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DISCOVERY OF THREE NEW MILLISECOND PULSARS IN TERZAN 5

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ABSTRACT

We report on the discovery of three new millisecond pulsars (namely J1748−2446aj, J1748−2446ak and J1748−2446al) in the inner regions of the dense stellar system Terzan 5. These pulsars have been discovered thanks to a method, alternative to the classical search routines, that exploited the large set of archival observations of Terzan 5 acquired with the Green Bank Telescope over 5 years (from 2010 to 2015). This technique allowed the analysis of stacked power spectra obtained by combining $\sim$ 206 hours of observation. J1748−2446aj has a spin period of $\sim$ 2.96 ms, J1748−2446ak of $\sim$ 1.89 ms (thus it is the fourth fastest pulsar in the cluster) and J1748−2446al of $\sim$ 5.95 ms. All the three millisecond pulsars are isolated and currently we have timing solutions only for J1748−2446aj and J1748−2446ak. For these two systems, we evaluated the contribution to the measured spin-down rate of the acceleration due to the cluster potential field, thus estimating the intrinsic spin-down rates, which are in agreement with those typically measured for millisecond pulsars in globular clusters. Our results increase to 37 the number of pulsars known in Terzan 5, which now hosts 25% of the entire pulsar population identified, so far, in globular clusters.

Keywords: Pulsars: Individual: J1748−2446aj, J1748−2446ak, J1748−2446al, Globular clusters: Individual: Terzan 5

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1. INTRODUCTION

Globular clusters (GCs) are the ideal factories for the formation of millisecond pulsars (MSPs): old and rapidly spinning neutron stars formed in a binary system through mass and angular momentum accretion from an evolving companion star (e.g. Alpar et al. 1982; Bhattacharya & van den Heuvel 1991). In fact, the large stellar densities in the cores of GCs favor dynamical interactions, such as exchange interactions and tidal captures, which can lead to the formation of a large variety of binary systems whose evolution generates stellar exotica like blue stragglers (e.g. Ferraro et al. 2009, 2012), low-mass X-ray binaries (e.g. Pooley et al. 2003), cataclysmic variables (e.g. Ivanova et al. 2006) and MSPs (e.g. Ferraro et al. 2001, 2003; Lorimer et al. 2003; Ransom et al. 2005; Hessels et al. 2007; Pallanca et al. 2014; Cadelano et al. 2015). As a consequence, the number of MSPs per unit mass in GCs turns out to be $\sim 10^3$ times larger than in the Galactic field. Furthermore, dynamical interactions could be also responsible for the production of exotic MSP systems, such as double MSP binaries and black hole - MSP binaries (e.g. Freire et al. 2004; Verbunt & Freire 2014), thus making GCs - particularly those with the denser cores - intriguing sites where to perform deep pulsar searches in the future.

To date, 146 MSPs are known in 28 GCs[1] but probably a very large population of several thousand MSPs is still to be unveiled (Bagchi et al. 2011; Chennamangalam et al. 2013; Turk & Lorimer 2013; Hessels et al. 2015). The number of MSPs identified in GCs per year decreased abruptly after 2011, thus showing the limit in performance and sensitivity reached by the current generation of radio telescopes. However, for more than one decade, GCs have been routinely observed at radio wavelength in order to obtain long term timing solutions of the identified MPSs. This resulted in the production of a large archive of tens of observations of the same region of the sky. The work presented here is aimed at showing the large possibilities of finding new pulsars by exploiting these huge archival data sets. At odds with traditional pulsar searches, which are based on the analysis of a single and long time sequence of data, we present here a method to search for pulsars by incoherently stacking the power spectra obtained from all the available observations. A similar procedure has been already successfully implemented in M15 by Anderson (1993), in Terzan 5 by Sulman et al. (2005), leading to the discovery of three isolated MSPs (namely J1748−2446af, J1748−2446ag and J1748−2446ah), and in 47 Tucanae by Pan et al. (2016), leading to the discovery of two additional pulsars in the cluster. All these pulsars are isolated. Indeed, due to the Doppler shifts of the spin frequency induced by the pulsar motion in binary systems, this method is only effective for discovering isolated pulsars or long period binary pulsars, the latter being less likely to survive in GCs because of stellar encounters.

Among the Galactic GCs, Terzan 5 turned out to be the prolific amazing MSP factory. In fact, 34 MSPs have been identified so far in this system (Ransom et al. 2005; Hessels et al. 2006; Prager et al. 2017, Ransom et al. 2018, in preparation), which is about $\sim 23\%$ of the total number of MSPs identified in GCs. Terzan 5 is, indeed, one of the most intriguing stellar systems in the Galaxy. Ferraro et al. (2009, 2016) found out that this system is probably not a genuine GC, but more likely the pristine remnant of a building block of the Galactic bulge, which was originally much more massive than today (Lanzoni et al. 2010).

Here we present the identification of three new MSPs in Terzan 5. In Section 2 we present the dataset and the stacking procedures that led us to the discovery of the new MSPs. In Section 3 we describe the main properties of these new systems and their timing solutions while in Section 4 we constrain some of their physical parameters. Finally we summarize and draw our conclusions in Section 5.

2. OBSERVATION AND DATA ANALYSIS

2.1. *Dataset and initial data reduction*

The work presented here has been performed by using 33 archival observations of Terzan 5 obtained with the 100-m Robert C. Byrd Green Bank Telescope (GBT) from August 2010 to October 2015. Observations were acquired at 1.5 GHz (L-band) and 2.0 GHz (S-band) using 800 MHz of bandwidth, although radio frequency interference (RFI) excision reduced the effective bandwidth to $\sim$ 600 MHz. Only one observation was obtained at 820 MHz using 200 MHz of bandwidth. Observation lengths vary from a minimum of 1.5 hours to 7.5 hours, the latter typical for the majority of the observations. Overall we have 1 observation obtained at 820 MHz with observation length of 7.3 hours, 20 observations obtained at 1.5 GHz with a total length of about 135 hours and, finally, 12 observations obtained at 2.0 GHz with a total observation length of about 64 hours. The total observation length, resulting from the stack of all these observations, is of about 9 days ($\sim$ 206 hours).

The data recorded by GUPPI were Full Stokes with 10.24 μs sampling and 512 channels, each coherently dedispersed in hardware to a DM of 238 pc cm^{-3}, which

[1] see http://www.naic.edu/~pfreire/GCpsr.html

is close to the cluster average. The total intensity (i.e. sum of two orthogonal polarizations) was extracted from those data and downsampled to 40.96 μs resolution for incoherent dedispersion into 23 DM trials.

The data have been processed using the PRESTO software suite (Ransom et al. 2002). We obtained 22 time series per observation ranging from a DM of 233 pc cm^{-3} to 244 pc cm^{-3} and spaced by 0.5 pc cm^{-3}, plus an additional time series at a control DM of 100 pc cm^{-3}. The time series have been transformed to the barycenter of the solar system using TEMPO[2] (Manchester et al. 2015). For each sample of the time series of each observation, we subtracted the mean of all the channels (i.e. we subtracted the DM=0 pc cm^{-3} time series) and excised some interference by removing samples with values higher than 4σ, where σ is the standard deviation of all the sample values. Since we aim at stacking together the power spectra of observations of different lengths, we manually added samples with null values to the time series of shorter length, thus obtaining time series of length equal to that of the longest one. We then applied a fast Fourier transform to all the time series and squared the complex amplitudes to obtain the power spectra. Finally, in the power spectra, we ignored all the spectral bins expected to contain the powers of all the known Terzan 5 pulsars and their harmonics (also accounting for the shifts due to the binary pulsar orbital motions). We also excised the most relevant RFI, identified by visual inspection of the power spectra.

2.2. *Stacking search procedures*

First of all, we normalized all the available power spectra dividing the spectral powers by the local median value. Then, we summed the 33 individual daily power spectra into a stacked power spectrum for each of the 22 DM trials and the control DM. These final stacked power spectra are nearly chi-squared distributed with 66 degrees of freedom. In all these stacked spectra, we performed an harmonic sum, by summing to each power bin the powers of the corresponding harmonic, from the second up to the eighth. This has been done to further enhance the spectral powers of the still unidentified pulsars. At the end of this, we had 22 stacked power spectra, plus the one at the control DM. In order to further remove periodic interference that can be still persistent in high DM spectra, we subtracted from each stacked power spectrum the control stacked spectrum obtained at DM=100 pc cm^{-3}. In this way, a large fraction of RFI, present in both the control and the science power spectra, are removed, leaving the signal of the still undiscovered pulsars virtually unaffected.

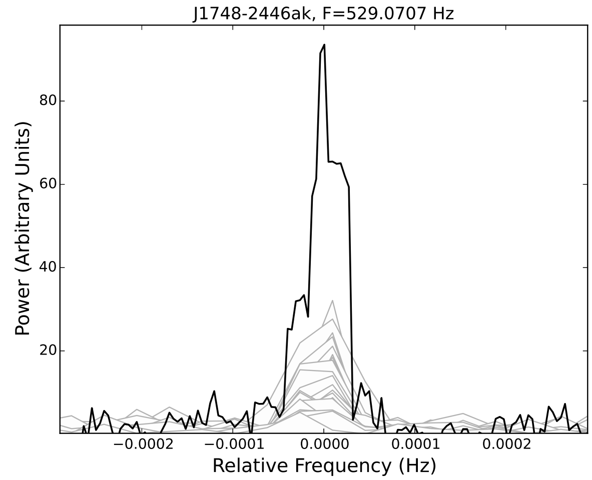

Figure 1. Power spectrum around the region of the newly discovered MSP J1748−2446ak (Ter5ak). We plotted in black the stacked and harmonic summed power spectrum obtained from $\sim$ 215 hours of archival observations, while in shaded gray we plotted the power spectra obtained from the single daily observations. The power in the stacked spectrum is spread over more bins than for single observations due to the effect of the harmonic sum.

In order to illustrate the effectiveness of the method, in Figure 1 we compare the stacked power spectrum for one of the newly discovered MSPs, with that obtained from a single observation where this MSP has a high signal to noise ratio. It can be clearly seen how the stacking procedure greatly enhances the spectral powers of such a faint object.

The next step is to select, in the stacked power spectra, the periodic signals that likely originate from a real pulsar instead of from RFI. To do this, we selected in the power spectra all the peaks above 4.5σ (σ is the standard deviation of the spectral powers) and saved them into a candidate file. We ended up with 22 candidates files, one per DM, each one containing $\sim$ 13000 candidate. Therefore the total number of candidates is about 3×10^5. We then applied a KD-tree algorithm to perform a selection of all these candidates. KD-trees are space-partitioning data structures used to organize points in multidimensional spaces and thus useful to perform pulsar searches in these spaces by implementing optimization problems such as the nearest neighbor search. In fact, in the DM-frequency phase space, pulsar candidates are expected to be closely segregated around their DM and spin frequency. On the other hand, RFI can appear in a large range of DMs, also with slightly different spin frequencies. We used the KD-tree routine included in the Scipy

[2] http://tempo.sourceforge.net

package[3]. Briefly, we built a 2D tree in a DM-frequency space. Then, for each candidate, we searched for the 1000 closest neighbors and selected only those with a spin frequency compatible (within a tolerance of 10^{-5} Hz) with that of the candidate. Since the pulsar signal is expected to be observed at contiguous DM values with an almost Gaussian distribution of powers around the true DM value, we selected as good candidates only those whose closest neighbors are found at contiguous DMs and with a maximum in the spectral power vs DM space. As an example, we show in Figure 2 the output of the KD-tree procedure for the case of the known MSP J1748−2446C (Ter5C). As can be seen, the algorithm found, for a candidate corresponding to Ter5C, neighbors at contiguous DMs, with a peak in the spectral powers very close to the MSP's true DM value. Moreover, the spin frequency does not show any variation at different DMs, as expected from a real pulsar. The same plot for the newly discovered pulsar Ter5aj is presented in Figure 3. Applying this procedure to our candidates, we discarded $\sim$ 97% of them and ended up with only $\sim$ 100 possible pulsar candidates, most of them close to the chosen threshold of 4.5σ. These have been individually analyzed, folding the single observations at the candidate frequency and DM corresponding to that of the maximum spectral power, allowing also a search in spin period, spin period derivative and DM in order to maximize the signal to noise ratio. The vast majority of the candidates turned out to be residual RFI, usually very bright only in few observations. Other candidates did not revealed any clear broadband pulsated signal across the observations and thus they have been discarded. We considered as genuine pulsars only those candidates that revealed a clear pulsated signal in more than one observation.

3. RESULTS

The method described in the previous section allowed us to discover three previously unknown MSPs in Terzan 5: J1748−2446aj, J1748−2446ak and J1748−2446al (hereafter, Ter5aj, Ter5ak and Ter5al, respectively). We plot in Figure 4 the average pulse profiles and the signals as a function of time for these three new MSPs in the brightest individual days. Moreover, we have been able to blindly re-detect all the other isolated MSPs known in the cluster[4].

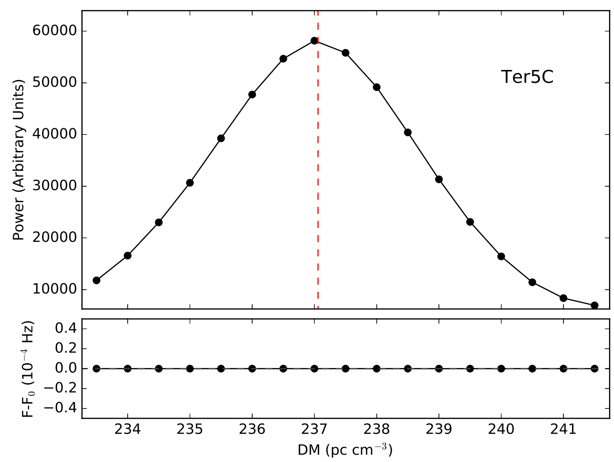

Figure 2. *Top panel:* Spectral powers of a candidate pulsar, corresponding to J1748−2446C (Ter5C), obtained from the stacked power spectra. The powers are plotted as a function of the DM as obtained from the KD-tree algorithm (see text). The red dashed vertical line is the MSP true DM as derived from its timing solution (Ransom et al. 2018, in preparation). *Bottom panel:* spin frequency difference across the different DMs in which the candidate has been found. In this case, the candidate has the same frequency in all the DMs, as expected from a real pulsar.

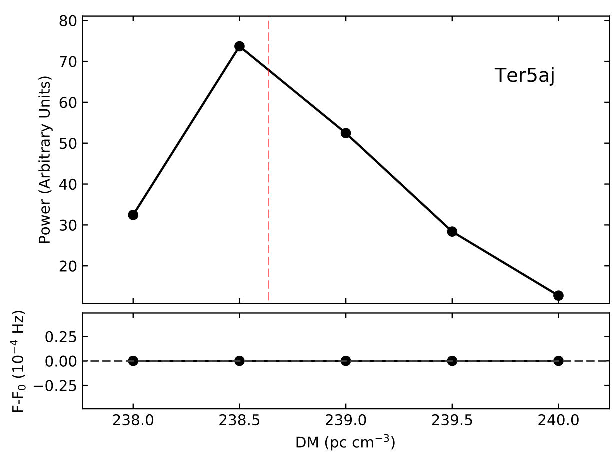

Figure 3. Same as in Figure 2 but for the newly discovered pulsar Ter5aj.

3.1. *Ter5aj*

Ter5aj has been discovered with a maximum spectral power at DM = 238.50 pc cm^{-3} (see Figure 3). Folding the single observations, we have been able to clearly identify it and confirm its pulsar nature in all the 33 GUPPI observations. As can be seen from the left panel of Figure 4 (see also the top panel of Figure 5), Ter5aj

[3] https://docs.scipy.org/doc/scipy-0.18.1/reference/generated/scipy.spatial.KDTree.html#scipy.spatial.KDTree

[4] To do this and to obtain the top panel of Figure 2, we re run the whole procedure without excising the signal of the known pulsars.

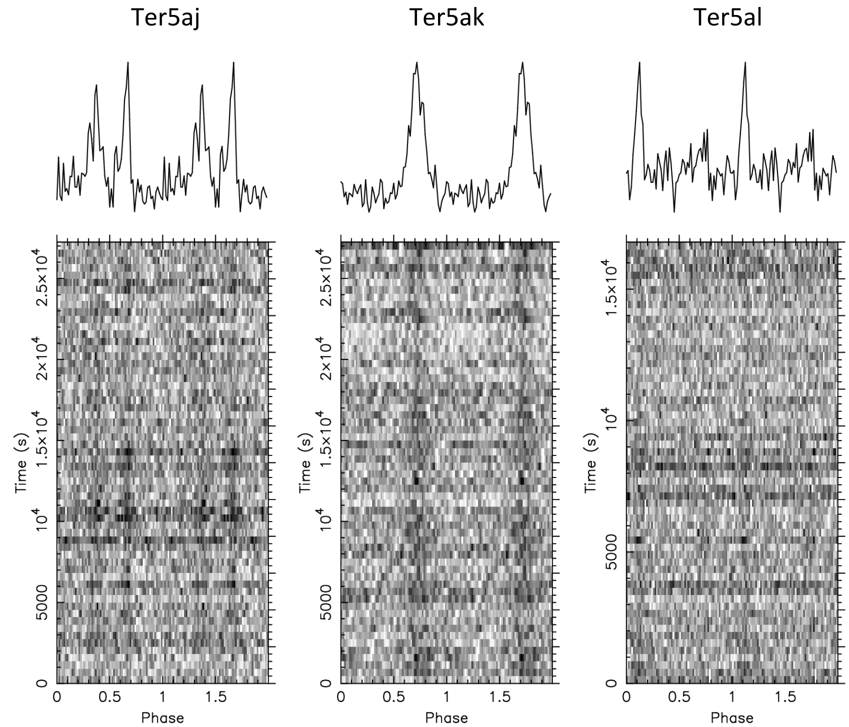

Figure 4. *Top panels:* Averaged pulse profiles of the best detections of Ter5aj (on the left), Ter5ak (in the middle) and Ter5al (on the right). *Bottom panel:* Intensity of the signal (gray scale) as a function of the rotational phase and time for each MSP.

presents a double peaked pulse shape, where the two peaks are separated by ~ 0.3 in phase. We extracted the pulse times of arrival (TOAs) with the `get_TOAs` routine within PRESTO, using a double Gaussian template, created by fitting the pulses obtained in the observations where this object has the highest signal to noise ratio (see left panel of Figure 4). We obtained one TOA per epoch for all the observations but those showing very good detections from which we have been able to obtain multiple TOAs. We phase connected all the ~ 6 years of data using standard procedures with TEMPO. An extra free parameter, called EFAC, has been included to account for underestimations of the TOA uncertainties (and therefore underestimations of the derived parameter uncertainties), thus obtaining a reduced $\chi^2 = 1.00$. The timing solution is tabulated in Table 1, the post-fit timing residuals are reported in the top panel of Figure 6 and the averaged pulse profile, obtained by summing all the daily detections, is reported in the top panel of Figure 5.

Ter5aj is an isolated MSP with a spin period of 2.96 ms and a DM = 238.63 pc cm^{-3}, very close to the cluster mean value. It is located 10.4$''$ north from the cluster gravitational center (Lanzoni et al. 2010, see Figure 7). Its spin period derivative is partially contaminated by the effect of the MSP motion in the cluster potential field. We will analyze this in more detail in Section 4.

We roughly estimated the pulsar mean flux density using the radiometer equation (see Appendix A1.4 of Lorimer & Kramer 2004) on daily detections, using a system equivalent flux density (SEFD) of 12.5 Jy, appropriate for the observations we used. The values so obtained have been calibrated by comparison with those obtained applying the same method to other three isolated MSPs (namely Ter5R, Ter5S and Ter5T), for which measurements made referencing a flux calibrator are available (Ransom et al. 2018, in preparation). The average values of both the L-band and S-band flux densities are reported in Table 1. The typical flux density of this object is of the order of that measured for the other faint isolated MSPs of this cluster (Ransom et al. 2018, in preparation).

3.2. *Ter5ak*

Ter5ak has been discovered with a maximum stacked spectral power at DM = 236.50 pc cm^{-3}. The pulsar nature of this candidate has been confirmed by folding the single observations, where it turned out to be visible in almost all of them. We managed to obtain a full timing solution for this object using similar methods described for Ter5aj, except that we obtained the initial timing solution using the TEMPO based phase-connection routine available at https://github.com/smearedink/phase-connect, to be described in Freire

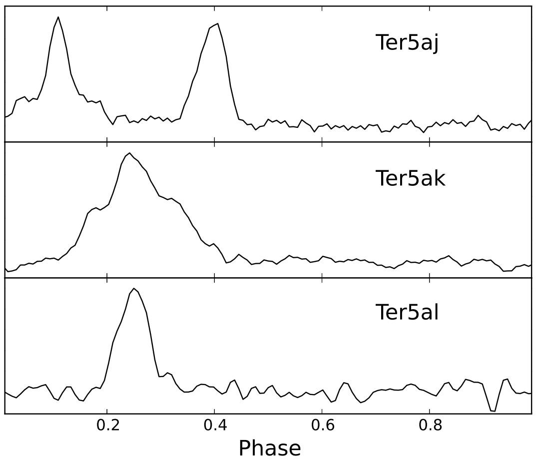

Figure 5. Averaged pulse profile of Ter5aj (top panel), Ter5ak (middle panel) and Ter5al (bottom panel), obtained by coherently summing all the GUPPI detections of the MSPs obtained at a central frequency of 1.4 GHz. The total integration time is of about 135 hours.

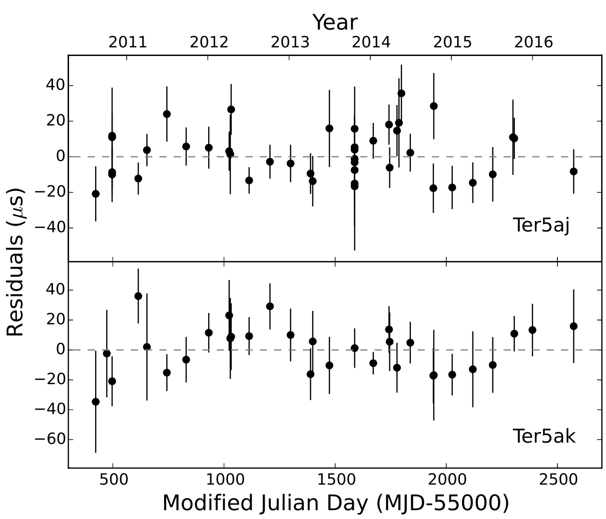

Figure 6. Timing residuals for Ter5aj (top panel) and Ter5ak (bottom panel).

& Ridolfi, in preparation. The timing solution is tabulated in Table 1, the post-fit residuals are reported in the bottom panel of Figure 6 and the averaged pulse profile in the middle panel of Figure 5.

Ter5ak is also an isolated MSP and it has a spin period of ~ 1.89 ms, hence it is the fourth fastest MSP in Terzan 5 and the fifth fastest among all the GC pulsars. Its DM of 236.707 pc cm^{-3} is well within the range covered by the other pulsars in the cluster. Its position with respect to the other cluster MSPs is reported in Figure 7, where it can be seen that it is located at about $17.4''$ east from the cluster center. As for Ter5aj, its spin period

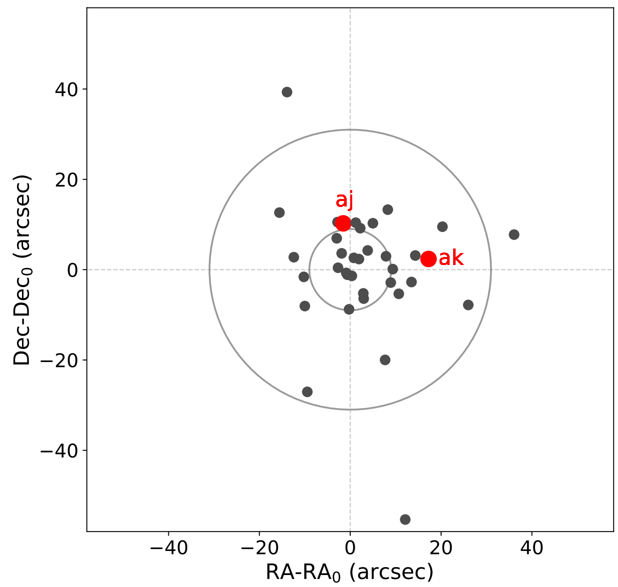

Figure 7. Positions of Ter5aj and Ter5ak with respect to the cluster gravitational center and to the other MSPs in the cluster. The inner and outer circles are the cluster core and half mass radius, respectively (Lanzoni et al. 2010).

first derivative is clearly contaminated by its motion in the cluster potential field (see Section 4). The average flux density is also in this case of the order of that of the faintest isolated MSPs of this cluster.

3.3. *Ter5al*

Ter5al is the last MSP identified in our analysis, with a weak spectral power peaked at DM = 236.50 pc cm^{-3}. We have been able to reveal this object in only ~ 20 observations, being under the detection limit in all the others. In the right panel of Figure 4, we report the detection plot of the observation where Ter5al has the highest signal to noise ratio. To date we have not been able to obtain a timing solution for this system, likely because of the insufficient number of good detections. In the ~ 20 detections we found no evidence of acceleration, thus it is likely another isolated system. Ter5al has a spin period of ~ 5.95 ms. We determined its DM by measuring the pulse TOAs in different sub-bands of the two brightest L-band observations and we found DM = 236.48(3) pc cm^{-3}.

The averaged pulse profile is reported in the bottom panel of Figure 5. This pulsar turns out to be extremely faint. Indeed its average flux density is of only $\sim 8 \mu Jy$ in L-band and $\sim 6 \mu Jy$ in S-band, making this pulsar the faintest in the cluster and also explaining the small number of good detections.

4. ACCELERATIONS AND PHYSICAL PARAMETERS

In this section we derive some constraints on the accelerations and on the main physical parameters of Ter5aj and Ter5ak, the two new MSPs for which we have been able to obtain a timing solution.

For the case of MSPs in GCs, the measured spin period derivative ($\dot{P}_{meas}$), derived through timing, does not represent a direct measurement of the MSP intrinsic spin-down, since it is the combination of different contributions (see, e.g., Phinney 1993). Indeed, any motion of a pulsar with respect to the observer produces a change of the observed spin period. In the case of GCs, the MSP motion in the cluster potential field induces a change that can be large enough to match or even exceed the value due to the intrinsic spin-down. Following Phinney (1993), $\dot{P}_{meas}$ can be written as follows:

$$\left(\frac{\dot{P}}{P}\right)_{meas} = \left(\frac{\dot{P}}{P}\right)_{int} + \frac{a_c}{c} + \frac{a_g}{c} + \frac{a_s}{c} \qquad (1)$$

where $\left(\dot{P}/P\right)_{int}$ is the ratio between the intrinsic spin-down and the pulsar spin period, a_c is the line of sight acceleration due to the GC potential field, a_g is the acceleration due to the Galactic potential, a_s is an apparent centrifugal acceleration (the so-called Shklovskii effect; Shklovskii 1970) and c is the speed of light. The two latter terms are expected to be negligible with respect to the former two, and following Prager et al. (2017, and references within) we know that $a_g = 5.1\times10^{-10} \pm 1.4\times 10^{-10}$ m s^{-2} and $a_s \sim 4.2 \times 10^{-12}$ m s^{-2}. According to Freire et al. (2005) and Prager et al. (2017), the acceleration along our line of sight (z) due to the cluster potential (a_c) can be written as:

$$a_c(z, x) = -3.5 \times 10^{-7} \left(\frac{\rho_c}{10^6\ M_\odot\ pc^{-3}}\right)\left(\frac{z}{0.2\ pc}\right) \times \times \left(\sinh^{-1}(x) - \frac{x}{\sqrt{1+x^2}}\right) x^{-3}\ \mathrm{m\ s^{-2}} \qquad (2)$$

where ρ_c is the cluster core density and $x \equiv r/r_c^{NS}$, where r_c^{NS} is the cluster core radius of the neutron star population and $r = \sqrt{r_\perp^2 + z^2}$ is distance of the pulsar from the cluster center. In the latter formula, $r_\perp = D\theta_\perp$ is the pulsar projected distance from the cluster center, where D is the distance of the cluster from the Sun and $\theta_\perp$ the pulsar angular offset from the cluster center.

Prager et al. (2017) used the ensemble of Terzan 5 MSPs, including Ter5aj and Ter5ak, to derive the cluster physical properties. They found $\rho_c = 1.58 \pm 0.13 \times 10^6\ M_\odot\ pc^{-3}$ and $r_c^{NS} = 0.16 \pm 0.01$ pc. Given the angular offsets of Ter5aj and Ter5ak from the cluster center (see Table 1) and the cluster distance of 5.9 kpc (Lanzoni et al. 2010), we measured the possible line of sight accelerations of these two MSPs for different values of the line of sight distance z. We found that the maximum allowed accelerations are $\pm3.4 \times 10^{-8}$ m s^{-2} and $\pm2.0 \times 10^{-8}$ m s^{-2} for Ter5aj and Ter5ak, respectively. We used these values to constrain, starting from Equation 1, the MSP intrinsic spin-down rates and, consequently, the characteristic ages, surface magnetic fields and spin-down luminosities. All these values are tabulated in Table 1 and, for both the MSPs, are in agreement with those typically expected for old and recycled pulsars and with that of the other Terzan 5 pulsars.

5. SUMMARY AND CONCLUSIONS

We used archival observations to search for new pulsars in the stellar system Terzan 5. Instead of using classical search routines based on the analysis of single observations, we developed an alternative method which combines multiple observations. In this method, stacked power spectra at different DMs are created by summing the spectral powers obtained in the single observations. In order to remove RFI, a control DM spectrum has been subtracted from all the stacked power spectra. All the candidates selected in these "corrected" stacked power spectra have been processed with a KD-Tree algorithm, in order to select those that are likely pulsar candidates and discard those that are more likely persistent RFI. This method turns out to be a quite powerful tool to search for very faint isolated pulsars in GCs and it opens the possibility to identify a significant number of still unknown pulsars by simply using the large amount of archived data collected in the last decades of GC observations. Together with the classical routine searches on single observations, it could be a complementary method to discover extremely faint pulsars by using the large amount of GC data that the new generation of radio telescopes (such as MeerKAT) are going to produce.

The stacking technique described in this work is of particular effectiveness in a high DM system like Terzan 5. Indeed, for typical 1.4 GHz observations, the high DM and very small scintillation bandwidth allow us to average, in the stacked power spectra, over many scintles, making negligible any effect due to diffractive scintillation. The only variability appreciable in the different terms of the power spectra sum is due to refractive scintillation, which can affect the flux densities of pulsars by typically up to a factor of ~ 2. On the other hand, in a low DM cluster such as, for example, 47 Tucanae, diffractive scintillation can change the measured flux densities by more than an order of magnitude.

Table 1. Timing parameters for the new Terzan 5 MSPs[a].

Parameter	Ter5aj	Ter5ak
Timing Parameters		
Right ascension, α (J2000)	$17^{\rm h}\,48^{\rm m}\,05^{\rm s}.0119(2)$	$17^{\rm h}\,48^{\rm m}\,03^{\rm s}.6860(2)$
Declination, δ (J2000)	$-24^\circ\,46'\,34''.85(7)$	$-24^\circ\,46'\,37''.83(8)$
Spin frequency, F (Hz)	337.96234149929(4)	529.07066473956(4)
Spin frequency derivative, $\dot{F}$ (10^{-14} s^{-2})	$-1.61313(7)$	$-2.4771(2)$
Spin frequency second derivative, $\ddot{F}$ (10^{-25} s^{-3})	$-1.8(4)$	-
Dispersion measure, DM (cm^{-3} pc)	238.633(6)	236.705(5)
MJD range	55423-57573	55423-57573
Epoch (MJD)	56498	56498
Data span (yr)	5.9	5.9
Number of TOAs	42	31
RMS timing residuals (μs)	12.51	17.03
EFAC	1.14	1.18
Reduced χ^2 value	1.00	1.00
Solar system ephemeris model	DE436	DE436
Derived Parameters		
Spin period, P (ms)	2.9589095505841(3)	1.8901066845055(1)
Spin period derivative, $\dot{P}$ (10^{-19})	1.41232(6)	0.88495(6)
Spin period second derivative, $\ddot{P}$ (10^{-30} s^{-1})	1.6(3)	-
Intrinsic spin period derivative, $\dot{P}_{\rm int}$ (10^{-19})	< 4.9	< 2.1
Characteristic age, τ_c (Myr)	> 98	> 142
Surface magnetic field, B_0 (10^8 G)	< 12.0	< 6.4
Spin-down luminosity, L_{SD} (10^{35} erg s^{-1})	< 7.3	< 12.4
Flux density at 1.5 GHz, $S_{1.5}$ (μJy)	34	30
Flux density at 2.0 GHz, $S_{2.0}$ (μJy)	18	16
Angular offset from cluster centre, $\theta_\perp$ ($''$)	10.4	17.4

[a]Numbers in parentheses are uncertainties in the last digits quoted. The time units are TDB and the adopted terrestrial time standard is UTC(NIST).

Therefore few of the power spectrum sums will have high values, while most of them will have much lower values, thus diluting the signal to noise ratio of the final sum. However, even in such conditions stacked power spectrum searches can reveal new pulsars, as demonstrated by Pan et al. (2016).

The application of the method to Terzan 5 led us to discover three additional MSPs in this stellar system. For two MSPs, we have been able to obtain a phase connected timing solution that confirmed their association with the GC, having a DM close to the cluster mean value and being located within $\sim 17''$ from the cluster gravitational center. These discoveries bring the total number of known MSPs in this system to 37, $\sim 25\%$ of the entire pulsar population identified so far in GCs.

Indeed Terzan 5 turns out to be the most efficient factory of MSPs in the Milky Way and the large number of X-ray sources (see, e.g., Heinke et al. 2006) and X-ray bursters (see the recent case of EXO 1745-248, Altamirano et al. 2015; Ferraro et al. 2015) suggest that this furnace is currently quite active.

Ferraro et al. (2009) first pointed out that, at odds with what is commonly thought, Terzan 5 probably is not a genuine GC, but a much more complex stellar system, since it hosts different stellar populations characterized by significantly different iron abundances (see also Origlia et al. 2011, 2013; Massari et al. 2014). Recently Ferraro et al. (2016) measured the ages of the two main sub-populations, (finding 12 and 4.5 Gyr for the sub-solar and super-solar metallicity component, respectively), thus identifying Terzan 5 as a site of multiple bursts of star formation in the Galactic bulge. In fact, the measured chemical patterns and the large age difference between the two main sub-populations could be naturally explained in a self-enrichment scenario where Terzan 5 was originally much more massive ($\sim 10^8 M_\odot$) than today ($\sim 10^6 M_\odot$; Lanzoni et al. 2010), and therefore able to retain the iron-enriched gas ejected by violent supernova explosions. The large number of type II supernovae required to explain the observed abundance patterns should have also produced a large population of neutron stars, mostly retained into the deep potential well of the massive *proto*-Terzan 5 and likely forming binary systems through tidal capture interactions. This, together with its large collision rate (Lanzoni et al. 2010), the largest among all Galactic globular clusters (see also Verbunt & Hut 1987), could have highly promoted pulsar re-cycling processes, which explains the production of the large population of MSPs and other stellar exotica now observed in the system.

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Facility: GBT

Software: Scipy (Jones et al. 2001), PRESTO (Ransom et al. 2002), TEMPO (Manchester et al. 2015)

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