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Article

Serendipitous Discovery of a 431 ms Pulsar in the Background of Westerlund 1

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Abstract: We report the discovery of PSR J1646–4545, a 431 ms isolated pulsar, in the direction of the young massive cluster Westerlund 1. The pulsar was found in data taken between the years 2005 and 2010 with the “Murriyang” Parkes radio telescope in Australia. Thanks to the numerous detections of the pulsar, we were able to derive a phase-connected timing solution spanning the whole data set. This allowed us to precisely locate the pulsar at the border of the cluster and to measure its spin-down rate. The latter implies a characteristic age of ~ 25 Myr, about twice as large as the estimated age of Westerlund 1. The age of PSR J1646–4545, together with its dispersion measure of ~ 1029 pc cm^{−3}, more than twice the value predicted by the two main galactic electron density models for Westerlund 1, makes the association of the pulsar with the cluster highly unlikely. We also report on ramifications from the presence of a magnetar in Westerlund 1 and the apparent lack of ordinary radio pulsars.

Keywords: Westerlund 1; pulsar; PSR J1646–4545



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1. Introduction

Young Massive Star Clusters (YMCs) are very dense agglomerations of young stars, conventionally defined as clusters with ages smaller than 100 Myr and masses of $\gtrsim 10^4 M_{\odot}$ [1]. Several YMCs are found in the Local Group, and they are most common in starburst and interacting galaxies.

With a total mass in the range of $(44\text{--}57) \times 10^3 M_{\odot}$ [2], Westerlund 1 [3,4] is the most massive YMC of the Local Group. The cluster is located in our galaxy, in the Ara Constellation, with center coordinates at Right Ascension $\alpha = 16^{\text{h}}47^{\text{m}}:04^{\text{s}}.00$ and Declination $\delta = -45^{\circ}51'04''.9$ [4], corresponding to a galactic longitude of $l = 339.55^{\circ}$ and galactic latitude of $b = -0.40^{\circ}$. It is also relatively nearby, with an estimated distance of 4.05 ± 0.20 kpc [5], which makes it a relatively easy target to study when compared to other YMCs. Westerlund 1 has been extensively observed at various wavelengths over time. Among these, X-ray observations made with *Chandra* in 2005, revealed that the cluster is the

host of a bright X-ray source, dubbed CXOU J164710.2–455216 (henceforth, CXOU J1647), which was identified as a magnetar spinning once every 10.61 s [6]. In September 2006, CXOU J1647 experienced an X-ray outburst [7], where its luminosity increased by a factor of 100 in just a few days [8]. The discovery of CXOU J1647 triggered searches for the possible pulsed radio emission produced by the source: a multi-year monitoring campaign of CXOU J1647 was therefore initiated at the “Murriyang” radio telescope near Parkes, Australia, where observations were carried out between 2006 and 2010 with an approximately bi-monthly cadence.

In this work, we report on the searches originally made to uncover the potential radio pulsations emitted by CXOU J1647. We also re-process the entire Parkes data set of Westerland 1, blindly searching for radio pulsations, as well as for single pulses potentially coming from CXOU J1647 or any possible other pulsars. The re-processing was motivated by the significantly more efficient pulsar searching algorithms and much larger computing power available today, and, for the single-pulse search part, by the recent discovery of Fast Radio Burst-like signals from the galactic magnetar SGR 1935+2154 [9].

The search has led to the serendipitous discovery of a new isolated pulsar, on which we report in this paper. In Section 2, we describe the data set. In Section 3, we report on the analyses used and their results. In Section 4, we discuss their implications and summarize our conclusions.

2. Observations

The data set used for this work consists of 83 observations acquired between September 2005 and February 2010 with the Australian 64 m “Murriyang” Parkes radio telescope. Their durations varied from 18 to 280 min. In addition to the multi-year follow-up campaign made to search for the radio pulsations of CXOU J1647, the data set includes one observation of Westerland 1 made in 2005 (prior to the discovery of the magnetar), which was part of a pilot survey aimed at YMCs. The vast majority of the observations were taken with the central beam of the Parkes 21 cm multi-beam receiver [10] pointed at the location of the magnetar with the exception of the first observation, which was pointed at the nominal center of Westerland 1. The central frequency used with the multi-beam receiver was either 1374 or 1390 MHz. About one-fourth of the observations were taken with “H-OH” receiver, at a central frequency of 1518 MHz, while a handful of observations were carried out with other single-beam receivers, which had higher central frequencies of ~ 2.2 and ~ 3.2 GHz. The total bandwidths used ranged between 256 MHz and 1152 MHz divided into 96, 192, 384 or 512 channels, 1-bit digitized in total-intensity only, with sampling intervals ranging between 125 and 750 μ s. VP: This is correct All the observations used in this work and their parameters are listed in Table 1.

Table 1. List of Parkes observations analyzed for this work. All of them were acquired using the Analogue Filterbank (AFB) backend. Δt_{obs} : observation length; f_c : central observing frequency; BW: observing bandwidth; N_{chan} : number of frequency channels; t_{samp} : sampling time.

Start Date and Time (UTC)	Δt_{obs} (min)	f_c (MHz)	BW (MHz)	N_{chan}	t_{samp} (μ s)
7 Sep 2005, 06:02	280	1390	256	512	750
14 Aug 2006, 10:06	70	1390	256	512	125
28 Sep 2006, 04:51	248	1390	256	512	200
2 Oct 2006, 01:29	119	1390	256	512	250
10 Nov 2006, 23:06	60	1374	288	96	250
24 Dec 2006, 04:03	59	1518	576	192	250
24 Dec 2006, 05:04	55	1518	576	192	250
26 Dec 2006, 03:41	45	1518	576	192	250
27 Dec 2006, 01:46	59	1518	576	192	250
27 Dec 2006, 04:45	58	1518	576	192	250
28 Dec 2006, 01:13	59	1518	576	192	250
28 Dec 2006, 23:22	59	1518	576	192	250

Table 1. *Cont.*

Start Date and Time (UTC)	Δt_{obs} (min)	f_c (MHz)	BW (MHz)	N_{chan}	t_{samp} (μs)
29 Dec 2006, 00:22	59	1518	576	192	250
6 Jan 2007, 01:14	100	2233	576	192	250
6 Jan 2007, 02:55	100	2233	576	192	250
14 Jan 2007, 02:07	18	1518	576	192	250
14 Jan 2007, 02:26	59	1518	576	192	250
15 Jan 2007, 01:15	47	1518	576	192	250
22 Jan 2007, 17:32	59	1518	576	192	250
22 Jan 2007, 18:33	59	1518	576	192	250
14 Feb 2007, 22:14	59	1518	576	192	250
15 Feb 2007, 15:58	40	1518	576	192	250
16 Feb 2007, 01:36	41	1518	576	192	250
21 Feb 2007, 19:18	90	3222	1152	384	250
14 Apr 2007, 19:56	53	1518	576	192	250
14 Apr 2007, 20:50	59	1518	576	192	250
3 May 2007, 19:17	53	1518	576	192	250
3 May 2007, 20:11	59	1518	576	192	250
20 May 2007, 18:35	53	1374	288	96	250
20 May 2007, 19:29	48	1374	288	96	250
6 Jun 2007, 16:57	53	1374	288	96	250
6 Jun 2007, 17:51	53	1374	288	96	250
14 Jul 2007, 06:38	53	1374	288	96	250
14 Jul 2007, 07:31	56	1374	288	96	250
18 Jul 2007, 07:11	60	1374	288	96	250
19 Jul 2007, 06:02	60	1374	288	96	250
21 Jul 2007, 08:24	60	1374	288	96	250
21 Jul 2007, 12:52	60	1374	288	96	250
21 Jul 2007, 15:21	51	1374	288	96	250
15 Aug 2007, 07:56	53	1374	288	96	250
15 Aug 2007, 08:49	60	1374	288	96	250
19 Sep 2007, 09:18	53	1374	288	96	250
19 Sep 2007, 10:11	60	1374	288	96	250
21 Oct 2007, 04:10	53	1374	288	96	250
21 Oct 2007, 05:09	180	1374	288	96	250
21 Oct 2007, 23:47	89	1374	288	96	250
22 Oct 2007, 05:36	144	1374	288	96	250
23 Oct 2007, 00:01	119	1374	288	96	250
23 Oct 2007, 05:02	180	1374	288	96	250
24 Oct 2007, 00:02	89	1374	288	96	250
24 Oct 2007, 07:12	50	1374	288	96	250
24 Oct 2007, 23:41	60	1374	288	96	250
26 Oct 2007, 23:39	50	1374	288	96	250
1 Nov 2007, 03:09	54	1374	288	96	250
19 Nov 2007, 23:43	60	1374	288	96	250
6 Dec 2007, 05:16	28	1390	256	512	250
6 Dec 2007, 05:51	80	1390	256	512	250
4 Jan 2008, 03:01	53	1374	288	96	250
4 Jan 2008, 03:55	31	1374	288	96	250
4 Jan 2008, 04:27	49	1374	288	96	250
10 Jan 2008, 04:09	44	1374	288	96	250
29 Jan 2008, 00:39	104	1374	288	96	250
29 Jan 2008, 02:24	50	1374	288	96	250
2 Feb 2008, 00:40	104	1374	288	96	250
26 Feb 2008, 23:10	60	1374	288	96	250
27 Feb 2008, 00:17	50	1374	288	96	250
5 Apr 2008, 13:33	75	1374	288	96	250
7 May 2008, 19:42	75	1374	288	96	250
31 May 2008, 18:06	78	1374	288	96	250
30 Jun 2008, 14:14	81	1374	288	96	250

Table 1. Cont.

Start Date and Time (UTC)	Δt_{obs} (min)	f_c (MHz)	BW (MHz)	N_{chan}	t_{samp} (μs)
5 Aug 2008, 12:53	89	1374	288	96	250
8 Sep 2008, 12:11	47	1374	288	96	250
18 Oct 2008, 09:19	61	1374	288	96	250
19 Dec 2008, 03:36	81	1374	288	96	250
18 Jan 2009, 01:29	92	1374	288	96	250
14 Feb 2009, 01:22	70	1374	288	96	250
17 Mar 2009, 20:08	81	1374	288	96	250
12 Apr 2009, 20:22	68	1374	288	96	250
7 Jun 2009, 08:49	70	1374	288	96	250
24 Sep 2009, 08:14	89	1374	288	96	250
9 Oct 2009, 08:08	82	1374	288	96	250
1 Dec 2009, 23:37	89	1374	288	96	250
2 Feb 2010, 18:59	80	1374	288	96	250

3. Data Analyses and Results

3.1. Initial Searches of Radio Pulsations from the Magnetar

With the aim of finding radio pulsations from CXOU J1647, the data targeting the magnetar were folded shortly after each observing run using the X-ray ephemerides published in Israel et al. [11] and a nominal dispersion measure (DM) of 300 pc/cm^3 . This initial value was derived using the estimated distance to the cluster and the NE2001 galactic electron density model [12]. Data archives with 1024 profile bins were created using the DSPSR (<https://sourceforge.net/projects/dpsr>, accessed on 19 August 2023) software [13] with time sub-integrations of 120 s and keeping all the frequency channels. This allowed us to search over the unknown DM with up to twice the nominal value without any loss of sensitivity and search $\pm 1 \text{ ms}$ around the nominal X-ray period (largely encompassing the X-ray ephemeris uncertainties for all our observing epochs) with a maximum broadening of the pulse in the individual sub-integrations compatible with a single time bin. We did this using the PDMP routine of the PSRCHIVE (<https://psrchive.sourceforge.net>, accessed on 19 March 2024, version 2024-03-06 6b89e7914) software package [14,15], running it six times over adjacent DM ranges of 100 pc cm^{-3} each. We also carried out a basic blind search spanning the same DM range as for the above targeted search (0 to 600 pc/cm^3) with SIGPROC [16], which uses a Fast Fourier Transform (FFT) to reveal periodic signals in the data.

No radio pulsations compatible with the spin period of the magnetar were found with a flux density upper limit between 70 and $190 \mu\text{Jy}$ at around 1.4 GHz, depending on the specific observation, and of 70 and $50 \mu\text{Jy}$, respectively, at 2.3 GHz and 3.2 GHz, conservatively assuming a 10% duty cycle and a pulsed signal-to-noise ratio (S/N) of 7.

3.2. Deep Periodicity Search

Compared to when the observations were taken, pulsar searching algorithms are now highly optimized and much more computationally efficient. Moreover, the rapid technological advances have led to significantly increased computing power currently being at our disposal. All of this translates into a much larger parameter space that can be searched for a given data set. Motivated by this possibility, we re-processed all the Westerland 1 data using state-of-the-art pulsar searching software, based both on Fourier-domain and time-domain methods.

First, we used the `rfifind` routine of the PRESTO (<https://github.com/scottransom/presto>, accessed on 19 August 2023, version 4.0) pulsar searching package [17] to look for radio frequency interference (RFI) in each observation. With this, we created masks indicating those frequency channels and time intervals that were corrupted by RFI and that should therefore be ignored in the subsequent analyses. Then, we determined the DM

range to search using the PyGEDM (<https://apps.datacentral.org.au/pygedm/>, accessed on 20 September 2023) software [18] based on the NE2001 [12] and YWM16 [19] galactic electron density models by estimating the expected DM along the line of sight towards Westerlund 1 at a distance of 4.05 kpc. The NE2001 and YWM16 models returned predicted DMs of ~ 307 and ~ 345 pc cm $^{-3}$, respectively. Given the much larger computing power at our disposal, we decided to search a significantly larger DM range, between 2 and 1500 pc cm $^{-3}$. Each observation was therefore de-dispersed using hundreds of DM trials (the exact number depended on the characteristics of each observation) in this range. The periodicity search was first performed using PULSAR_MINER (https://github.com/alex88ridolfi/PULSAR_MINER, accessed on 19 August 2023) [20], a semi-automated pipeline based on PRESTO. For each de-dispersed time series, the pipeline performed a Fourier-domain search targeting both isolated and binary pulsars. The latter are targeted with an “acceleration search” algorithm, which can account for the possible motion of a pulsar along a binary orbit, with the constraint that the length of the data be shorter than 10 per cent of the binary orbital period [21]. This was executed using PRESTO’s `accelsearch` routine. For the latter, we allowed the pulsar spin frequency to drift up to 200 Fourier bins (using the `-zmax 200` option of `accelsearch`) due to the Doppler shift induced by the orbital motion. Each observation was searched in its full length, as well as, whenever possible, in shorter segments of 60, 30 and 15 min, so as to potentially be sensitive to binary pulsars with orbits as short as ~ 150 min. Additionally, an optimized version of the phase-modulation search algorithm [22], which is sensitive to the ultra-compact binary systems with orbital periods $\ll 10$ h, is currently being developed and tested against this data set. The results of this application will be presented elsewhere.

In a second stage, we processed the data with RIPTIDE (<https://github.com/v-morello/riptide>, accessed on 20 September 2023, version v0.2.4) [23], a time-domain pulsar searching pipeline based on a highly optimized version of the Fast Folding Algorithm (FFA, Staelin [24]). The FFA is significantly more sensitive than Fourier-domain methods for pulsars with long spin periods ($\gtrsim 1$ s). However, it cannot per se account for possible binary motions (unless one applies corrections to the data before running the FFA, e.g., Wongphechauxsorn et al. [25]). Therefore, in our case, it only targeted isolated pulsars. We ran RIPTIDE on all the cleaned and de-dispersed time series previously produced. For each observation, both pipelines produced diagnostic plots of potential pulsar candidates, which were visually inspected.

With both pipelines, we were able to easily re-detect PSR B1641–45, an extremely bright isolated pulsar with a spin period of 455 ms and a DM of 450 pc cm $^{-3}$, located at about 25 arcminutes from the nominal center of Westerlund 1 (therefore well outside the cluster), which was first discovered by Komesaroff et al. [26]. Despite being well outside the primary beam, its mean flux density was sufficient to allow detection in all of the observations. Its distance, constrained by HI absorption measurement [27], ranges in the 4.5 ± 0.4 kpc interval [28].

We also discovered a new long-period pulsar, named PSR J1646–4545, with a spin period of 431 ms, a DM of 1029 pc cm $^{-3}$, and no signs of acceleration, suggesting it being isolated. The pulsar was easily detected with a high S/N by both pipelines in almost all the observations. Example diagnostic plots produced by the PULSAR_MINER and RIPTIDE pipelines showing the new pulsar are displayed in Figures 1 and 2, respectively. In Figure 3, we show a high-S/N integrated pulse profile of PSR J1646–4545, obtained by summing 24 bright detections at a central frequency of 1374 MHz. The pulse profile is broad, with a pulse width at half-maximum of ~ 78 ms, corresponding to about 18 per cent of the pulse period. This value is much larger than the typical duty cycles at half-maximum of non-recycled pulsars: according to the ATNF pulsar catalog (<https://www.atnf.csiro.au/research/pulsar/psrcat>, accessed on 15 April 2024 (v2.1.1)), it is larger than that of 97 per cent of all pulsars with spin periods longer than 30 ms and a surface magnetic field $B > 10^{11}$ G. The profile is also slightly asymmetric, with the trailing part hinting that scattering may be involved.

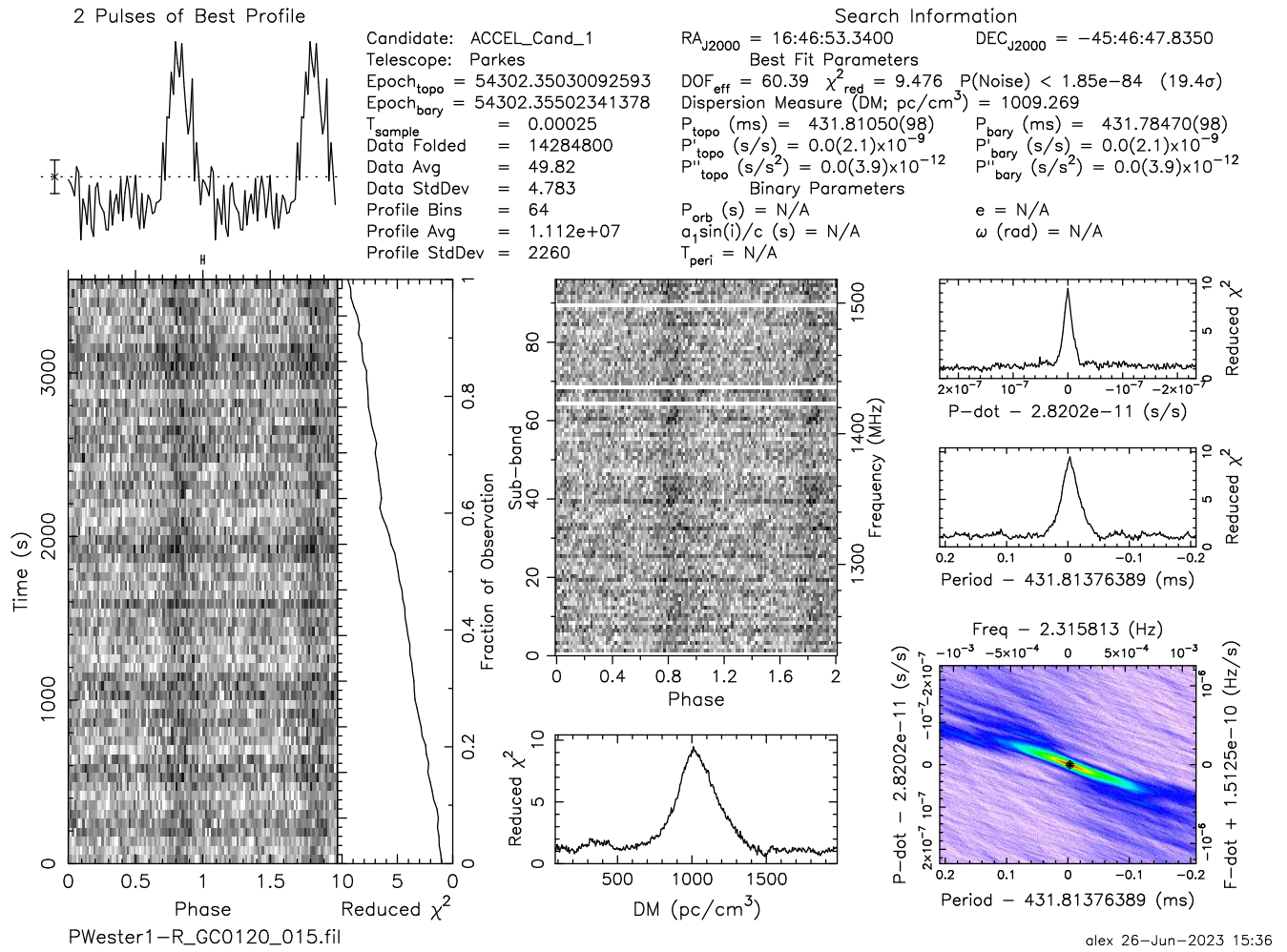


Figure 1. Diagnostic plot for the new 431 ms isolated pulsar PSR J1646–4545 as produced by the PULSAR_MINER Fourier-domain searching pipeline applied to the 21 July 2007 observation.

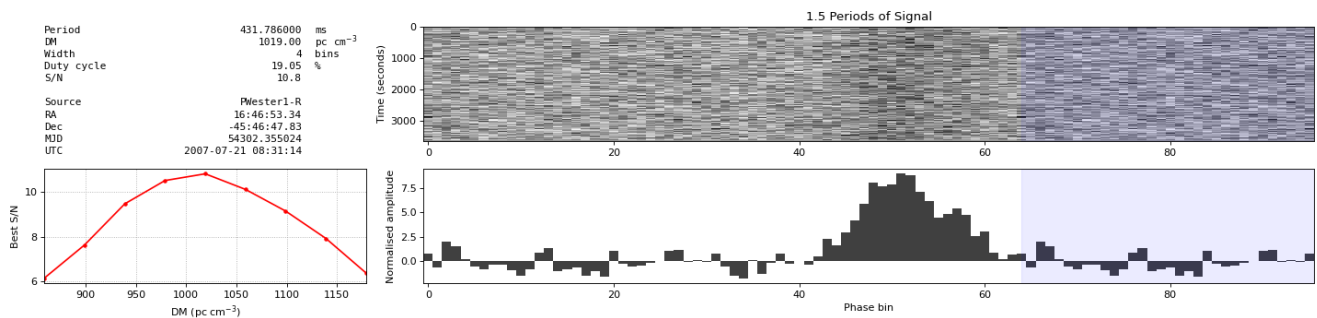


Figure 2. Diagnostic plot for the new 431 ms isolated pulsar PSR J1646–4545 as produced by the RIPTIDE FFA searching pipeline applied to the 21 July 2007 observation.

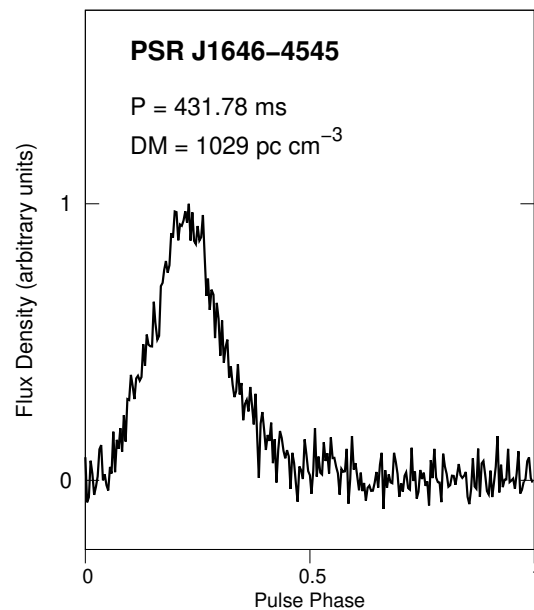


Figure 3. Integrated pulse profile of PSR J1646–4545 obtained by summing 24 bright detections of the pulsar at a central frequency of 1374 MHz and with a bandwidth of 288 MHz.

3.3. Single Pulse Search

We also performed a single pulse search throughout the data set to look for bright sporadic events such as bright single pulses emitted by pulsars as well as potential fast radio bursts [29,30] that could serendipitously be present in our field of view or potentially linked to the magnetar. To do this, we searched each observation using the Heimdall (<https://sourceforge.net/projects/heimdall-astro>, accessed on 23 August 2023) [31] software. An initial RFI flagging was conducted using a spectral kurtosis algorithm [32] provided by the YOUR (<https://github.com/thepetabyteproject/your>, accessed on 23 August 2023, version 0.6.6) package [33] and the noisiest channels found were parsed through Heimdall via the `-zap_chans` option. We then used Heimdall to search excesses in the DM range of 0–3000 pc cm^{-3} , with a DM trial array sampled to have a S/N loss for each trial of 1% and searched for events with a maximum boxcar width of 512 time bins. No evidence of single pulses/bursts has been found above a S/N threshold of 10.

3.4. Timing of the New Pulsar PSR J1646–4545

The new pulsar PSR J1646–4545 was clearly detected in 73 different observations, spanning more than 4 years. All these detections were processed with DSPSR and PSRCHIVE to obtain a total of 217 times of arrival (TOAs) across the whole time span covered by the data. We then used the TEMPO2 (<https://bitbucket.org/psrsoft/tempo2>, accessed on 19 August 2023) pulsar timing software [34] to derive a phase-connected timing solution. This allowed us to precisely measure the pulsar position, which locates it at ~ 5.97 arcmin northwest of the nominal center of Westerlund 1 (see Figure 4), and its first spin period derivative, which is $\dot{P} = 2.78(3) \times 10^{-16}$. All the parameters of the pulsar with their $1-\sigma$ uncertainties derived with the TEMPO2 timing are reported in Table 2. The corresponding timing residuals are shown in Figure 5.

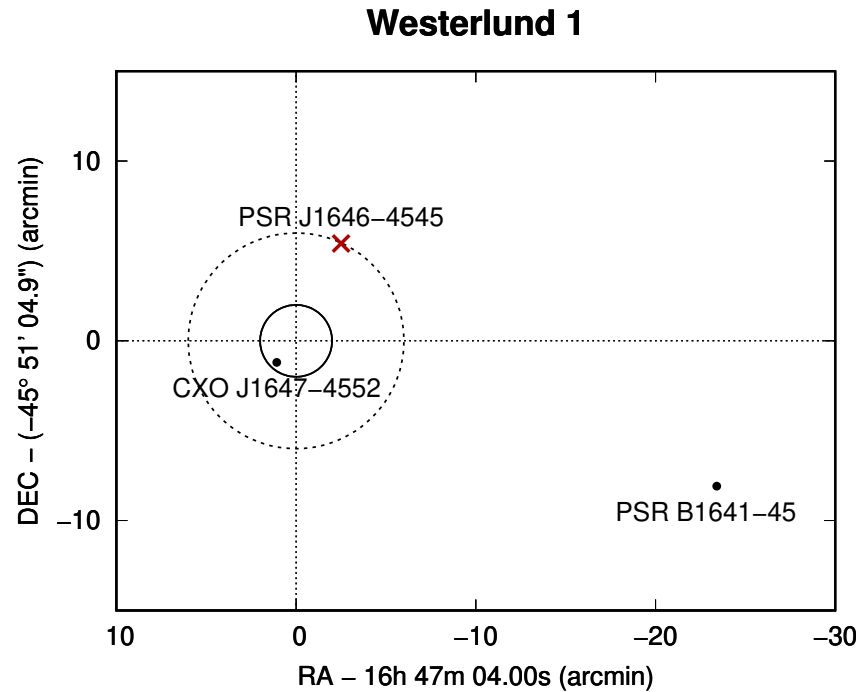


Figure 4. Position of the newly discovered PSR J1646–4545 (red cross) with respect to the nominal center of Westerlund 1 (intersection of the dotted lines) and the positions of the X-ray magnetar CXOU J1647 and the radio pulsar PSR B1641–45 (black dots). The inner solid circle, at 2 arcmin, shows the effective radius of Westerlund 1, defined as the radius containing about 50 per cent of the Gaia-EDR3 sources belonging to the cluster [5]. The outer dashed circle, at 6 arcmin, contains about 75 per cent of the same sample.

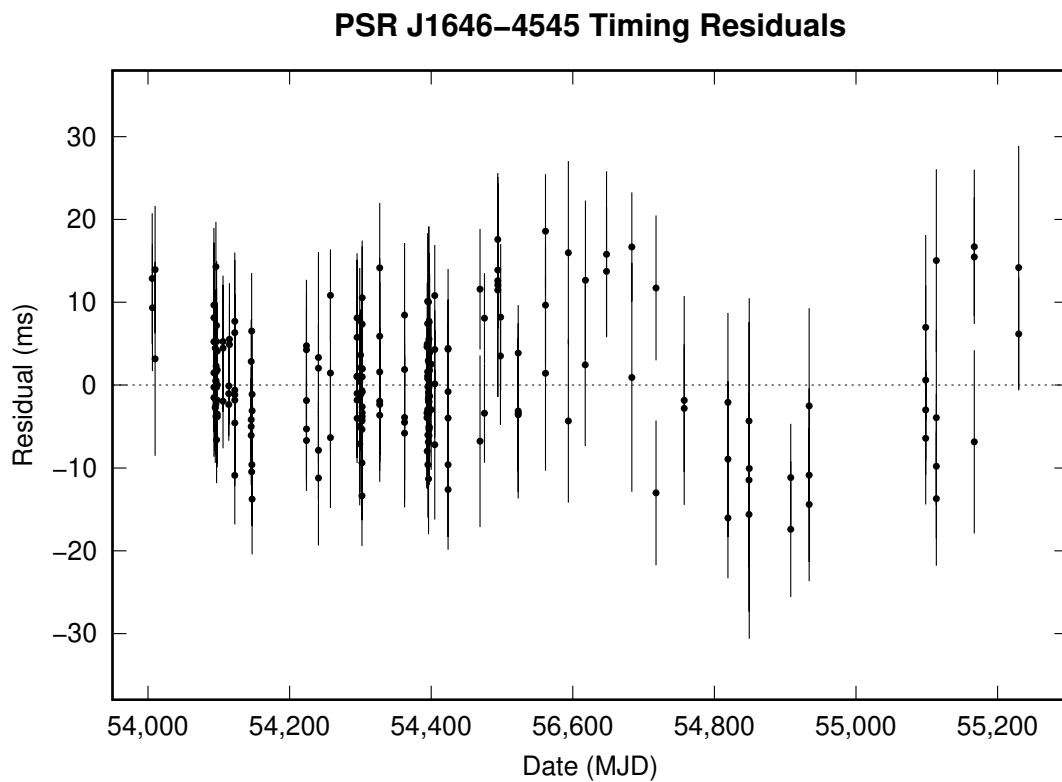


Figure 5. Timing residuals of PSR J1646–4545. The leftover unmodeled trend, visible in the residuals, is likely due to timing noise.

Table 2. Timing parameters for PSR J1646–4545 as derived by the phase-connected timing solution obtained in this work. All the quoted uncertainties on the last digits (in parentheses) are 1σ .

Pulsar	PSR J1646–4545
Right Ascension, α (J2000)	16:46:49.66(4)
Declination, δ (J2000)	−45:45:39.8(8)
Spin Frequency, f (s^{-1})	2.3159744218(2)
1st Spin Frequency derivative, $\dot{f}$ (Hz s^{-2})	$-1.49(1) \times 10^{-15}$
2nd Spin Frequency derivative, $\ddot{f}$ (Hz s^{-3})	$3.0(5) \times 10^{-24}$
Reference Epoch (MJD)	54,217.000
Start of Timing Data (MJD)	54,006.245
End of Timing Data (MJD)	55,229.834
Dispersion Measure, DM (pc cm^{-3})	1029(3)
Solar System Ephemeris	DE421
Terrestrial Time Standard	UTC(NIST)
Time Units	TDB
Number of TOAs	217
Residuals RMS (ms)	6.7
Derived Parameters	
Spin Period, P (s)	0.43178369786(3)
1st Spin Period derivative, $\dot{P}$ (s s^{-1})	$2.78(3) \times 10^{-16}$
Spin Down Age, τ_{sd} (Myr)	24.6
Surface Magnetic Field, B_s (G)	3.51×10^{11}
Spin-down Luminosity, $\dot{E}$ (erg s^{-1})	1.36×10^{32}

4. Discussion

As outlined in the previous sections, our search observations, pointed at the X-ray magnetar CXOU J1647 in the young massive stellar cluster Westerlund 1, did not show any pulsed radio emission from the magnetar itself. However, they revealed one new pulsar, PSR J1646–4545, the parameters of which argue, for the most part, against its belonging to Westerlund 1. In the following, we thoroughly discuss this putative association and the implications of the lack of any bona fide radio pulsars in the cluster.

4.1. The Case of PSR J1646–4545

In order to discuss if PSR J1646–4545 belongs to Westerlund 1, we separately examine the three most relevant parameters resulting from the campaign run at the Murriyang radio telescope, namely, the position, the dispersion measure, and the spin-down age of the pulsar.

4.1.1. The Position of the Pulsar

According to Navarete et al. [5], the effective radius of Westerlund 1 is $r = 2'$, although stars belonging to the cluster can be found at least up to $6'$ from the center. Given that, the location of PSR J1646–4545 at ~ 5.97 arcmin northwest of the nominal center of Westerlund 1 [4] is only marginally compatible with its belonging to the cluster. Because of its relatively long spin period and the large rms of the timing solution, no measurement of the proper motion has been possible for PSR J1646–4545 to date. This prevents us from directly inferring if the neutron star could have significantly traveled from the position of the original supernova to the current location. However, at the GAIA3 distance of 4.05 ± 0.20 kpc, $6'$ corresponds to 7.0 ± 0.4 pc; thus, even a small kick velocity at birth of just ~ 10 km/s would have allowed PSR J1646–4545 to easily move from the center of Westerlund 1 to the outskirts of the cluster in less than ~ 1 Myr (the upper limit for the age of the cluster being about ten times larger, see later). It should also be noted that the aforementioned value of r was somehow biased towards the high-mass tail (up to tens of solar masses) in the distribution of the stellar content of this young cluster [5], while relatively lower-mass stars like PSR J1646–4545 (the mass of which is expected in the ~ 1 – $2 M_{\odot}$ range (https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html, accessed

on 10 April 2024)) might be found at an even larger radius from the center. Moreover, it has been suggested [35] that Westerlund 1 did not experience any mass segregation at birth and at origin had a similar or larger size than currently seen; this could support the presence of a neutron star at the offset position of PSR J1646–4545.

At the moment, PSR J1646–4545 is the closest known pulsar to the Westerlund 1 center, being four times closer than the second ranked, PSR B1641–45 (see Section 3). According to the ATNF pulsar catalog, in the area of the sky surrounding Westerlund 1, the surface density of previously discovered radio pulsars (none of which are expected to be associated with Westerlund 1) is in the range $1\text{--}3\text{ deg}^{-2}$. In particular, it is 2.4 deg^{-2} in a circle of radius 1.5 deg from the Westerlund 1 center; while looking at a wider rectangular strip of 9 deg (in RAJ) and thickness 3 deg (in DecJ) centered at same position as above, one obtains a lower value of 1.4 deg^{-2} . These surface densities are typical of sky regions chosen in the galactic disk and including the galactic center (i.e., galactic longitude $-90 < l < +90$). For instance, the surface density is 2.4 deg^{-2} within $[-1; +1]\text{ deg}$ in galactic latitude and 1.0 deg^{-2} within $[-3; +3]\text{ deg}$. Taking these numbers at face value, there is a chance probability of $\sim 2\%$ of finding a pulsar unrelated to Westerlund 1 within $6'$ from its center. However, it is worth noting that this probability must be taken cautiously, since this results from the combination of various pulsar surveys performed in the area, each with its own search parameters, which are different with respect to the search experiment presented in this paper.

4.1.2. The Dispersion Measure of the Pulsar

Another observation that can be used to investigate the association of PSR J1646–4545 with Westerlund 1 is the value of its DM, which is $1029 \pm 3\text{ pc cm}^{-3}$. The mean of the DMs for the known pulsars within 1.5 deg from the center of Westerlund 1 is 463 pc cm^{-3} , with a standard deviation of 177 pc cm^{-3} . There are two outliers in this population, with DM values of 718 pc cm^{-3} and 925 pc cm^{-3} . As reported in Section 3, according to the NE2001 and YMW16 models, the predicted DMs for a pulsar included in Westerlund 1 are 307.6 pc cm^{-3} and 344.6 pc cm^{-3} , respectively (for the distance of 4.05 kpc); in this context we also note that the second closest pulsar to the center of Westerlund 1, PSR B1641–45, has a distance measured via HI absorption (i.e., independently from its DM value of 450 pc cm^{-3}) and that was used to calibrate the YMW16 model in that area of the sky, lending additional reliability to the prediction of this model. The measured DM for PSR J1646–4545 would imply a distance of 10.4 kpc and 6.3 kpc for the NE2001 and YMW16 model, respectively. All in all, these considerations all strongly point against the membership of PSR J1646–4545 to the cluster.

However, since Westerlund 1 is the most massive YMC in the Local Group (see Section 1), one may wonder if the high wind losses from the young star population could sustain an intra-cluster gas dense enough to explain the excess DM of $\sim 700\text{ pc cm}^{-3}$ of PSR J1646–4545 with respect to the predictions. Indeed, a set of concatenated ATCA observations made at 5.5 GHz and 9 GHz [36] and an observing campaign carried out at 3 mm with ALMA [37], both aimed to imaging the central region of Westerlund 1, revealed diffuse emission over $\sim 0.3'$ scales (corresponding to linear scales of $\sim 0.3\text{ pc}$) as well as the presence of several much more compact clouds without an optical counterpart (unfortunately, none of the mentioned observing campaigns covered the position of the pulsar and thus it is not possible to constrain the presence of any cloud along the line of sight to PSR J1646–4545.). For a gas cloud projected along the line-of-sight to a pulsar with a size of $s \sim 0.3\text{ pc}$ and a gas ionization fraction $\chi = n_e/n_H$ (where n_e is the free electron number density and n_H is the hydrogen equivalent number density), the excess DM would imply a number density $n_H = (\Delta\text{DM})/(s\chi) \sim 2.3 \times 10^3\text{ cm}^{-3}/\chi$. For small χ , the implied $n_H \gtrsim 10^5\text{ cm}^{-3}$ goes well beyond what is seen in observed gas clouds. Such a high n_H value might be comparable to that recently predicted for the molecular gas retained in young star clusters (e.g., Silich et al. [38]), but the offset position of PSR J1646–4545 also does not favor this hypothesis.

4.1.3. The Age of the Pulsar

From the combination of P and $\dot{P}$, it is possible to infer the so-called *spin-down age* of a pulsar, as $\tau_{\text{sd}} = P/(2\dot{P})$. For most of the ordinary pulsars (i.e., those not “recycled” in a binary system), τ_{sd} can be used as a proxy for the real age of the underlying neutron star (see e.g., Lorimer and Kramer [39]), although with large errors, especially for relatively old objects ($> \text{Myr}$). For PSR J1646–4545 the spin-down age is $\tau_{\text{sd}} \sim 25 \text{ Myr}$.

The age of Westerlund 1 has been long debated and its value often reviewed. Early observations indicated a very young age of $4 \pm 1 \text{ Myr}$ (Muno et al. [6] and reference therein). More recently, the observation of several giant and supergiant stars led Rocha et al. [40] to suggest that multiple episodes of star formation, closely spaced in time, occurred in Westerlund 1, the oldest of which dates back to no more than $\sim 12 \text{ Myr}$ ago. Similar considerations have also been developed by Navarete et al. [5] via the use of Binary Population and Spectral Synthesis (BPASS) models for the red supergiants with solar abundance, and by Beasor et al. [41]. Given these results, τ_{sd} is at least twice larger than the estimated age of Westerlund 1.

On the other hand, τ_{sd} coincides with the pulsar age only under the following hypotheses: (i) applicability of the formula for the magneto-dipole emission in a vacuum (see Lorimer and Kramer [39]); (ii) a non-decaying magnetic field; and (iii) an initial spin rate much higher than the measured one. Relaxing some of these commonly adopted assumptions can easily produce a true age that is shorter by factor of 2 (or more) than the measured τ_{sd} . In particular, in the case of point (ii), if we take into account some magnetic field evolution ([42,43]), the age estimate of the pulsar would reduce substantially and would be compatible with being even as short as 1 Myr (see the result of a detailed calculation of the evolution reported in Figure 6).

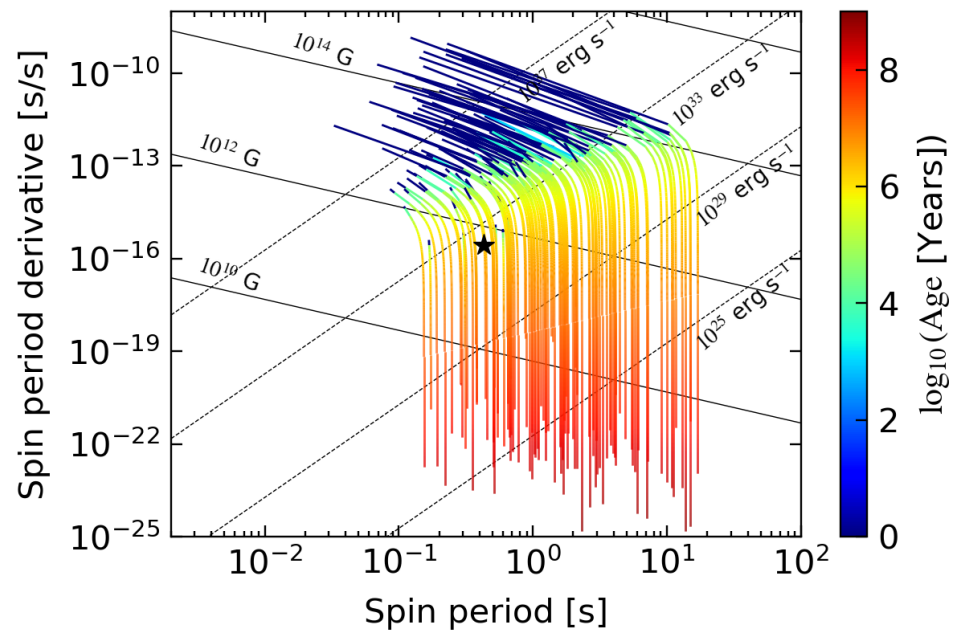


Figure 6. Evolution of synthetic pulsars in the P - $\dot{P}$ diagram over 1 Gyr, taking into account B-field evolution (adapted from Michele Ronchi’s PhD thesis; see also [42,43]). The black star indicates the position of PSR J1646–4545 in the diagram.

4.2. No Radio Pulsars in Westerlund 1

The absence of pulsed radio emissions from the magnetar CXOU J1647 is not surprising per se. Over a total sample of about 30 cataloged magnetars, only six showed transient phases of regular and/or bursty radio emission so far (<https://www.physics.mcgill.ca/~pulsar/magnetar/main.html>, accessed on 5 June 2024). However, the lack of any ordinary

radio pulsars in Westerlund 1 in combination with the presence of a highly magnetized neutron star deserves some considerations, which we develop in the following. The association of CXOU J1647 with Westerlund 1 was discussed by Munro et al. [6] on the basis of its very close sky position with respect to the center of the cluster. They found a 0.03 percent chance probability of finding an X-ray pulsar so close to the center of Westerlund 1. If we restrict ourselves to only magnetars with X-ray emission that are located within 2 degrees from the galactic plane, we find an even lower chance probability of 0.0037 per cent. If CXOU J1647 were in fact not associated to Westerlund 1, then the estimate of the minimum progenitor mass given in Munro et al. [6], $\sim 35\text{--}40 M_{\odot}$, should also be revised.

As reported in Section 3, our deepest observations of Westerlund 1 reached a flux density sensitivity limit of $S_{\text{lim}} \sim 70 \mu\text{Jy}$ at 1.4 GHz. Given the distance $d \sim 4.05 \text{ kpc}$ of the open cluster (see Section 1), this translates into a pseudo-luminosity upper limit for any possible pulsar hosted in Westerlund 1 of $L_{\text{lim}} = S_{\text{lim}} d^2 \sim 1.15 \text{ mJy kpc}^2$. According to the ATNF database, $\sim 80\%$ of the radio pulsars with a cataloged pseudo-luminosity L_{1400} at 1.4 GHz, have $L_{1400} > L_{\text{lim}}$. This percentage progressively increases if one restricts the sample to only radio pulsars younger than the age of Westerlund 1 (see above), e.g., it becomes $\sim 84\%$ for pulsars younger than 12 Myr and then grows to more than 90% for pulsars younger than 6 Myr. Assuming that the observed radio pulsar pseudo-luminosity distribution function (as derived from the ATNF database) is applicable to Westerlund 1, this means that our search might have only missed ordinary pulsars in Westerlund 1 which are at the faintest end of the pulsar pseudo-luminosity function at 1400 MHz. Provided that they have a radio beam that points towards us, these faint sources (if any) could be detected with deeper searches at more sensitive radio telescopes.

Alternatively, given the large sampled fraction of the pseudo-luminosity distribution, one can ascribe our null result to the complete absence of active ordinary pulsars currently hosted in Westerlund 1. This could be simply understood as due to the young age of the open cluster (see Section 4.1.3), i.e., the stars belonging to Westerlund 1 might not have had yet the time to produce any neutron stars, and, in turn, any radio pulsars. On the other hand, we know that Westerlund 1 hosts at least one neutron star, the magnetar CXOU J1647. In order to reconcile these two contrasting considerations, one needs to invoke the occurrence of some peculiar evolutionary factor capable of sustaining earlier formation of neutron stars with a very high magnetic field.

In particular, the case for a massive progenitor star has been since long proposed (and supported by population synthesis calculations, e.g., [44] and references therein) in the framework of the so-called *fossil scenario* (e.g., [45]) for the formation of magnetars. If this holds true, magnetars should be more massive than the neutron stars underlying the ordinary radio pulsars (a characteristic which could not be tested yet). On the other hand, the magnetars' progenitors should evolve off the main sequence earlier than the stars leading to the formation of ordinary radio pulsars. The peculiar case of Westerlund 1, which hosts one magnetar and no known radio pulsars, thus seems to support the second prediction of this model.

5. Conclusions

In this work, we have reported on a series of pulsar search observations, pointed at the X-ray magnetar CXOU J1647, included in the open stellar cluster Westerlund 1. The main observational results are as follows:

- No pulsed radio emission from the magnetar CXOU J1647 was detected;
- A new ordinary pulsar, PSR J1646–4545, was discovered at the rim of the cluster. This fact, together with the measured dispersion measure and the age of the pulsar, strongly suggests that PSR J1646–4545 is a pulsar located in the background of Westerlund 1;
- Despite the search sampling a large portion of the pulsar pseudo-luminosity function, no pulsars were discovered in Westerlund 1.

The presence of the magnetar CXOU J1647 in Westerlund 1 has also been discussed in view of the absence of bona fide pulsars in the same cluster. This might favor models for which the magnetars' progenitors are more massive than the progenitors of the ordinary pulsars.

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References

1. Portegies Zwart, S.F.; McMillan, S.L.W.; Gieles, M. Young Massive Star Clusters. *Annu. Rev. Astron. Astrophys.* **2010**, *48*, 431–493. [[CrossRef](#)]
2. Andersen, M.; Gennaro, M.; Brandner, W.; Stolte, A.; de Marchi, G.; Meyer, M.R.; Zinnecker, H. Very low-mass stellar content of the young supermassive Galactic star cluster Westerlund 1. *Annu. Rev. Astron. Astrophys.* **2017**, *602*, A22. [[CrossRef](#)]
3. Westerlund, B. A Heavily Reddened Cluster in ARA. *Publ. Astron. Soc. Pac.* **1961**, *73*, 51. [[CrossRef](#)]
4. Clark, J.S.; Negueruela, I.; Crowther, P.A.; Goodwin, S.P. On the massive stellar population of the super star cluster Westerlund 1. *Annu. Rev. Astron. Astrophys.* **2005**, *434*, 949–969. [[CrossRef](#)]
5. Navarete, F.; Damineli, A.; Ramirez, A.E.; Rocha, D.F.; Almeida, L.A. Distance and age of the massive stellar cluster Westerlund 1. I. Parallax method using Gaia-EDR3. *Mon. Not. R. Astron. Soc.* **2022**, *516*, 1289–1301. [[CrossRef](#)]
6. Munro, M.P.; Clark, J.S.; Crowther, P.A.; Dougherty, S.M.; de Grijs, R.; Law, C.; McMillan, S.L.W.; Morris, M.R.; Negueruela, I.; Pooley, D.; et al. A Neutron Star with a Massive Progenitor in Westerlund 1. *Astrophys. J.* **2006**, *636*, L41–L44. [[CrossRef](#)]
7. Krimm, H.; Barthelmy, S.; Campana, S.; Cummings, J.; Israel, G.; Palmer, D.; Parsons, A. Swift detects a hard X-ray burst from AXP CXOU J164710.2-455216. *GRB Coord. Netw.* **2006**, *5581*, 1.
8. Munro, M.P.; Gaensler, B.M.; Clark, J.S.; de Grijs, R.; Pooley, D.; Stevens, I.R.; Portegies Zwart, S.F. Exciting the magnetosphere of the magnetar CXOU J164710.2-455216 in Westerlund 1. *Mon. Not. R. Astron. Soc.* **2007**, *378*, L44–L48. [[CrossRef](#)]
9. Mereghetti, S.; Savchenko, V.; Ferrigno, C.; Götz, D.; Rigoselli, M.; Tiengo, A.; Bazzano, A.; Bozzo, E.; Coleiro, A.; Courvoisier, T.J.L.; et al. INTEGRAL Discovery of a Burst with Associated Radio Emission from the Magnetar SGR 1935+2154. *Astrophys. J.* **2020**, *898*, L29. [[CrossRef](#)]
10. Staveley-Smith, L.; Wilson, W.E.; Bird, T.S.; Disney, M.J.; Ekers, R.D.; Freeman, K.C.; Haynes, R.F.; Sinclair, M.W.; Vaile, R.A.; Webster, R.L.; et al. The Parkes 21 CM multibeam receiver. *Publ. Astron. Soc. Aust.* **1996**, *13*, 243–248. [[CrossRef](#)]
11. Israel, G.L.; Campana, S.; Dall’Osso, S.; Munro, M.P.; Cummings, J.; Perna, R.; Stella, L. The Post-Burst Awakening of the Anomalous X-Ray Pulsar in Westerlund 1. *Astrophys. J.* **2007**, *664*, 448–457. [[CrossRef](#)]
12. Cordes, J.M.; Lazio, T.J.W. NE2001.I. A New Model for the Galactic Distribution of Free Electrons and its Fluctuations. *arXiv* **2002**, arXiv:astro-ph/0207156.
13. van Straten, W.; Bailes, M. DSPSR: Digital Signal Processing Software for Pulsar Astronomy. *Publ. Astron. Soc. Aust.* **2011**, *28*, 1–14. [[CrossRef](#)]
14. Hotan, A.W.; van Straten, W.; Manchester, R.N. PSRCACHE and PSRFITS: An Open Approach to Radio Pulsar Data Storage and Analysis. *Publ. Astron. Soc. Aust.* **2004**, *21*, 302–309. [[CrossRef](#)]

15. van Straten, W.; Demorest, P.; Osłowski, S. Pulsar Data Analysis with PSRCHIVE. *Astron. Res. Technol.* **2012**, *9*, 237–256. [CrossRef]
16. Lorimer, D.R. SIGPROC: Pulsar Signal Processing Programs. Astrophysics Source Code Library. record ascl:1107.016. 2011. Available online: <https://ui.adsabs.harvard.edu/abs/2011ascl.soft07016L> (accessed on 1 September 2023)
17. Ransom, S. PRESTO: Pulsar Exploration and Search TOolkit. Astrophysics Source Code Library.ascl: 1107.017. 2011. Available online: <https://ui.adsabs.harvard.edu/abs/2011ascl.soft07017R%2F/abstract> (accessed on 19 August 2023).
18. Price, D.C.; Flynn, C.; Deller, A. A comparison of Galactic electron density models using PyGEDM. *Publ. Astron. Soc. Aust.* **2021**, *38*, e038. [CrossRef]
19. Yao, J.M.; Manchester, R.N.; Wang, N. A New Electron-density Model for Estimation of Pulsar and FRB Distances. *Astrophys. J.* **2017**, *835*, 29. [CrossRef]
20. Ridolfi, A.; Gautam, T.; Freire, P.C.C.; Ransom, S.M.; Buchner, S.J.; Possenti, A.; Venkatraman Krishnan, V.; Bailes, M.; Kramer, M.; Stappers, B.W.; et al. Eight new millisecond pulsars from the first MeerKAT globular cluster census. *Mon. Not. R. Astron. Soc.* **2021**, *504*, 1407–1426. [CrossRef]
21. Johnston, H.M.; Kulkarni, S.R. On the Detectability of Pulsars in Close Binary Systems. *Astrophys. J.* **1991**, *368*, 504. [CrossRef]
22. Ransom, S.M.; Cordes, J.M.; Eikenberry, S.S. A New Search Technique for Short Orbital Period Binary Pulsars. *Astrophys. J.* **2003**, *589*, 911–920. [CrossRef]
23. Morello, V.; Barr, E.D.; Stappers, B.W.; Keane, E.F.; Lyne, A.G. Optimal periodicity searching: Revisiting the fast folding algorithm for large-scale pulsar surveys. *Mon. Not. R. Astron. Soc.* **2020**, *497*, 4654–4671. [CrossRef]
24. Staelin, D.H. Fast folding algorithm for detection of periodic pulse trains. *IEEE Proc.* **1969**, *57*, 724–725. [CrossRef]
25. Wongpicheauxsorn, J.; Champion, D.J.; Bailes, M.; Balakrishnan, V.; Barr, E.D.; Bernadich, M.C.i.; Bhat, N.D.R.; Burgay, M.; Cameron, A.D.; Chen, W.; et al. The High Time Resolution Universe Pulsar survey—XVIII. The reprocessing of the HTRU-S Low Lat survey around the Galactic Centre using a Fast Folding Algorithm pipeline for accelerated pulsars. *Mon. Not. R. Astron. Soc.* **2024**, *527*, 3208–3219. [CrossRef]
26. Komesaroff, M.M.; Ables, J.G.; Cooke, D.J.; Hamilton, P.A.; McCulloch, P.M. Results and Implications of a Recent Search for High-Dispersion Pulsars. *Astrophys. Lett.* **1973**, *15*, 169.
27. Frail, D.A.; Weisberg, J.M. A Critical Evaluation of Pulsar Distance Measurements. *Astron. J.* **1990**, *100*, 743. [CrossRef]
28. Verbiest, J.P.W.; Weisberg, J.M.; Chael, A.A.; Lee, K.J.; Lorimer, D.R. On Pulsar Distance Measurements and Their Uncertainties. *Astrophys. J.* **2012**, *755*, 39. [CrossRef]
29. Bailes, M. The discovery and scientific potential of fast radio bursts. *Science* **2022**, *378*, abj3043. [CrossRef]
30. Petroff, E.; Hessels, J.W.T.; Lorimer, D.R. Fast radio bursts at the dawn of the 2020s. *Annu. Rev. Astron. Astrophys.* **2022**, *30*, 2. [CrossRef]
31. Barsdell, B.R.; Bailes, M.; Barnes, D.G.; Fluke, C.J. Accelerating incoherent dedispersion. *Mon. Not. R. Astron. Soc.* **2012**, *422*, 379–392. [CrossRef]
32. Nita, G.M.; Hellbourg, G. A Cross-Correlation based Spectral Kurtosis RFI Detector. In Proceedings of the 2020 XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio Science, Rome, Italy, 29 August–5 September 2020; pp. 1–4. [CrossRef]
33. Aggarwal, K.; Agarwal, D.; Kania, J.W.; Fiore, W.; Thomas, R.A.; Ransom, S.M.; Demorest, P.B.; Wharton, R.S.; Burke-Spolaor, S.; Lorimer, D.R.; et al. Your: Your Unified Reader. *J. Open Source Softw.* **2020**, *5*, 2750. [CrossRef]
34. Edwards, R.T.; Hobbs, G.B.; Manchester, R.N. TEMPO2, a new pulsar timing package - II. The timing model and precision estimates. *Mon. Not. R. Astron. Soc.* **2006**, *372*, 1549–1574. [CrossRef]
35. Gennaro, M.; Goodwin, S.P.; Parker, R.J.; Allison, R.J.; Brandner, W. Hierarchical formation of Westerlund 1: A collapsing cluster with no primordial mass segregation? *Mon. Not. R. Astron. Soc.* **2017**, *472*, 1760–1769. [CrossRef]
36. Andrews, H.; Fenech, D.; Prinja, R.K.; Clark, J.S.; Hindson, L. A radio census of the massive stellar cluster Westerlund 1. *Annu. Rev. Astron. Astrophys.* **2019**, *632*, A38. [CrossRef]
37. Fenech, D.M.; Clark, J.S.; Prinja, R.K.; Dougherty, S.; Najarro, F.; Negueruela, I.; Richards, A.; Ritchie, B.W.; Andrews, H. An ALMA 3 mm continuum census of Westerlund 1. *Annu. Rev. Astron. Astrophys.* **2018**, *617*, A137. [CrossRef]
38. Silich, S.; Turner, J.; Mackey, J.; Martínez-González, S. Molecular Gas Properties in Young Stellar Clusters with a Suppressed Star Cluster Wind. *Astrophys. J.* **2023**, *944*, L32. [CrossRef]
39. Lorimer, D.R.; Kramer, M. *Handbook of Pulsar Astronomy*; Cambridge University Press: Cambridge, UK, 2004; Volume 4.
40. Rocha, D.F.; Almeida, L.A.; Damineli, A.; Navarete, F.; Abdul-Masih, M.; Mace, G.N. Distance and age of the massive stellar cluster Westerlund 1—II. The eclipsing binary W36. *Mon. Not. R. Astron. Soc.* **2022**, *517*, 3749–3762. [CrossRef]
41. Beasor, E.R.; Smith, N.; Andrews, J.E. Don't Believe the Hype(r): The Yellow Supergiants of Westerlund 1. *Astrophys. J.* **2023**, *952*, 113. [CrossRef]
42. Ronchi, M.; Rea, N.; Graber, V.; Hurley-Walker, N. Long-period Pulsars as Possible Outcomes of Supernova fallback Accretion. *Astrophys. J.* **2022**, *934*, 184. [CrossRef]
43. Graber, V.; Ronchi, M.; Pardo-Araujo, C.; Rea, N. Isolated pulsar population synthesis with simulation-based inference. *arXiv* **2023**, arXiv:2312.14848.

44. Olausen, S.A.; Kaspi, V.M. VizieR Online Data Catalog: The McGill Magnetar Catalog (Olausen+, 2014). 2014. Available online: <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJS/212/6> (accessed on 26 April 2024).
45. Ruderman, M. Pulsars: Structure and Dynamics. *Annu. Rev. Astron. Astrophys.* **1972**, *10*, 427. [[CrossRef](#)]

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