Statistical Study of Physical Parameters of Rotating Radio Transients Postprint

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Abstract

Rotating radio transients have been discovered for nearly 20,yr, yet their specific origin remains insufficiently understood. This study collected literature to identify a total of 182 discovered rotating radio transients, updated the rotating radio transient database, and conducted statistical analysis on observational parameters including spatial position, period, period derivative, dispersion measure, distance, characteristic age, characteristic magnetic field, Faraday rotation measure, and linear polarization degree. It was found that, except for Faraday rotation measure, the logarithms of all other aforementioned observational parameters follow a normal distribution. Compared with pulsars, rotating radio transients exhibit similar spatial positions, with average values of period, period derivative, and surface magnetic field being slightly larger than those of normal pulsars; characteristic age and Faraday rotation measure fall within the range of normal pulsars, while spin-down luminosity, dispersion measure, and distance are smaller than those of pulsars. These results hold significant importance for investigating the physical origin of rotating radio transients.

Full Text

Preamble

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Statistical Study of the Physical Parameters of Rotating Radio Transients

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Abstract

Rotating radio transients (RRATs) were discovered nearly 20 years ago, yet their specific origin remains unclear. This paper collects data on 182 discovered RRATs from the literature, updates the RRAT database, and performs statistical analyses of observational parameters including spatial position, period, period derivative, dispersion measure, distance, characteristic age, characteristic magnetic field, Faraday rotation measure, and linear polarization degree. We find that, except for Faraday rotation measure, the logarithms of all other observational parameters follow a normal distribution. Compared with pulsars, RRATs exhibit similar spatial distributions, with average values of period, period derivative, and surface magnetic field slightly larger than those of normal pulsars. Their characteristic ages and Faraday rotation measures fall within the range of normal pulsars, while their spin-down energy loss rates, dispersion measures, and distances are smaller than those of pulsars. These results carry important implications for investigating the physical origin of RRATs.

Keywords: stars: pulsars: general, pulsars: rotating radio transients, methods: data analysis

1 Introduction

Compared with the long history of optical telescopes, radio astronomy observations have only about 80 years of history, yet entered its golden age just three decades later. Since Hewish et al. [?] discovered the first pulsar, the realization of high time-resolution techniques in radio telescopes has provided opportunities to study the dynamic radio sky, opening up the unexplored field of fast radio transients. In recent years, many radio transients have been discovered in the radio band, such as intermittent pulsars [?], fast radio bursts (FRB) [?], and rotating radio transients (RRAT) [?]. Because RRAT radiation typically consists of sporadic single pulses, RRAT searches can only be conducted using single-pulse search methods, unlike pulsar searches that employ periodicity search techniques. The first RRAT was discovered by McLaughlin et al. [?] in 2006 using the Parkes 64 m radio telescope in Australia with single-pulse search techniques. Following the discovery of RRATs, periodicity searches and pulsar timing observations revealed that these new celestial objects have precise periods and period derivatives, just like pulsars. Subsequent investigations found that they also belong to the category of rapidly rotating neutron stars and may represent pulsars at a certain evolutionary stage [?, ?, ?].

As of June 2023, 182 RRATs have been discovered (see Appendix for details). RRATs exhibit the following characteristics: their periods range from 0.1 s to 7 s, individual pulse burst durations vary from 0.5 ms to 100 ms, and their flux density distribution is broad, ranging from 10 mJy to 10 Jy [?]. The pulse widths of rotating radio transients are also similar to those of ordinary pulsars [?], with intervals between adjacent pulses ranging from several minutes to tens of hours [?, ?]. Despite being discovered nearly two decades ago, the physical origin of RRATs has not been well explained. Various theories have been proposed to explain their origin: Burke-Spolaor and Bailes [?] suggested that RRATs represent a late evolutionary stage of pulsars; Wang et al. [?] proposed that RRATs are extreme nulling pulsars; and theories by Li [?] and Luo et al. [?] indicate that rotating radio transients are "dead" pulsars resulting from interactions between pulsar magnetospheres and surrounding material.

The nature of RRATs remains undetermined. Therefore, statistical studies of various RRAT parameters are crucial for investigating their origin and evolution. However, previous statistical studies of rotating radio transients have been scarce. This paper collects data on discovered RRATs from the literature to update the RRAT database, performs statistical analyses of observational parameters including spatial position, period, period derivative, dispersion measure, characteristic age, characteristic magnetic field, Faraday rotation measure, and linear polarization degree, and compares these parameters with those of pulsars to provide statistical evidence for studying the origin and evolution of RRATs.

2 Statistical Inventory of RRAT Parameters

Through literature collection, we identified 182 known RRATs. Appendix Table 1 presents the relevant parameters for these 182 RRATs. From left to right, each column represents: RRAT name, right ascension (RA), declination (DEC), Galactic longitude (GL), Galactic latitude (GB), dispersion measure (DM), period (P), period derivative ($\dot{P}$), surface magnetic field B_{surf}, spin-down energy loss rate $\dot{E}$, characteristic age τ_c, burst rate, distance, Faraday rotation measure (RM), linear polarization degree (L/I), and reference literature for each parameter. This work updates the RRAT database and performs statistical analyses of the determined observational parameters, with results shown in Figure 1 [Figure 1: see original paper]. We find that the dispersion measures, distances, and spatial positions of most RRATs are determined. Using the dispersion measures provided in the literature and the YMW16 Galactic electron density model [?], we recalculated the distances to RRATs.

Additionally, burst rates are available for only 101 RRATs, accurate periods for 119 RRATs, and period derivatives, characteristic ages, surface magnetic fields, and spin-down energy loss rates for 55 RRATs. Faraday rotation measures are provided for 23 RRATs, and linear polarization degrees for 22 RRATs. Some RRATs lack detected periods and burst rates primarily because only a single burst was detected or because the burst rate varies significantly. Period derivatives, characteristic ages, surface magnetic fields, and spin-down energy loss rates require long-term timing observations to obtain. Faraday rotation and linear polarization measurements require polarimetric observations. The scarcity of single-pulse bursts from RRATs and insufficient telescope sensitivity in the past have increased the difficulty of obtaining these parameters. The Five-hundred-meter Aperture Spherical radio Telescope (FAST), currently the world' s most sensitive radio telescope, will be capable of conducting long-term timing observations and single-pulse polarimetric observations of RRATs within its sky coverage, thereby determining these parameters and providing important observational evidence for studying the origin, evolution, and radiation mechanisms of RRATs.

[Figure 1: see original paper] Statistics of the determined observation parameters of rotating radio transients, with all data from Table 1 of the appendix. From left to right, they are Polarization, Rotation measure (RM), Dipolar surface magnetic field (B_{surf}), Characteristic age (τ_c), Spin-down energy loss rate ($\dot{E}$), Period derivative ($\dot{P}$), Burst rate, Period (P), Dispersion measure (DM), and Distance, respectively.

3 Spatial Distribution of RRATs

Previous statistical studies of pulsar spatial distributions have found that most ordinary pulsars are concentrated near the Galactic plane, while older millisecond pulsars are diffusely distributed across the entire celestial sphere [**?**, **?**]. The spatial distribution of pulsars is significant for studying their evolutionary history. RRATs are a new type of transient source discovered only in the past decade, later found to have numerous connections with pulsars, though their specific physical origin remains unclear. Therefore, studying the spatial distribution of RRATs is important for exploring their nature and early evolution. Figure 2 [Figure 2: see original paper] shows the spatial distribution of 182 RRATs and 3700 pulsars in Galactic coordinates, with black stars representing RRATs and gray dots representing pulsars (pulsar data from the Australia Telescope National Facility (ATNF) Pulsar Catalogue[1]). Approximately half of the RRATs are distributed near the Galactic plane, a small fraction are located at high Galactic latitudes, and the remainder are diffusely distributed across the celestial sphere. To further reveal the relationship between RRAT spatial distribution and other parameters, we analyzed the correlations between period, characteristic age, characteristic magnetic field, spin-down energy loss rate, and Galactic latitude for 55 RRATs with measured period derivatives and 3700 pulsars. As shown in Figure 3 [Figure 3: see original paper], RRATs are similar to pulsars in that their periods show no significant correlation with Galactic latitude, characteristic age shows an overall positive correlation with Galactic latitude, while characteristic magnetic field and spin-down energy loss rate show overall negative correlations with Galactic latitude. This indicates that, like pulsars, most older RRATs have drifted away from the Galactic plane due to proper

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[1] https://www.atnf.csiro.au/people/pulsar/psrcat/index.html

motion during their long evolutionary history.

[Figure 2: see original paper] The spatial distribution of 182 RRATs and 3700 pulsars. The black stars represent RRATs, and the gray circles represent pulsars.

4 Distribution on the Period-Period Derivative Diagram

The period-period derivative diagram (P-$\dot{P}$) is important for studying the physical properties and evolutionary processes of RRATs. Figure 4 [Figure 4: see original paper] shows the distribution of RRATs, pulsars, magnetars, intermittent pulsars, and nulling pulsars on the P-$\dot{P}$ diagram. We also plot constant magnetic field lines, constant age lines, and death lines. The magnetic field strength is calculated using the formula $B_{\text{surf}} = 3.2 \times 10^{19}\sqrt{P\dot{P}}$ G [?], while the characteristic age is obtained from the formula $\tau_c = P/(2\dot{P})$. Additionally, we plot three different types of death lines: the first death line defined by Chen and Ruderman in 1993 (CR93) [?] with the equation $4\lg B_{\text{surf}} - 7.5\lg P = 49.3$; the second and third death lines derived by Zhang et al. [?] from two models, where the second is the death line equation for dipolar magnetic fields under the vacuum gap model (referred to as the "CR V" model): $\lg\dot{P} = 2.75\lg P - 14.62$; and the third is the death line for dipolar magnetic fields under the CR SCLF model: $\lg\dot{P} = 2.5\lg P - 14.56$.

From Figure 4, we can see that RRATs are relatively dispersed on the P-$\dot{P}$ diagram but all lie within the range of ordinary pulsars, close to intermittent pulsars and nulling pulsars. Four RRATs are located near the magnetar region: RRAT J1840-0840 [?], RRAT J0736-6304, RRAT J1819-1458, and RRAT J1854+0306, all with characteristic magnetic field strengths as high as 10^{13} G. RRAT J1819-1458 has detected X-ray radiation [?] and two glitch events, with the second glitch causing a significant and long-term decrease in spin-down rate [?]. Lyne et al. [?] suggested that if such glitch events occur every 30 years, the spin-down rate of RRAT J1819-1458 and its derived magnetic dipole moment would decrease to zero on a timescale of thousands of years, implying that RRAT J1819-1458 may begin its life cycle in the magnetar region of the P-$\dot{P}$ diagram, suggesting that RRATs may represent a transitional stage from magnetars to pulsars.

Pulsars provide electromagnetic radiation through their rotational energy. As pulsars age, their rotational energy gradually decreases, their periods become longer, and their radiation gradually weakens. When a pulsar' s rotational energy weakens to a certain extent, its radiation will gradually diminish until it stops, at which point the radio pulsar is considered "dead." Pulsars below the death line cannot radiate outward, so the death line is defined as the critical point determining whether a pulsar can radiate. Li [?] proposed that RRATs are dying pulsars whose radiation results from interactions between the pulsar magnetosphere and an external dust disk, implying that RRATs should be located below the death line. However, Figure 4 shows that only one RRAT, J2311+67 [?] (or PSR J2310+6706, red star in Figure 4), has just crossed these three standard death lines, with a few near the death line but above it. This indicates that most RRATs are active pulsars, which does not align well with Li' s theoretical predictions [?]. Unfortunately, flux density and related parameters for RRAT J2311+67 have not been obtained, though its burst rate of 60 per hour has been measured. We hope future observations will conduct more in-depth single-pulse polarimetric observations to study its radiation mechanism. Additionally, Figure 4 shows that the positions of RRATs overlap with most nulling pulsars, further supporting Wang et al.' s [?] suggestion that RRATs are pulsars with very large nulling fractions. Of course, our results will require large-sample pulsar timing observations of RRATs in the future to study their spin-down laws and obtain important parameters such as period derivatives, thereby providing crucial clues to the origin of RRATs.

[Figure 4: see original paper] The distribution of pulsars, intermittent pulsars, nulling pulsars, magnetars, and RRATs on the period-period derivative diagram. In the figure, the black dotted lines are iso-age lines, the black dashed lines are iso-magnetic field lines, and the red, blue, and black dotted lines are the death lines corresponding to the CR93, CR SCLF, and CR V models, respectively.

5 Statistical Distributions of Various Parameters

To further analyze the evolutionary relationship between RRATs and pulsars, we performed statistical analyses of RRAT observational parameters including spatial position, period, period derivative, dispersion measure, characteristic age, characteristic magnetic field, Faraday rotation measure, and linear polarization degree, and compared them with corresponding pulsar parameters. In our analysis, all parameters are presented using normalized probability density histograms with corresponding cumulative distributions.

Figure 5 [Figure 5: see original paper] shows the probability density and cumulative histograms of the logarithmic period distribution ($\lg P$) for RRATs and pulsars. The $\lg P$ distribution of RRATs approximately follows a Gaussian distribution (mean = 0.17, standard deviation = 0.47). The $\lg P$ distribution of pulsars is bimodal, with the first Gaussian component representing millisecond pulsars (mean = -2.42, standard deviation = 0.22) and the second representing normal pulsars (mean = -0.20, standard deviation = 0.38). Clearly, the $\lg P$ distribution of RRATs lies within the distribution range of normal pulsars but is overall slightly longer.

The period derivative describes how quickly a pulsar' s rotation changes; a larger period derivative means faster spin-down, more rotational energy loss over the same time, and stronger radiation from the converted energy. Figure 6 [Figure 6: see original paper] shows the probability density and cumulative histograms of the logarithmic period derivative distribution ($\lg \dot{P}$) for RRATs and pulsars. Fitting reveals that the $\lg \dot{P}$ of RRATs follows a single Gaussian distribution with mean and standard deviation of -14.2 and 0.36, respectively. The $\lg \dot{P}$ of pulsars follows a bimodal Gaussian distribution, with millisecond pulsars having a mean of -19.84 and standard deviation of 0.51, and normal pulsars having a mean of -14.2 and standard deviation of 0.93. These results indicate that the period derivative distribution of RRATs is consistent with that of normal pulsars.

The spin-down energy loss rate of pulsars and RRATs is calculated as $\dot{E} = 3.95 \times 10^{24} J\, s^{-1} (\dot{P}/10^{-15})(1/P)^3$. Figure 7 [Figure 7: see original paper] shows the logarithmic spin-down energy loss rate ($\lg \dot{E}$) distribution for RRATs and pulsars. The $\lg \dot{E}$ value is proportional to the period derivative and inversely proportional to the cube of the period, with the spin-down energy providing the rotational energy for neutron stars. Both RRATs and pulsars show Gaussian distributions in $\lg \dot{E}$. Fitting yields a mean and standard deviation of 31.79 and 1.23 for RRATs, and 34.29 and 1.52 for pulsars. RRATs have smaller $\dot{E}$ values compared to pulsars.

Pulsars gradually slow their rotation by losing rotational energy through radiation, creating a strict correspondence between spin-down and age. Using a pulsar' s rotation period and its first derivative, astronomers can estimate its "birth time," i.e., its characteristic age (τ_c, see equation (2)), which is generally considered the true age of the pulsar. Figure 8 [Figure 8: see original paper] shows the logarithmic characteristic age ($\lg \tau_c$) distribution histograms for RRATs and pulsars. The $\lg \tau_c$ of RRATs follows a single-peaked distribution, while pulsars show a bimodal distribution. Gaussian fitting yields a mean of 6.55 and standard deviation of 0.61 for RRATs. For pulsars, the means are 6.79 and 9.72 with corresponding standard deviations of 1.04 and 0.37. Clearly, the characteristic ages of RRATs fall within the age range of normal pulsars.

Magnetic field strength is an important physical parameter describing celestial formation and a key reference for evolution. Figure 9 [Figure 9: see original paper] shows the logarithmic dipolar surface magnetic field ($\lg B_{\text{surf}}$) distribution for RRATs and pulsars. The $\lg B_{\text{surf}}$ of RRATs shows a single-peaked distribution (mean = 12.51, standard deviation = 0.64), while pulsars show a bimodal distribution corresponding to normal pulsars (mean = 12.08, standard deviation = 0.49) and millisecond pulsars (mean = 8.33, standard deviation = 0.27). Most RRATs have magnetic field strengths comparable to those of normal pulsars, but some are slightly stronger, reaching 10^{13} G and approaching magnetar field strengths.

When pulsar emission signals travel through the Galaxy, they pass through various media with different electron densities and ionization degrees, causing changes in propagation speed and pulse shape—this phenomenon is called dispersion. The dispersion measure is calculated as $\mathrm{DM} = \int_0^d n_e\, dl$, where l is the path length along the line of sight, d is the straight-line distance from the pulsar to Earth, and n_e is the electron number density. The dispersion measure can be used to calculate the distance to the pulsar. Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper] show the logarithmic DM and distance distributions for RRATs and pulsars (pulsar DM and distance data from the ATNF Pulsar Catalogue). Similar to pulsars, the logarithmic DM (lg DM) and distance (lg Distance) of RRATs also follow single Gaussian distributions, with mean values slightly smaller than those of pulsars. RRAT distances are generally less than 10 kpc. Some theories suggest RRATs are pulsars emitting giant pulses from very far away, where only giant pulses can be detected due to the large distance, while weaker normal pulses cannot [?]. However, our statistical results show that both DM and distance are smaller for RRATs than for pulsars, which is inconsistent with this theory. Of course, this discrepancy may also be due to the low burst rates and generally weak radiation of RRATs. So far, few RRATs with large DM have been detected, but we anticipate that more distant RRATs may be discovered with higher-sensitivity telescopes in the future.

Polarimetric observations of pulsars provide further understanding of radiation mechanisms, surrounding environments, magnetic field structures, and constraints on the geometry of pulsar emission regions. Previous observations have found a 90° polarization position angle jump in RRAT J1819-1458 [?] and a classic “S”-shaped curve in the polarization position angle of RRAT J0139+3336 [?]. Additionally, related studies [?, ?] indicate that RRAT polarization is similar to that of ordinary pulsars. Therefore, polarization analysis is equally important for studying the radiation mechanisms and geometry of RRATs. However, due to low burst rates and weak radiation flux, polarization studies of RRATs are highly dependent on telescope sensitivity, resulting in linear polarization measurements for only 22 RRATs. Moreover, the integrated profiles used to measure linear polarization for these 22 RRATs consist of only a few sub-integrations, with RRAT J1048-5838’ s polarization being single-pulse linear polarization and the integrated profiles of the remaining RRATs composed of 2-41 single pulses [?]. Figure 12 [Figure 12: see original paper] shows the logarithmic distribution of linear polarization degrees for these 22 RRATs and pulsars. Both follow single Gaussian distributions, but RRATs have slightly higher linear polarization degrees overall. The higher linear polarization of RRATs may be due not only to possible physical mechanisms but also because the linear polarization degree of pulsars here refers to that of their integrated profiles, while RRAT pulses are relatively scarce—some RRATs have only single-pulse linear polarization measured, or even if integrated profile polarization is measured, the profiles consist of only a few single pulses. RRATs may be similar to ordinary pulsars in that although single pulses have high linear polarization, the integrated profiles composed of hundreds of single pulses may not show high linear polarization [?, ?]. This requires long-term observations with high-sensitivity radio telescopes to obtain stable integrated profiles for confirmation.

Faraday rotation measure is also an important observable in pulsar studies, reflecting the magnetic field direction between the pulsar and observer along the line of sight. RM is given by RM $= (e^3/2\pi m_e^{2c^{4)}} \int_0^d n_e B_{||}\, dl$, where n_e is the free electron density, e is the elementary charge, m_e is the electron mass, $B_{||}$ is the magnetic field component along the line of sight, l is the path length along the line of sight, and d is the straight-line distance from the pulsar to Earth. A positive RM indicates the magnetic field points toward the observer, while a negative RM indicates it points away. For pulsars and RRATs, RM can directly reveal the large-scale magnetic field structure of the Galactic disk [**?**]. Figure 13 [Figure 13: see original paper] shows the logarithmic distribution of the absolute Faraday rotation measure ($\lg|\mathrm{RM}|$) for RRATs and pulsars. Although the number of RRAT $\lg|\mathrm{RM}|$ values is small and the distribution may not be representative, both still show single-peaked distributions, with the RRAT $\lg|\mathrm{RM}|$ distribution being more dispersed but falling within the range of pulsar $\lg|\mathrm{RM}|$ values.

[Figure 10: see original paper] Logarithmic distribution of dispersion measure for pulsars and RRATs. The upper panel shows the probability density histogram, and the lower panel shows the cumulative histogram. Black and gray represent pulsars and RRATs, respectively, with dashed lines indicating the corresponding fitted curves.

[Figure 11: see original paper] Logarithmic distribution of distance for pulsars and RRATs. The upper panel shows the probability density histogram, and the lower panel shows the cumulative histogram. Black and gray represent pulsars and RRATs, respectively, with dashed lines indicating the corresponding fitted curves.

[Figure 12: see original paper] Logarithmic distribution of linear polarization for RRATs and pulsars. The upper panel shows the probability density histogram, and the lower panel shows the cumulative histogram. Black and gray represent pulsars and RRATs, respectively, with dashed lines indicating the corresponding fitted curves.

[Figure 13: see original paper] Logarithmic distribution of the absolute value of Faraday rotation measure ($|\mathrm{RM}|$) for RRATs and pulsars. The upper panel shows the probability density histogram, and the lower panel shows the cumulative histogram. Black and gray represent pulsars and RRATs, respectively, with dashed lines indicating the corresponding fitted curves.

6 Conclusions

Statistical analysis of RRAT observational parameters is crucial for studying their origin and evolution. This paper collected previously published RRAT data, identified 182 discovered RRATs, updated the RRAT database, and performed statistical analyses of observational parameters including spatial position, period, period derivative, dispersion measure, characteristic age, characteristic magnetic field, Faraday rotation measure, and linear polarization degree, with comparisons to pulsars. We find that the spatial positions of RRATs are similar to those of pulsars, with average values of period, period derivative, and surface magnetic field slightly larger than those of normal pulsars. Their characteristic ages and Faraday rotation measures fall within the normal pulsar range, while their spin-down energy loss rates, dispersion measures, and distances are smaller than those of pulsars. Except for Faraday rotation measure, the logarithms of all other observational parameters follow a normal distribution. Because most RRATs exhibit sporadic single-pulse bursts, the number of detectable RRATs is very small. Additionally, the weak radiation of RRATs, limited by radio telescope sensitivity, prevents in-depth single-pulse polarimetric and timing observations like those conducted for most pulsars. This has resulted in nearly one-third of RRATs lacking important evolutionary parameters such as period derivatives, characteristic ages, characteristic magnetic fields, and spin-down energy loss rates, and only 22 RRATs having polarimetric observations. These factors severely limit the sample size available for parameter statistical analysis. Nevertheless, our results remain important for investigating the physical origin of RRATs.

Furthermore, our statistical results will provide guidance for large scientific facilities such as FAST to conduct RRAT-related research. We anticipate that more sensitive radio telescopes like FAST and the Square Kilometre Array (SKA) will detect more RRATs and enable studies of their radiation and rotational characteristics. Multi-wavelength observations of special RRATs, such as the four high-magnetic-field RRATs J0736-6304, J1819-1458, J1840-0840, and J1854+0306, as well as RRAT J2311+67 located below the death line, will help investigate their connection to magnetars and lead to breakthroughs in theories regarding RRAT origin and evolution.

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