A Study of 10 Rotating Radio Transients Using Parkes Radio Telescope postprint

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Date: 2024-05-10T00:00:00+00:00

Abstract

Rotating Radio Transients (RRATs) are a relatively new subclass of pulsars that emit detectable radio bursts sporadically. We analyzed 10 RRATs observed using the Parkes telescope, with eight of these observed via the ultra-wide-bandwidth low-frequency (UWL) receiver. We measured the burst rate and produced integrated profiles spanning multiple frequency bands for three RRATs. We also conducted a spectral analysis on both integrated pulses and individual pulses of three RRATs. All of their integrated pulses follow a simple power law, consistent with the known range of pulsar spectral indices. Their average spectral indices of single pulses are −0.9, −1.2, and −1.0 respectively, which are within the known range of pulsar spectral indices. Additionally, we find that the spreads of single-pulse spectral indices for these RRATs (ranging from −3.5 to +0.5) are narrower compared to what has been observed in other RRATs. Notably, the average spectral index and scatter of single pulses are both relatively small. For the remaining five RRATs observed at the UWL receiver, we also provide the upper limits on fluence and flux density. In addition, we obtain the timing solution of PSR J1709-43. Our analysis shows that PSRs J1919+1745, J1709-43, and J1649-4653 are potentially nulling pulsars or weak pulsars with sparse strong pulses.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:045010 (10pp), 2024 April

A Study of 10 Rotating Radio Transients Using the Parkes Radio Telescope

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Received 2023 October 23; revised 2024 February 7; accepted 2024 February 26; published 2024 March 27

Abstract

Rotating Radio Transients (RRATs) represent a relatively new subclass of pulsars characterized by sporadic, detectable radio bursts. We analyzed 10 RRATs observed with the Parkes telescope, eight of which were observed using the ultra-wide-bandwidth low-frequency (UWL) receiver. We measured burst rates and generated integrated profiles across multiple frequency bands for three RRATs, and conducted spectral analysis on both integrated and individual pulses for these three sources. All integrated pulses follow a simple power law, consistent with known pulsar spectral indices. Their average single-pulse spectral indices are −0.9, −1.2, and −1.0, respectively, which fall within the established range for pulsars. Additionally, we find that the spreads of single-pulse spectral indices for these RRATs (ranging from −3.5 to +0.5) are narrower than those observed in other RRATs. Notably, both the average spectral index and the scatter of single pulses are relatively small. For the remaining five RRATs observed with the UWL receiver, we provide upper limits on fluence and flux density. We also obtained a timing solution for PSR J1709-43. Our analysis suggests that PSRs J1919+1745, J1709-43, and J1649-4653 are potentially nulling pulsars or weak pulsars with sparse strong pulses.

Key words: (stars:) pulsars: general -stars: neutron -stars: individual (PSRs J1919+1745, 1909+0641, 0628+0909)

1. Introduction

Pulsars serve as cosmic lighthouses and powerful tools for numerous astronomical investigations. They are commonly utilized to test General Relativity (GR; e.g., Kramer et al. 2006; Antoniadis et al. 2013) and are frequently timed for Pulsar Timing Arrays (PTAs) due to their stable spin periods (e.g., Hobbs et al. 2010; Manchester et al. 2013). Pulsars also enable probing of the interstellar medium (ISM; Han et al. 2018). While most known pulsars have been discovered through periodicity-based searches (Lorimer & Kramer 2012), Rotating Radio Transients (RRATs), a subclass of canonical pulsars, were detected through single-pulse searches rather than standard Fourier domain searches or conventional folding techniques (McLaughlin et al. 2006; Keane & McLaughlin 2011).

RRATs are notable for their sporadic emissions, with only a few pulses detected each hour (e.g., Keane et al. 2011). Another intriguing characteristic is their similarity to Fast Radio Bursts (FRBs)—extremely bright, millisecond-duration burst events. Single RRAT pulses appear indistinguishable from FRB pulses. Dispersion Measure (DM) quantifies the time delay caused by interstellar and intergalactic media. Generally, FRBs exhibit larger DM values due to their extragalactic origin (Bhandari et al. 2018), while RRATs show relatively lower DM values (Dong et al. 2023). Previous studies have attempted to identify potentially misclassified FRBs as RRATs, particularly when sources have only been detected through single-pulse searches (Keane 2016; Rane & Loeb 2016). Magnetars—neutron stars with extremely high magnetic fields (Kaspi & Beloborodov 2017)—have been suggested as possible sources of high-energy phenomena such as FRBs (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020). Consequently, discovering more RRATs and magnetars can provide insights into the distribution of Galactic pulsars and help characterize the populations of RRATs, FRBs, and magnetars.

RRATs are Galactic pulsars characterized by extremely variable single-pulse emission. They emit individual pulses followed by long periods of no detectable emission. However, only a few telescopes with high sensitivity are capable of detecting such intermittent emissions and obtaining sufficient single-pulse and periodic emission statistics. This inherent detection challenge has resulted in incomplete knowledge regarding the fraction of RRATs that exhibit nulling behavior. Currently, many RRATs lack precisely measured rotation periods, and approximately two-thirds have not had their burst rates determined due to insufficient follow-up observations. This data gap significantly hinders proper characterization of these sources (McKenna et al. 2023). Consequently, long-term monitoring and timing observations are essential for RRATs.

The sporadic emission mechanism of RRATs remains unknown, primarily due to detection difficulties. Despite the discovery of nearly 170 RRATs as of 2023 (e.g., Tyul' bashev et al. 2018; Good et al. 2021), their elusive nature has posed significant challenges in understanding their emission behavior. Since their initial discovery, several models have been proposed to explain these phenomena, including: normal pulsars exhibiting extreme nulling (e.g., Wang et al. 2007; Burke-Spolaor & Bailes 2010), fallback of supernova-trapped plasma released from material radiation belts (Luo & Melrose 2007), and interference from asteroidal or circumpulsar debris (Cordes & Shannon 2008). Alternatively, the mechanism could be related to processes within the pulsar magnetosphere (e.g., Timokhin 2010; Li et al. 2012; Melrose & Yuen 2014). Recent efforts have focused on understanding this phenomenon. To establish potential connections between RRATs and normal pulsars, Zhou et al. (2023) conducted an in-depth analysis of 76 Galactic RRATs and their emission patterns, concluding that RRATs are predominantly weaker pulsars with occasional strong pulses or extreme nulling pulsars.

In this paper, we present observations of 10 RRATs conducted at the Parkes 64 m radio telescope using the ultra-wide-bandwidth low-frequency (UWL) receiver, which covers the continuous frequency range of 704–4032 MHz (Hobbs et al. 2020). This receiver system provides unprecedented broadband information, including valuable polarization data, that is pivotal for advancing our understanding of radiation phenomena and ISM effects such as scintillation and DM variability (e.g., Karako-Argaman et al. 2015; Heald et al. 2020). Apart from its large fractional bandwidth, the UWL receiver also has low system temperature, enabling effective operation even in the presence of strong mobile phone transmissions (Hobbs et al. 2020). In recent years, the UWL receiver has played a crucial role in numerous scientific projects related to high-precision pulsar timing, broadband analysis of pulsar profiles, and detection of new pulsars and transient sources. Additionally, we analyze the emission characteristics of two RRATs observed with other receivers at the Parkes telescope.

2. Observations

The Parkes Radio Telescope data archive has been publicly available since 1991, with datasets for numerous observations released after an 18-month embargo (Hobbs et al. 2011). Our observations were obtained under project code P1016 – "Instant GRRATification." The RRATs in our sample were observed using the Multibeam, H-OH, 10/50 cm, and UWL receivers (e.g., Manchester et al. 2013; Hobbs et al. 2020). Most observations employed the UWL receiver system, with 3328 MHz of bandwidth centered at 2368 MHz and folded in real time into 1024 phase bins. This receiver provides continuous frequency coverage from 704 to 4032 MHz with low system temperature (Hobbs et al. 2020). PSRs J1649-4653 and J1709-43 were observed with the Multibeam Receiver, which provides 256 MHz of bandwidth divided into 1024 frequency channels and folded in real time into 1024 phase bins. The H-OH receiver typically provides 512 MHz bandwidth, while the 10/50 cm receiver provides 1024 MHz. All data were recorded in PSRFITS format (Hotan et al. 2004). We used five backend systems during observations: MEDUSA and the Parkes Digital FilterBank systems (PDFB1, PDFB2, PDFB3, and PDFB4; Hobbs et al. 2006).

We investigated 10 RRATs in the CSIRO pulsar data archive, with all observation data publicly available as of 2021. UWL receiver data were acquired in search mode, while H-OH, Multibeam, and 10/50 cm receiver data were acquired in fold mode. Table 1 summarizes the observations, listing fundamental telescope and project information. Search-mode datasets were subsequently folded using DSPSR (van Straten & Bailes 2011) at the rotation periods, and DMs for the RRATs were obtained using PSRCAT (Manchester et al. 2005).

The PAZ tool in PSRCHIVE (Hotan et al. 2004) was used to eliminate narrowband and impulsive radio frequency interference (RFI). To further mitigate potential RFI contamination, we utilized the PFITS_{ZAPPROFILE} tool in PFITS to process all data. PFITS is a software package designed for reading, manipulating, and processing PSRFITS-format pulsar astronomy data from both search and fold modes. Flux density calibration was performed through observations of the radio galaxy Hydra A (3C 218), with calibration methods described in Liu & Yu (2020). Calibration data were applied to RRAT observations using the PAC tool to flatten the bandpass and transform polarization products to Stokes parameters. To convert measured intensities to absolute flux densities, we used PAAS to form noise-free standard templates from observations and then employed PSRFLUX to obtain flux density values.

To obtain spectral information for RRATs, we divided the frequency bands into several parts and utilized the PULSAR_{SPECTRA} software to find the best-fitting model and produce publication-quality plots (Swainston et al. 2022).

3.1. Identification of Single Pulses

The first step in our analysis is to discern pulses originating from the RRATs. The intermittent nature of RRAT emissions renders Fourier-based techniques or conventional folding search algorithms impractical. Following the method of Xie et al. (2022), we employed a single-pulse search method to specifically target individual pulses surpassing a predefined signal-to-noise ratio (S/N) threshold. Generally, a single-pulse phase can be segmented into two components: the on-pulse region and the off-pulse region. The off-pulse energy is commonly characterized by a Gaussian distribution. We set a minimum detection threshold of 5σ for each pulse, where σ represents the standard deviation of the off-pulse region. To filter out RFI, we exclusively considered pulses whose times of arrival (ToAs) derived from the brightest pulse during an observation fell within a 5% deviation from the expected phase. To minimize potential contamination from RFI, each pulse was visually inspected, including examination of its frequency-phase plots. The total number of detected pulses, the count of filtered pulses, and the burst rates for all target RRATs are listed in Table 1. We detected single pulses in only three RRATs (PSRs J1919+1745, J1909+0641, and J0628+0909).

The integrated profiles of all observations for these three RRATs are shown in the upper panels of Figure 1 [Figure 1: see original paper], with on-pulse and off-pulse regions indicated by filled blue and gray areas, respectively. The lower panels of Figure 1 display single-pulse stacks of 15 individual pulses for each RRAT, with burst pulses signified by red solid lines. It is evident that all three RRATs exhibit sporadic emissions. The burst rate of PSR J1919+1745 is 847 h^{-1}, substantially higher than that of PSR J0628+0909 (60 h^{-1}) and PSR J1909+0641 (58 h^{-1}).

3.2. Profile Analysis

A flux calibration procedure was applied to all observational data. For search-mode data, we conducted observations of each RRAT either once or twice, with each observation lasting approximately one hour. To manage individual file sizes, data were automatically divided into multiple files. We utilized all observation files to generate a cumulative pulse profile, aiming to enhance the S/N. For fold-mode data, our analysis focused only on the integrated profile of PSR J1709-43. The sub-integration lengths across 103 observations varied between 10, 20, 30, or 50 minutes. To analyze frequency-dependent characteristics of the integrated pulse profile, we utilized single observational data acquired at three frequencies: 732, 1369, and 3094 MHz. Each observation file contained 30 sub-integrations, and pulse profiles were observed across all sub-integrations. Therefore, the sub-integration length across observations did not exert a significant influence on the integrated profile.

3.3. Flux Density Measurements and Spectral Properties

We utilized the PULSAR_{SPECTRA} software package developed by Swainston et al. (2022), which incorporates robust statistical techniques to determine the optimal fitting model and calculate corresponding spectral parameters. This publicly available software presents a comprehensive suite of tools dedicated to systematic cataloging of pulsar flux density and automated spectral fitting. The use of this software facilitates identification of the most appropriate spectral model. Notably, the Python-based software implements five spectral models: simple power law, broken power law, log-parabolic spectrum, power law with high-frequency cut-off, and power law with low-frequency turnover. These models are adequate for describing the spectra of the vast majority of pulsars, with the simple and broken power-law models being the most widely employed. Although these models are morphological, the spectral index may potentially be associated with other pulsar parameters. The spectral fitting routine implements the method illustrated in Jankowski et al. (2018). To compare the five models, we applied the Akaike Information Criterion (AIC) as a metric, evaluating how much information the model retains about the data without overfitting. The model yielding the lowest AIC is considered most accurate for describing the pulsar's spectrum. A more comprehensive description of the PULSAR_{SPECTRA} software package can be found in Swainston et al. (2022). We present spectral fitting results from integrated pulses of several RRATs and apply a similar spectral analysis procedure to individual pulses with high S/N.

4.1. Search-Mode Data

Radio emission from pulsars is affected by propagation through the ISM in both frequency and time domains, spanning durations from seconds to several hours. This phenomenon is recognized as diffractive scintillation. We estimate the scattering time, τ , at a reference frequency of 1400 MHz using the empirical relationship to DM acquired by Kumamoto et al. (2021):

$$\tau_s = 0.00194 \times \mathrm{DM}^{1.0}$$

For the wide frequency band of the UWL receiver, we apply the typical relation τ $^{-4}$ (Komesaroff et al. 1972) to estimate scattering time at 950 and 3500 MHz. The scintillation bandwidth in MHz, Δ _d, is given by Cordes & Rickett (1998) as:

$$\Delta\nu_d = 1.16 \times 10^{-3} \times \mathrm{DM}^{-1.2} \times \nu_0^{4.4}$$

We estimated scintillation bandwidth for three RRATs at frequencies of 950, 1400, and 3500 MHz, as shown in Table 2 .

The entire observation bandwidth was divided into several sub-bands. For PSRs J1919+1745 and J0628+0909, the minimum bandwidth of each sub-band is 100 MHz, while for PSR J1909+0641 it is 200 MHz. The estimated scintillation bandwidths for PSRs J1919+1745, J1909+0641, and J0628+0909 are all significantly smaller than the minimum bandwidth of each corresponding sub-band. Therefore, the impact of scintillation effects on flux density is deemed negligible in this study.

4.1.1. PSR J1919+1745

We obtained 835 burst pulses, constituting approximately 48% of all detected single pulses. In Figure 2 [Figure 2: see original paper], we present integrated profiles of the entire frequency band using 62 observations, as well as those of nine sub-bands. All profiles exhibit narrow double-peak characteristics. The observed pulse width is 0.6 ms and shows negligible variation with frequency. The peak flux densities of the two components in the total integrated profile are similar. At lower frequencies (918-1600 MHz), the latter component dominates. At middle frequencies (1601-2368 MHz), the flux densities of both peaks are comparable. At higher frequencies (2369-4032 MHz), the earlier component shows a slightly larger peak flux density. Furthermore, the flux densities of both peaks exhibit a decreasing trend with increasing frequency.

Using the method described in Section 3.3, we found that the spectra of both integrated and individual pulses can be characterized by a simple power law of the form:

$$S_\nu = c \times \left(\frac{\nu}{\nu_0}\right)^\alpha$$

where α is the spectral index, $_0$ is the center frequency, and c is a constant.

Figure 3 Figure 3: see original paper shows that the spectral index of the integrated pulses is −0.9, which is flatter compared to the average spectral index of most pulsars (−1.60 ± 0.03, Jankowski et al. 2018). A spectral fitting analysis was conducted on a sample of 49 individual pulses with high S/N, and all results followed the simple power law. The average spectral index of these 49 single pulses is −1.0, ranging from −3.5 to 0.01. An example of a single-pulse spectrum is displayed in Figure 3(b).

4.1.2. PSR J1909+0641

During the 2-hour observation period, we identified 116 burst pulses, corresponding to a burst rate of 58 h^{-1}. The integrated profiles encompassing the entire frequency band and six sub-bands exhibit a distinct narrow feature, as depicted in Figure 4 [Figure 4: see original paper]. The pulse width across various frequency bands is 0.08 ms, and the peak flux density follows the general trend of decreasing with increasing frequency.

We performed spectral analysis on the integrated pulse as well as on seven distinct single pulses. Notably, all spectra exhibited a simple power-law distribution. As affirmed in Figure 5 Figure 5: see original paper, the spectral index of the integrated pulse is −1.2, which is relatively flatter compared to the average spectral index of pulsars. Furthermore, the average spectral index of individual pulses is approximately −1.0, spanning from −1.5 to 0.05, as presented in Figure 5(b).

4.1.3. PSR J0628+0909

We detected 61 individual pulses in 1 hour, corresponding to a burst rate of 60 h^{-1}. The pulse width is 0.11 ms. The data were split into seven sub-bands, and we input the flux densities of these sub-bands into the PULSAR_{SPECTRA} flux density catalog. The spectrum of an integrated pulse can be characterized as a simple power law with a spectral index of −1.3, which is relatively flatter than the average spectral index of normal pulsars. We implemented spectral fitting on 22 high S/N single pulses using the same approach. The vast majority of single-pulse spectra also follow a simple power law, as presented in Figures 6(a) and (b), with an average spectral index of −1.0 and a range of −1.9 to 0.5. Notably, there is one intriguing single pulse that could be divided into 11 sub-bands, and its spectrum can be modeled as a high-frequency cut-off power law, as shown in Figure 6 Figure 6: see original paper, which takes the form:

$$S_\nu = c \times \left(\frac{\nu}{\nu_0}\right)^{\alpha} \times \exp\left[-\left(\frac{\nu}{\nu_c}\right)^{2}\right]$$

where α is the spectral index, _c is the cut-off frequency, and c is a constant. This model exhibits spectrum steepening or interruption at high frequencies. A possible explanation suggests that radiation originates in the inner (polar) gap, where electrons are accelerated in an electric field increasing from zero at the star' s surface. In this process, electron acceleration reaches a maximum and decreases to zero as their velocity approaches the speed of light, with all emitted power concentrated within the radio frequency band (Kontorovich & Flanchik 2013).

4.1.4. Other RRATs in Search Mode

For the remaining RRATs observed with the UWL receiver, we could not create reliable profiles. Therefore, we were unable to carry out subsequent processing and analysis as done for the previous three RRATs.

Limits on the flux density of a single pulse can be described by the equation (Tang et al. 2021):

$$S_{\min} = \frac{\sigma \times T_{\text{sys}}}{G \times \sqrt{\Delta\nu \times t_{\text{obs}}}}$$

where T_{sys} = 22 K is the system temperature, G = 1.8 K Jy^{-1} is the antenna gain for the Parkes UWL receiver, t_{obs} is the observation time, σ is the root-mean-square (rms) noise level, and Δ is the full 3300 MHz bandwidth. For periodic signals, Equation (5) should be multiplied by $\sqrt{\delta}$, where δ is the duty cycle. Due to the absence of a measured pulse width for PSR J1850+15 in previous investigations, we assumed a pulse width of 1 ms and a flat spectrum. Our non-detection of signals with S/N above 7 places a fluence limitation of 13 mJy ms. Detailed parameters regarding flux density and fluence limits for the five RRATs are listed in Table 3 .

4.2. Fold-Mode Data

4.2.1. PSR J1709-43

We collected observational data spanning 7.2 years, from MJD 55537 to 58168, comprising 103 observations conducted entirely in fold mode. Pulse profiles were detected in 41 observations (40% of the dataset). The majority exhibited continuous pulse signals across all sub-integrations, while only seven observations experienced nulling. Notably, the highest detection rate was obtained at 1400 MHz, accounting for 56% of observations. Three total intensity pulse profiles of PSR J1709-43 at 732, 1369, and 3094 MHz are in good agreement, exhibiting a narrow single-peaked structure, as presented in Figure 7 [Figure 7: see original paper]. These profiles follow the trends of decreasing width and peak flux density with increasing frequency.

In addition to the analysis presented in Section 3, we performed a timing analysis for PSR J1709-43, enabling us to determine its rotation period and period derivative. The full timing solutions are listed in Table 4 .

4.2.2. PSR J1649-4653

Similar to PSR J1709-43, we collected data for PSR J1649-4653 covering 11 years, from MJD 54220 to 58222, with a total observation time of 10 hours. All observations were carried out in fold mode. Out of these, 65 observations (51%) detected burst pulse profiles. Figure 8 [Figure 8: see original paper] illustrates the variation of peak flux density of J1649-4653 with time. The flux density of PSR J1649-4653 is significantly weak, with a value of 0.14 ± 0.02 mJy for detectable pulse profiles.

5. Discussion

We calculated burst rates for three RRATs: PSRs J1919+1745, J1909+0641, and J0628+0909. These rates were compared with results from the Arecibo telescope (Deneva et al. 2009) and the Five-hundred-meter Aperture Spherical Telescope (FAST; Hsu et al. 2023), as detailed in Table 5 . Notably, J1919+1745 exhibited exceptional behavior with an observed burst rate of 847 h^{-1}, significantly exceeding the previously reported rate of 320 h^{-1} from Arecibo. Furthermore, burst pulses constituted 50% of all observed individual pulses. Consequently, we suggest that PSR J1919+1745 may be reclassified from an RRAT to a nulling pulsar.

For PSR J1909+0641, the observed burst rate was 58 h^{-1}, slightly lower than the rate of 67 h^{-1} observed at Arecibo. For PSR J0628+0909, the burst rate observed in this study was 60 h^{-1}, compared to 141 h^{-1} reported by Arecibo (S/N > 5) and 270 h^{-1} reported by FAST (S/N > 7). We collected 103 fold-mode observations for PSR J1709-43, detecting pulse profiles in 41 observations (40%). Pulse signals were visible across all sub-integrations for most observations, with only seven experiencing nulling. For PSR J1649-4653, we collected 128 fold-mode observations, detecting pulse emissions in approximately 51% (65 observations). Our analysis suggests that variations in burst rates can be attributed to three primary factors.

First, variations in telescope sensitivity and observation bandwidth play a vital role. When telescopes with higher sensitivity are employed, it is possible to detect a greater number of burst pulses. The different burst rates observed for PSR J0628+0909 may be attributed to varying telescope sensitivities, with FAST demonstrating the highest sensitivity and correspondingly the highest burst rate. Second, variations in observation duration can influence results. The observation durations at FAST and Arecibo were comparatively shorter than those at Parkes. Lastly, burst rates of RRATs may exhibit temporal evolution.

We analyzed integrated profiles spanning multiple frequency sub-bands for PSRs J1919+1745, J1909+0641, and J1709-43. A notable trend emerged: peak flux densities exhibited a diminishing trend with increasing frequency, consistent with previous results. Subsequently, we conducted analysis and fitting of flux density across various frequency sub-bands for both integrated and single pulses using the automated spectral fitting software PULSAR_{SPECTRA}.

We present spectral analyses of integrated pulses from three RRATs: PSRs J1919+1745, J1909+0641, and J0628+0909. All consistently follow a simple power law, with integrated results aligning with previous work reporting that 79% of pulsars exhibit simple power-law spectra (Jankowski et al. 2018).

We also applied similar spectral analysis to individual pulses with high S/N. The calculated mean single-pulse spectral indices for the three RRATs are presented in Table 6 . However, there is limited literature available for comparing single-pulse spectral results. Previous studies by Shapiro-Albert et al. (2018) reported mean spectral indices for PSRs J1819-1458, J1317-5759, and J1913+1330 as -1.1, -0.6, and -1.2, respectively, with single-pulse spectral indices ranging from -7 to $+4$. Xie et al. (2022) reported a mean single-pulse spectral index of -3.2 for PSR J0139+3336, with an extensive range from -11.85 to $+3.83$. The frequency ranges for these observations were relatively narrow, spanning 288 and 500 MHz, respectively. Meyers et al. (2019) reported a single-pulse mean spectral index of -2.2 for PSR J2335-0530, ranging from -2.8 to -1.5, with observational data covering a broad frequency range (154.24 MHz with 30.72 MHz bandwidth and 1396 MHz with 256 MHz bandwidth). Our results exhibit relatively lower scatter compared to those of Shapiro-Albert et al. (2018) and Xie et al. (2022), which may be attributed to our broader frequency range (3300 MHz) and longer observation duration.

6. Summary

We performed an analysis of emission properties for 10 RRATs, obtaining burst rates for three RRATs and integrated profiles across multiple frequency bands for three RRATs. We conducted an in-depth wideband analysis of integrated pulse and single-pulse spectral characteristics using the PULSAR_{SPECTRA} software package. Our findings indicate that the vast majority of these characteristics align with a simple power-law model, featuring relatively flat spectral indices and comparatively small scatter in single-pulse spectral indices. For five additional RRATs observed with the UWL receiver, we provide upper limits on fluence and flux density. Furthermore, we derived a timing solution for PSR J1709-43. Based on the classification of 76 recently discovered RRATs by FAST in the previous work of Zhou et al. (2023), we suggest that PSRs J1919+1745, J1709-43, and J1649-4653 may be nulling pulsars or weak pulsars with sparse strong pulses.

Acknowledgments

The Parkes radio telescope is part of the Australia Telescope National Facility, funded by the Australian Government to operate as a National Facility managed by CSIRO. This paper includes archived data obtained through the CSIRO Data Access Portal. This work is supported by the Major Science and Technology Program of Xinjiang Uygur Autonomous Region (grant no. 2022A03013-4), the Zhejiang Provincial Natural Science Foundation of China (grant no. LY23A030001), the National SKA Program of China (grant nos. 2020SKA0120100, 2022YFC2205201, 2020SKA0120200), the Natural Science Foundation of Xinjiang Uygur Autonomous Region (grant no. 2022D01D85), the National Natural Science Foundation of China (NSFC, grant nos. 12041304, 12273100, and 12041303), the West Light Foundation of Chinese Academy of Sciences (grant no. WLFC 2021-XBQNXZ-027), and the open program of the Key Laboratory of Xinjiang Uygur Autonomous Region (grant no. 2020D04049).

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References

Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, Sci, 340, 448
Bhandari, S., Keane, E. F., Barr, E. D., et al. 2018, MNRAS, 475, 1427
Bochenek, C. D., Ravi, V., Belov, K. V., et al. 2020, Natur, 587, 59
Burke-Spolaor, S., & Bailes, M. 2010, MNRAS, 402, 855
CHIME/FRB Collaboration, Andersen, B. C., Bandura, K. M., et al. 2020, Natur, 587, 54
Cordes, J. M., & Rickett, B. J. 1998, ApJ, 507, 846
Cordes, J. M., & Shannon, R. M. 2008, ApJ, 682, 1152
Deneva, J. S., Cordes, J. M., McLaughlin, M. A., et al. 2009, ApJ, 703, 2259
Dong, F. A., Crowter, K., Meyers, B. W., et al. 2023, MNRAS, 524, 5132
Good, D. C., Andersen, B. C., Chawla, P., et al. 2021, ApJ, 922, 43
Han, J. L., Manchester, R. N., van Straten, W., & Demorest, P. 2018, ApJS, 234, 11
Heald, G., Mao, S., Vacca, V., et al. 2020, Galax, 8, 53
Hobbs, G., Archibald, A., Arzoumanian, Z., et al. 2010, CQGra, 27, 084013
Hobbs, G. B., Edwards, R. T., & Manchester, R. N. 2006, MNRAS, 369, 655
Hobbs, G., Manchester, R. N., Dunning, A., et al. 2020, PASA, 37, e012
Hobbs, G., Miller, D., Manchester, R. N., et al. 2011, PASA, 28, 202
Hotan, A. W., van Straten, W., & Manchester, R. N. 2004, PASA, 21, 302
Hsu, J. A., Jiang, J. C., Xu, H., Lee, K. J., & Xu, R. X. 2023, MNRAS, 518, 1418
Jankowski, F., van Straten, W., Keane, E. F., et al. 2018, MNRAS, 473, 4436
Karako-Argaman, C., Kaspi, V. M., Lynch, R. S., et al. 2015, ApJ, 809, 67
Kaspi, V. M., & Beloborodov, A. M. 2017, ARA&A, 55, 261
Keane, E. F. 2016, MNRAS, 459, 1360
Keane, E. F., Kramer, M., Lyne, A. G., Stappers, B. W., & McLaughlin, M. A. 2011, MNRAS, 415, 3065
Keane, E. F., & McLaughlin, M. A. 2011, BASI, 39, 333
Komesaroff, M. M., Hamilton, P. A., & Ables, J. G. 1972, AuJPh, 25, 759
Kontorovich, V. M., & Flanchik, A. B. 2013, Ap&SS, 345, 169
Kramer, M., Stairs, I. H., Manchester, R. N., et al. 2006, Sci, 314, 97
Kumamoto, H., Dai, S., Johnston, S., et al. 2021, MNRAS, 501, 4490
Li, J., Spitkovsky, A., & Tchekhovskoy, A. 2012, ApJL, 746, L24
Li, X.-D. 2006, ApJL, 646, L139

Liu, B., & Yu, S. 2020, in Big Data in Astronomy: Scientific Data Processing for Advanced Radio Telescopes, ed. L. Kong et al., 165 (Amsterdam: Elsevier)
Lorimer, D. R., & Kramer, M. 2012, Handbook of Pulsar Astronomy (Cambridge: Cambridge Univ. Press)
Luo, Q., & Melrose, D. 2007, MNRAS, 378, 1481
Manchester, R. N., Hobbs, G., Bailes, M., et al. 2013, PASA, 30, e017
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
McKenna, D. J., Keane, E. F., Gallagher, P. T., & McCauley, J. 2024, MNRAS, 527, 4397
McLaughlin, M. A., Lyne, A. G., Keane, E. F., et al. 2009, MNRAS, 400, 1431
McLaughlin, M. A., Lyne, A. G., Lorimer, D. R., et al. 2006, Natur, 439, 817
Melrose, D. B., & Yuen, R. 2014, MNRAS, 437, 262
Meyers, B. W., Tremblay, S. E., Bhat, N. D. R., et al. 2019, PASA, 36, e034
Rane, A., & Loeb, A. 2016, arXiv:1608.06952
Shapiro-Albert, B. J., McLaughlin, M. A., & Keane, E. F. 2018, ApJ, 866, 152
Swainston, N. A., Lee, C. P., McSweeney, S. J., & Bhat, N. D. R. 2022, PASA, 39, e056
Tang, Z., Zhang, S., Dai, S., Li, Y., & Wu, X. 2021, arXiv:2106.04821
Timokhin, A. N. 2010, MNRAS, 408, L41
Tyul' bashev, S. A., Tyul' bashev, V. S., & Malofeev, V. M. 2018, A&A, 618, A70
van Straten, W., & Bailes, M. 2011, PASA, 28, 1
Wang, N., Manchester, R. N., & Johnston, S. 2007, MNRAS, 377, 1383
Xie, J., Wang, J., Wang, N., et al. 2022, ApJL, 940, L21
Zhou, D. J., Han, J. L., Xu, J., et al. 2023, RAA, 23, 104001

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