 6km	Rescaled
Flux (μJy)	142				564	**643**	839	**643**	761	**643**	715	**643**
	178				285		218		270		313	
	C	360					172	132	202	171	178	160
	D	220			244	278	311	238			285	256
	E	210									365	328
	F	150							318	268		
	J	540							175	148	268	241
	Q	50					287	220				

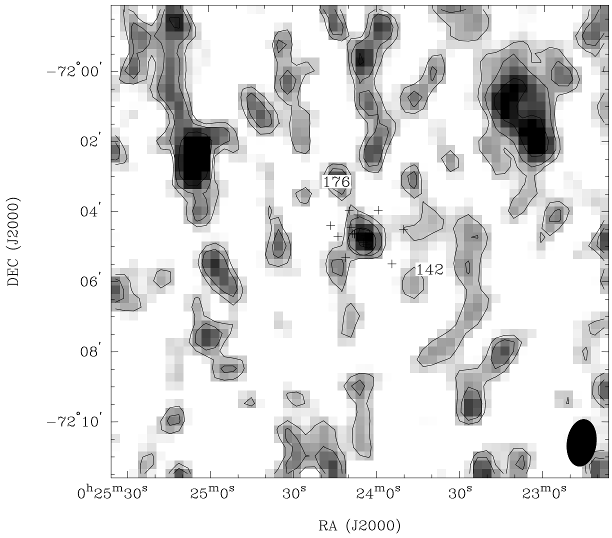

Figure 4: Image from 2000-Dec-27 that shows both the pulsars and the two constant sources, 142 and 178, removed. This then forms part of the image in figure 6. The range is from 0 to 400μJy, and the contours are at 3, 6, 12, 24 $\ldots\times$ the RMS from figure 1. Since the RMS of this image is 50μJy, the contours are at 1.7, 3.4, 6.8σ. The peak of the core in this image is 380μJy.

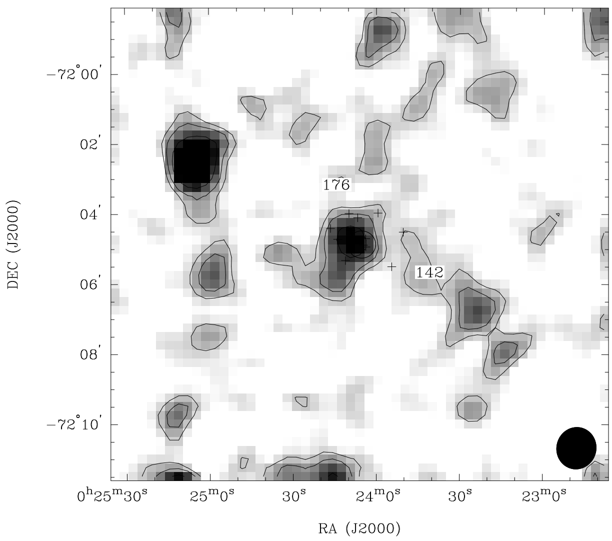

Figure 5: This is all the days data combined, with all point sources away from the core, and the two constant sources, 142 and 178 subtracted, but the pulsars left intact. The contours are at 3, 6, 12, 24 $\ldots\times$ the RMS from figure 1. Since the RMS of this image is 60μJy, the contours are at 1.4, 2.8, 5.6 $\ldots\sigma$. The range of the image is 0 to 400μJy. The peak of the core in this image is $530\pm60\mu$Jy/beam, and the integrated flux is $\sim$ 810Jy (fitted for gaussian)

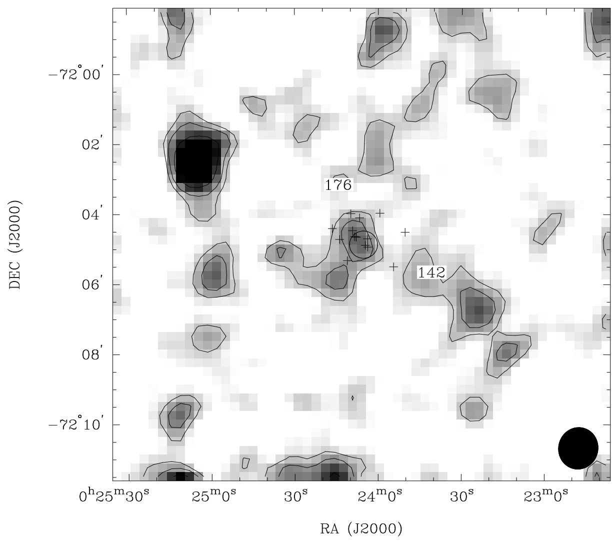

Figure 6: This is all the days data combined, with all point sources away from the core, the two constant sources, 142 and 178, and the pulsars, subtracted. The contours are at 3, 6, 12, 24 $\ldots\times$ the RMS from figure 1. Since the RMS of this image is 60μJy, the contours are at 1.4, 2.8, 5.6 $\ldots\sigma$. The range of the image is 0 to 400μJy. The peak of the core in this image is $280\pm60\mu$Jy/beam, and the integrated flux is $\sim$ 415μJy (fitted for Gaussian)

4 Discussion

The image with all pulsars still present (figure 5) shows that we do not even measure all of the flux from the known pulsars - let alone any extra from the unresolved pulsars. This is unexplained, but once the bright pulsars are also subtracted (figure 6), there is a similar amount of flux from the unresolved pulsars, to those visible on any one day.

The most obvious cause of the loss of flux, is in self calibration - when calibrating for amplitude and phase, any object not appearing in the model will be scaled down. The possibilities for self-calibration are to use the 6km image as a model, and calibrate for phase only, or to calibrate for amplitude as well, making sure that the rms gain is not scaled to unity. A final alternative is to form a smaller image (because of computational requirements) using the 6th antenna for each day (or for all days combined), that will suffer because of poor UV coverage, and using that as a model in self-calibrating each day. This may have the benifit of including at least some more flux from the core, because of the presence of smaller baselines than those in the McConnell and Ables' (2000) 6km mosaic. The results from testing the peak and approximate integrated flux from each of these methods is in table 3, but since this work is incomplete, some of the methods are from a previous non-optimised mosaic (without the pulsars subtracted), and

Table 3: Peak and integrated flux from different methods of self-calibration.
1: no calibration.
2: Selfcalibration, phase only, model: McConnell and Ables (2000).
3: Amplitude and phase, MIRIAD: OPTIONS=NOSCALE.
4: Amplitude and phase, model: smaller image containing 6th antenna

Calibration and flux measurement on	**Calibration Type**	**Peak flux (μJy/beam)**	**Integrated flux(μJy)**
all days combined	1	515	893
all days combined	2	422	622
all days combined	3	347	703
only 2000-Dec-27	3	465	525
only 2000-Dec-27	4	482	605

some are from only one day (2000-Dec-27).

It is clear that we would not have so much "missing" flux, if a self-calibration was performed on each day, using the full 6 antennae from that day, and so this will be used in the future. One problem faced is that there is a lack of good UV coverage, so this process will not necessarily be trivial.

Incorrect flux measurements from Camilo et. al. (2000) cannot be ruled out either - if their fluxes are systematically higher, we can not expect to measure an extended component equal to the sum of pulsar fluxes for the 15 measured pulsars.

Even though we do not see all the flux from the known pulsars, we do see some extra flux once the resolved ones are subtracted, that indicated we are seeing some of the extended component we are looking for, although it is may not be equal in intensity to the resolved pulsars listed in Camilo et. al, 2000, depending on the sucess of the self-calibration method proposed above. Some possible mechanisms for there not being the expected unresolved flux are summarised below.

Equation 1 implies a power law with index -1. If this is not correct, and the exponent is actually more negative, then there will not be as much flux in the lower luminosity decade, and there will be less extended flux. This is also a more elegant solution than having a low luminosity cutoff around $L_{400} \sim 1$ mJy kpc^2[1].

If for some reason, the fainter pulsars are systematically more spread out than the sudden $3r_c$ boundary for the brighter pulsars[2], and are distributed far enough that synthesised beam of $\sim$ 60" attenuates the integrated flux appreciably, then the flux due to the decade of low luminosity pulsars will be less than the decade of higher luminosity pulsars, although a physical reason for any possible difference in distribution has not been discovered.

One promising sign is that it seems (within the error caused by noise in the images) that the integrated flux of the core once the pulsars visible on each day are subtracted, is half that of the total flux before subtraction. If indeed, we are seeing all the flux present, and the fluxes listed in Camilo et. al. are wrong, then there is a good chance the prediction of roughly 10 times more pulsars (whose beam is in our direction) being present in 47-Tuc than we currently resolve is correct - ie perhaps more than 40, since we see up to 4. Care needs to be taken however, since there may be other sources near the core that are not pulsars, and weren't subtracted, that may influence the fitting, particularly since the fit was not for a point source.

References

[1] Camilo, F., Lorimer, D.R., Freire, P., Lyne, A.G. and Manchester, R.N. 2000, ApJ, 535, 975

[2] Freire, P.C., Camilo, F., Lorimer, D.R., Lyne, A.G., Manchester, R.N. and D'Amico, N. 2000, MNRAS, submitted.

[3] McConnell, D., Deacon, R., Ables, J.G. 2000, PASA, submitted.