



Investigating the Relationship Between Mass, Emission Type, Characteristic Age and Orbital Properties in the Evolution of 38 ATNF Binary Pulsars

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Abstract

Binary pulsars involve the interaction of neutron stars with a companion, which may be a main-sequence star, white dwarf, another neutron star or other stellar objects. In this paper, we look into possible demonstrations of existing relationships between the neutron star mass, the binary mass, the type of emission, and the orbital properties of a dataset of 38 binary pulsars extracted from the ATNF catalog, to investigate how these factors can play into predicting the pulse periods of these pulsars, 10 Myrs into the future. According to the plots, companion mass and total mass have a moderately positive correlation to Eccentricity ($r = 0.570$ and $r = 0.566$ respectively), while Eccentricity and Characteristic Age are moderately negatively correlated ($r = -0.534$), and pulsar period has a weak correlation with binary period ($r = 0.247$) and a moderate negative correlation to characteristic age ($r = -0.485$). Additionally, the results from the parameter relations as well as their evolution graphs have been used to make inferences into the undetermined companion type of PSR J1954+2529, which we propose to possibly be a main sequence companion, due to similar evolutionary periods.

Keywords: Binary pulsars, Eccentricity, Companion Mass, Spin Period Evolution, Characteristic Age

I. Introduction

Pulsars are defined as rapidly rotating, highly magnetised neutron stars that originate from explosions of massive stars (1). The formation of a neutron star commences during the evolution of a binary star system, when the greater star undergoes a supernova explosion. A binary pulsar consists of a neutron star and its companion, which are either white dwarfs, neutron stars, main sequence stars, with recent theories of X-Ray binaries with black hole companions (1). Since the discovery of the first binary pulsar, the Hulse-Taylor pulsar in 1974, several studies examining binary pulsars (2), (3), and (4) have shed light on the formation, evolution and parameters of binary pulsars.

The neutron star survives through the accretion of mass from the binary, often resulting in high energy emissions such as X-Ray emissions (3). Several distinctions have been made regarding the parameters of these binaries, which include the period, the speed at which the pulsar rotates; the spin down rate, the rate at which a pulsar slows down; the eccentricity, a

measure of how elliptical the path of the pulsar is; and the characteristic age, the age of the pulsar with approximation to its spin rate (1). In the equation,

$$\tau = \frac{P}{2\dot{P}}, \quad (\text{eq.1})$$

Where τ represents the characteristic age of a pulsar, P represents the period, and $\dot{P}$ represents the first derivative of the spin rate, in a relationship that shows characteristic age to be inversely proportional to the period derivative, and directly proportional to the period. However, the spin down rates of binary pulsars work in a more complex manner, due to mass accretion resulting in X-Ray emissions (3), meaning that characteristic age does not account for it, given the existence of recycled pulsars (1). Recycled pulsars are binaries wherein the companion is massive enough to overflow its own Roche Lobe, allowing the neutron star to spin-up by accreting the matter of the companion (1), thus forming millisecond pulsars (5).

The spin period of a binary pulsar increases as it slows down and loses its kinetic energy throughout its lifetime, which can be mathematically modelled by the equation,

$$\dot{E} = 4\pi^2 I \dot{P} P^{-3}, \quad (\text{eq.2})$$

where $\dot{E}$ represents the magnitude of spin-down luminosity, or the rate at which the pulsar loses its kinetic energy, I represents its rotational inertia, $\dot{P}$ represents the first derivative of the spin period, and P represents the spin period (6).

Moreover, the distinctions of binary pulsars also depend on their companions, and are distinguished in terms of their masses, namely as high-mass systems, intermediate-mass systems, and low-mass systems (1, 5). The formation of the binary depends on factors such as the kick velocity, alongside the amount of mass that is ejected during the supernova explosion, where an asymmetric explosion may result in high values of eccentricity in the binary pulsar (1), meaning that the formation of the binary plays a vital role in determining the period, spin-down rate and orbital eccentricities of the resulting binary (5).

In this paper, we aim to analyze relations between the aforementioned parameters of 38 binary pulsars from Australia Telescope National Facility (7). We also simulate their evolution using Python scripts in JupyterLab and Google Collab, to explore how their parameters may change in the future.

II. Methods

2.1 Computational Analysis and the dataset

The 38 binary pulsars from the Australia Telescope National Facility (ATNF) were chosen due to the availability of all eccentricities in the dataset. Relationships between parameters such as period, spin-down period, eccentricity, orbital period, characteristic age and companion mass were examined by plotting and analyzing the characteristics against one another through Jupyter Notebook and Collab with the assistance of the Python Packages Pandas for database filtering, Numpy for managing numeral calculations, such as calculating characteristic age and the mass of the companion, and Matplotlib for modelling relations between the aforementioned parameters concerning the 38 selected pulsars. The dataset of 38 binary pulsars extracted from the ATNF catalogue, along with their parameters, masses, emission types, and characteristic ages, is presented in Appendix A (Table 1).

The values of all of the parameters were extracted from the database of the ATNF catalog (7) with the exception of the following:

- a. The mass of the pulsar (M1) J0453+1559, $1.56 M_{\odot}$, was extracted from its discovery paper by Martinez et al. (8).
- b. The mass of the pulsar J0621+1002, $1.7 M_{\odot}$, was extracted from its discovery paper by Splaver et al. (9).
- c. The mass of the pulsar J1807-2459B, $1.36 M_{\odot}$, was extracted from the paper by Lynch et al. (10).
- d. The mass of the pulsar J1829+2456, $1.3 M_{\odot}$, was extracted from its foundational paper by Haniewicz et al. (11).
- e. The other values for M1 are taken to be the canonical model, as stated by Torsett and Chakraborty (12).
- f. The values for M2 were calculated with the MinMass equation given in the ATNF catalog (7), using Post-Keplerian equations where $i=90$ degrees and NS mass = 1.35 Solar Masses.
- g. The companion type of PSR J1551-0658 was extracted from the 2022 paper by Bangale et al. (13), detailing a study of 72 pulsars.
- h. The Black widow companion pulsars PSR J1959+2048, PSR J1836-2354A, and PSR J1810+1744 are listed as the Ultra-light or UL category in the catalog database, and their Black widow classifications were discovered by (14).

2.2 The Composition of the Dataset

- a. Fully Recycled Millisecond Pulsars (MSPs) are MSPs that have $P < 10$, $\dot{P} \lesssim 10^{-20}$, and often have low-mass Helium White Dwarf Companions (5). In the extracted dataset, there are 10 Recycled MSPs with He WD companions, namely PSR J0101-6422, PSR J1312+0051, PSR J1431-5740, PSR J2019+2425, PSR J2236-5527, PSR J1855-1436, PSR J1835-0114, PSR J1825-0319, PSR J1822-0848, PSR J1806+2819, PSR J1709+2313. Additionally, there have been systems where fully recycled pulsars have a CO WD binary (5).
- b. Mildly Recycled/Intermediate Pulsars are MSPs that have $10 < P < 100$ ms, $10^{-20} < \dot{P} < 10^{-18}$, and often have massive CO WDs (5). Our selected dataset consists of three IMSPs, namely PSR J0621+1002, PSR J0721-2038, and PSR J1727-2946.
- c. Slow/Non-Recycled Pulsars are MSPs where P often exceeds 100 ms, and often have a Neutron Star binary (5). The dataset consists of two such pulsars, namely PSR J1930-1852 and PSR J1811-1736.
- d. Black Widow companions are present in binary pulsars where a rapid accretion of mass takes place, leading to X-ray emissions, and have companion masses $\ll 0.1 M_{\odot}$, leading to an ultra-light classification on the ATNF catalog database (15). Three such pulsars are present in our selection, namely PSR J1959+2048, PSR J1836-2354A, and PSR J1810+1744.
- e. Massive Main Sequence Binaries are predominantly found in binary systems that survive the first Supernova explosion and contain a young pulsar. They typically have eccentricity values greater than 0.5 (16). Our dataset consists of two such binary pulsars, namely PSR J0045-7319 and PSR J1740-3052.
- f. PSR J1954+2529 was first discovered by Parent et al. (16), as an unusual, non recycled pulsar, whose eccentricity of 0.11 was surprisingly low compared to pulsars with MS Companions, and yet had a close period value of 0.931 s, to that of PSR J0045-7319, 0.926 s (16).

III. Results

3.1: Relations between Parameters in the Dataset

As the companion of J1300+1240 is planetary and has an unusual eccentricity that affects the statistical coefficients of the overall graph, it has been excluded from the graphs examining

relationships between parameters of the dataset, but has been included in the evolution simulation graph in Section 3.2.

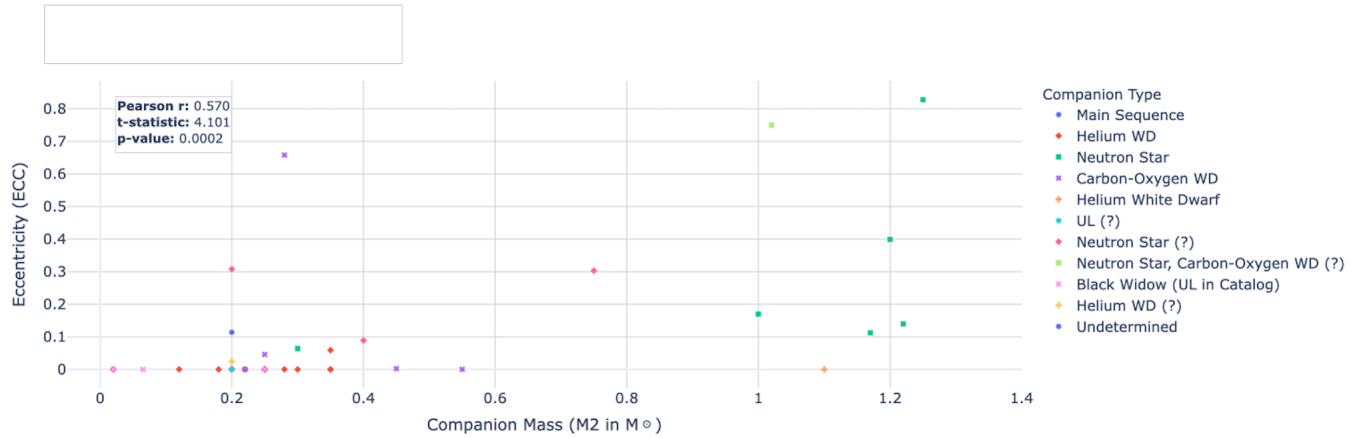


Figure 1: Eccentricity vs. Companion Mass. The relationship between eccentricity and the mass of the binary companion, is shown to be moderately positive, with the correlation coefficient 0.57, a t-statistic of 4.101, and a p-value of 0.0002.

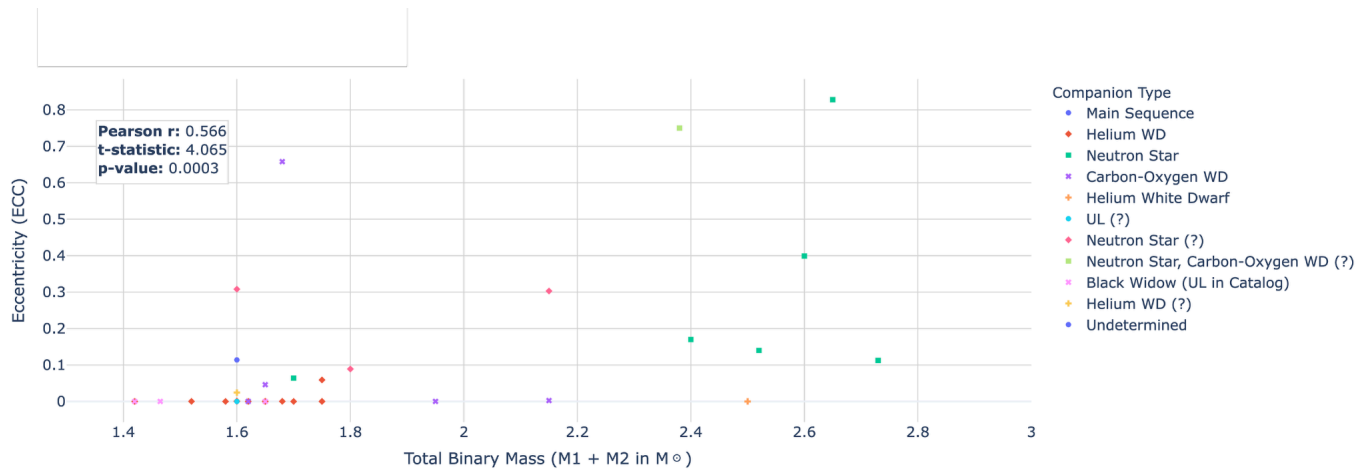


Figure 2: Eccentricity vs. Total Binary Mass. The relationship between Eccentricity and the total Binary Mass is shown to be moderately positive, with a correlation coefficient of 0.566, a t-statistic of 4.065 and a p-value of 0.0003.

The eccentricities of the binary pulsars are shown to have moderately positive relations with both the companion mass and the total mass of the binary pulsar (Fig. 1 and 2). In both cases, the t-statistic is around 4, signalling the absence of a null relation between the parameters. This is further backed by p values significantly lesser than 0.05.

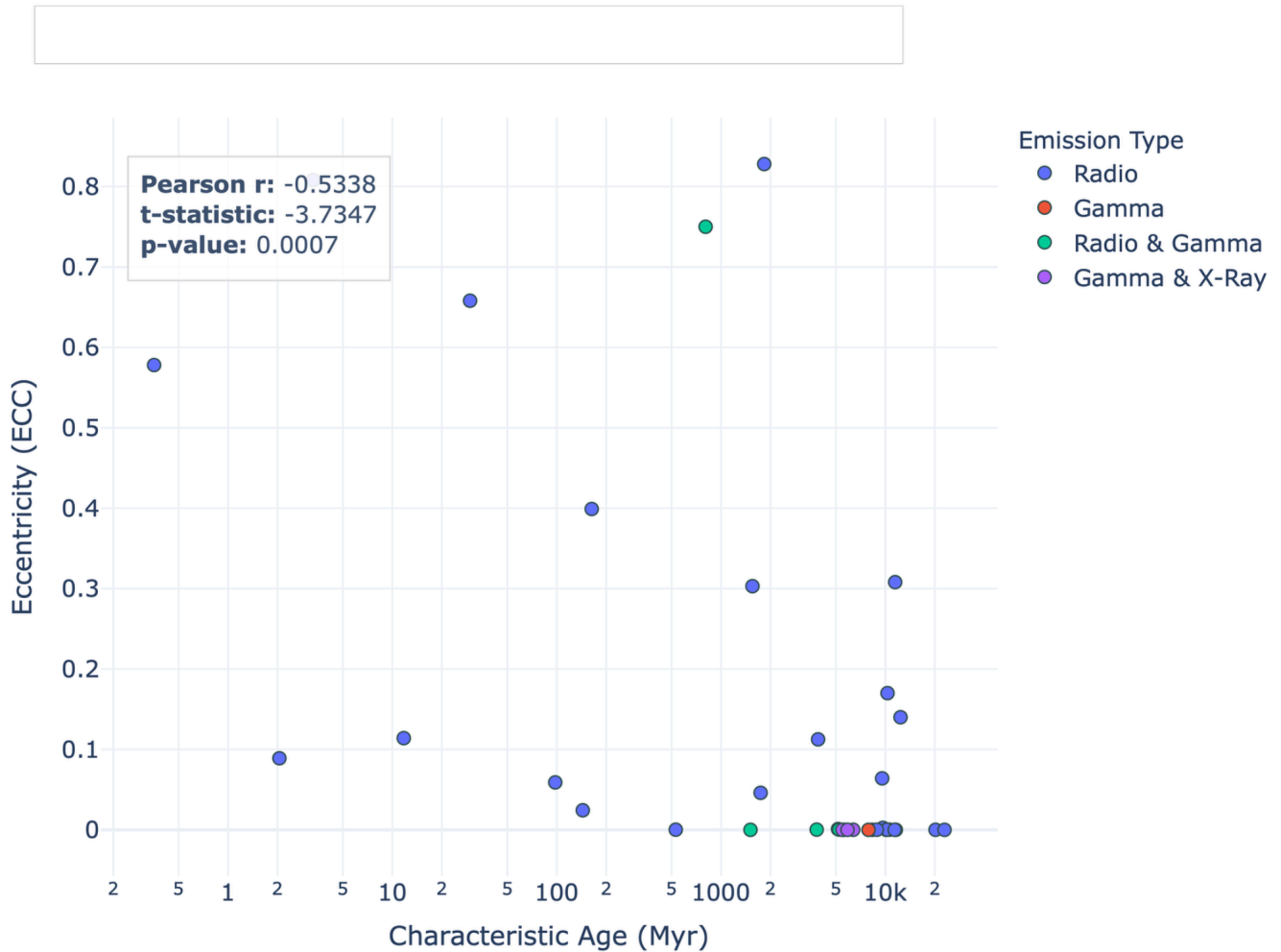


Figure 3: Eccentricity vs. Characteristic Age by Emission Type. The relationship between Eccentricity and Characteristic Age has a moderately negative correlation ($r = -0.534$), with a t-statistic of -3.7347 and a p-value of 0.0007.

Moreover, eccentricity is shown to have a moderately negative correlation with characteristic age, with a t-statistic above -2 and a *p* value lesser than 0.05, signalling statistical significance (Fig. 3).

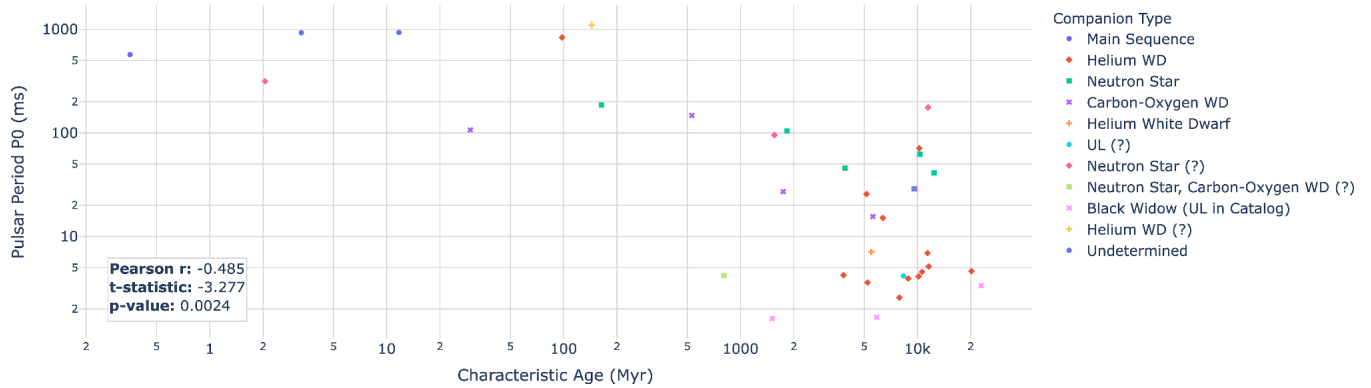


Figure 4: Spin Period vs. Characteristic Age. The relationship between the Pulsar spin Period and characteristic age has a moderately negative correlation ($r = -0.485$), with a t-statistic of -3.277 and a p-value of 0.0024.

Pulsar spin period is shown to have a moderately negative correlation with characteristic age and binary spin period (Fig. 4). The relation with characteristic age has a t-statistic of around -3, with a p value significantly lesser than 0.05, signalling statistical significance and lesser chance of a null relationship.

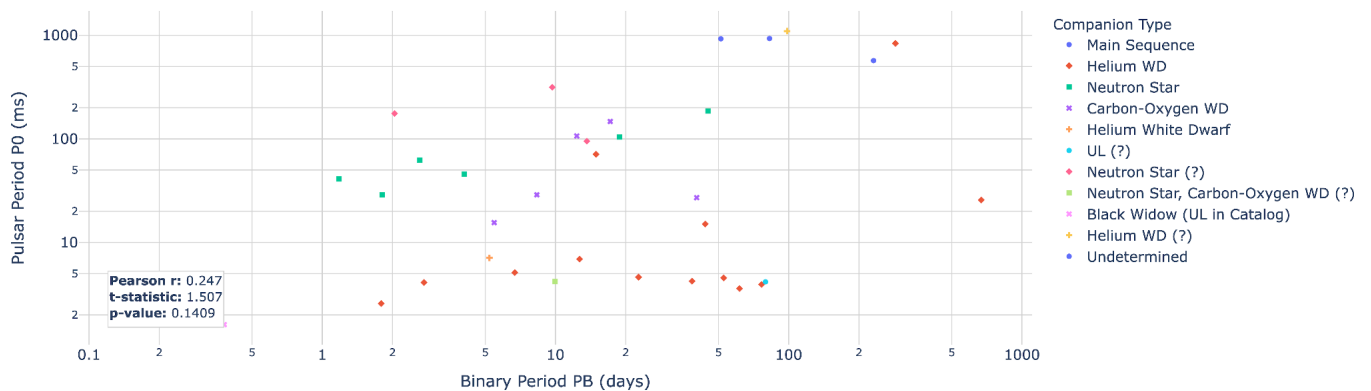


Figure 5: Pulsar spin period vs. Binary Period. The relationship between the Pulsar spin Period and the binary period has a weak positive correlation ($r = 0.247$), with a t-statistic of 1.507 and a p-value of 0.1409.

However, the relation between pulsar period binary spin period has a t-statistic below 2, and a p value higher than 0.05, signalling a lack of statistical significance in the relation of the two parameters, bringing in the possibility of a null relationship (Fig. 5).

It is also observed that the binary pulsars with higher emission types, i.e., Gamma and X-Rays, are shown to have higher Characteristic ages and lower eccentricities. According to Table 1, Gamma emissions are mostly seen in the MSPs in the dataset, with the exception of PSR J1806+2819.

3.2: Evolution Plots of the Dataset

The periods of the 38 Pulsars, 10,000,000 years into the future were simulated, by manipulating the equation used to find Characteristic Age (1, 18), yielding the following equation:

$$P(t) = \sqrt{P^2 + 2P\dot{P}t} \quad (\text{eq.3})$$

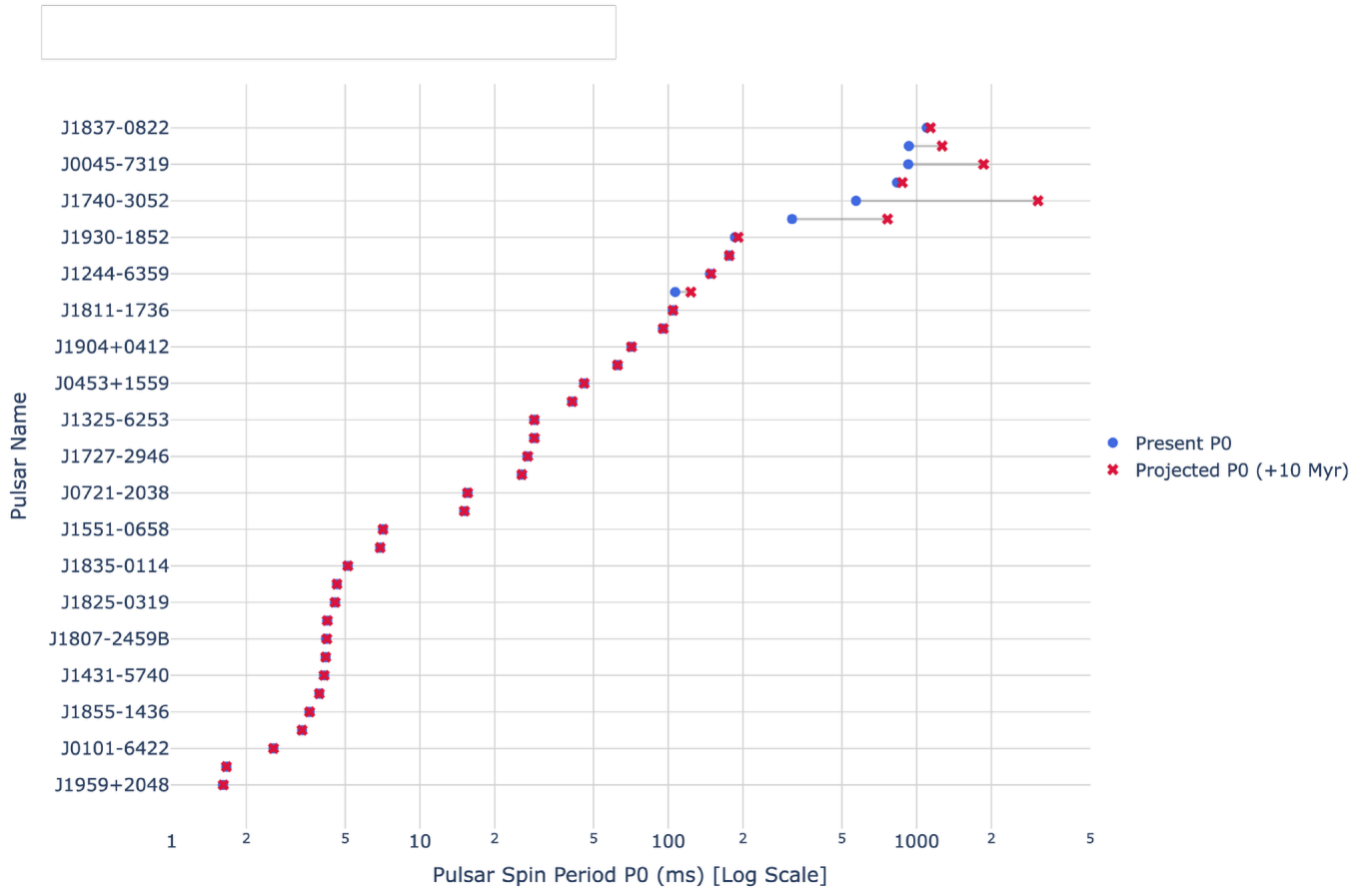


Figure 6: Present Spin Period vs. Projected (+10 Myr). Graph depicting the spin periods of the 38 pulsars, 10 Myr into the future, in comparison to present spin periods.

Figure 6 depicts a broad view of the simulated future pulse periods, which shows indiscernible change over long periods of time, with the exceptions of PSRs J1837-0822, J1954+2529, J0045-7319, J1822-0848, J1740-3052, and J1755-2550. Given that the majority in the pulsars

that undergo comparatively larger changes in spin period consists of Helium White-Dwarves and Main Sequence Stars, the spin down periods were simulated by companion type of the pulsars.

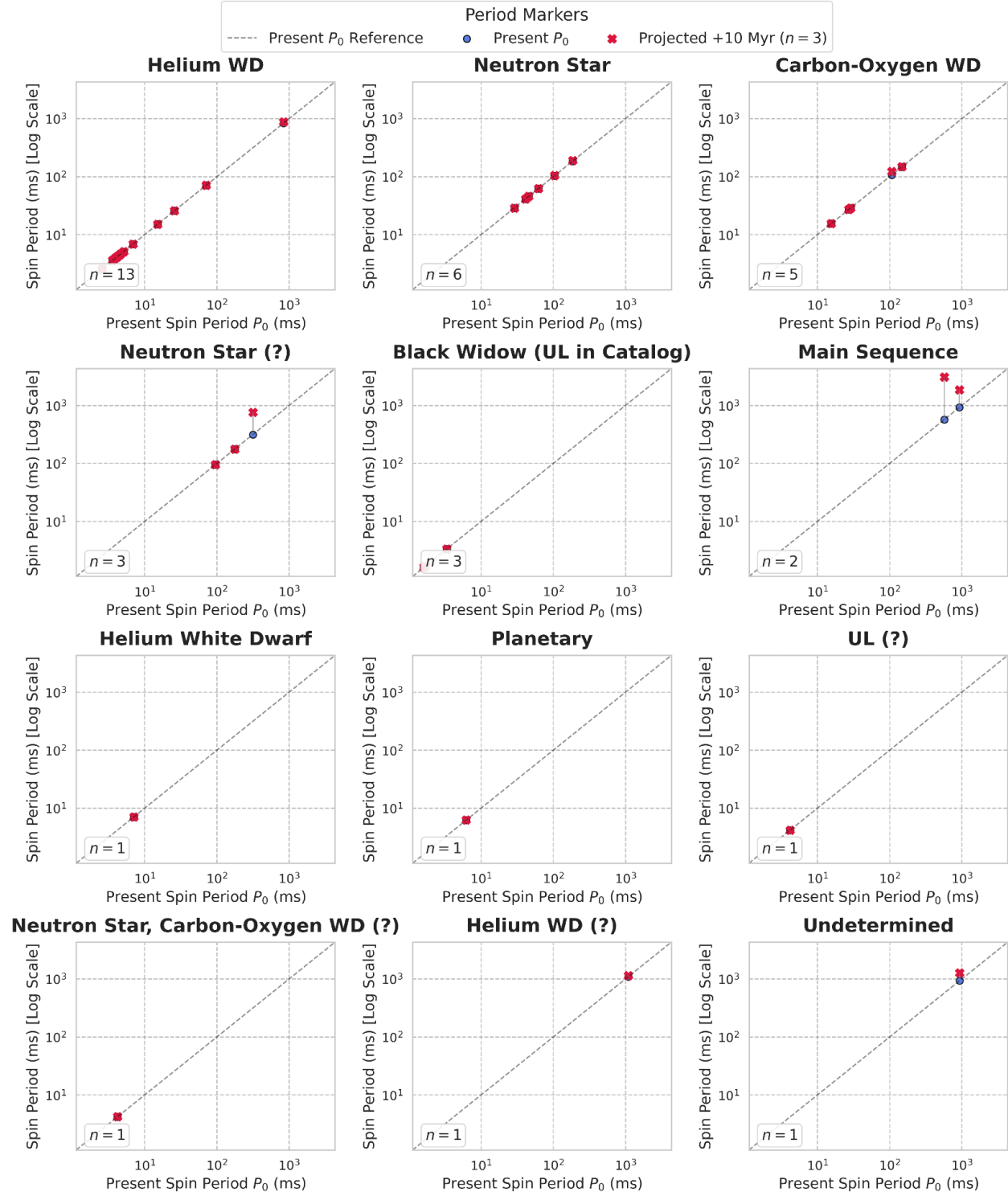


Figure 7: Spin Period Evolution. Present vs. Future by Companion type: Graphs depicting the future pulse periods of the 38 pulsars, separated in each graph by their companion type. A braking index of 3 was assumed.

Figure 7 shows the similar trend occurring in all the MS Companion Pulsars in the sample size, while it disappears in the overall sample of Helium White Dwarfs. However, it continues in PSR J1954+2529, the pulsar with the undetermined companion, which may signal to the fact that it has a MS companion.

IV. Discussion

4.1 Connecting the Relation Graphs to the Evolution graphs

Neutron star companions are shown to have higher companion masses, ranging from 1 to 1.3 solar masses (Fig. 1), which includes two slowly-recycled pulsars, PSR J1930-1852 and 1811-1736 (Table 1). However, they do not undergo significantly noticeable period evolution (Fig. 6), except for one binary pulsar with a doubtful Neutron Star companion, PSR J1755-2550 (Fig. 7). Double Neutron Stars, or DNSs are generally seen in the mildly recycled form due to the mass accretion significantly diminishing its magnetic dipole braking, which in turn decelerates the energy loss rate. The deceleration would explain the unchanged value in terms of period spin evolution, given that the same reason allows it to be observed as a radio pulsar on a larger timescale (17).

Main Sequence Companion Pulsars undergo noticeable change in terms of period evolution in the future (Fig. 6 and 7), and have high companion masses with medium to high eccentricity values (Table 1), as seen in the cases of PSR J0045-7319 and PSR J1740-3052. The trend carries on to the undetermined companion, PSR J1954+2529, wherein a period change is noticeable in the evolution, suggesting further that it may be a main sequence companion. Nevertheless, there is significant debate as to its companion due to the fact that it has a low eccentricity value but a close pulse period, compared to Main Sequence Binaries such as J0045-7319 (16). Binary pulsars are generally formed from binary systems. However, when the more massive component undergoes a supernova explosion, the system generally is unbounded (15). The systems that do survive the first explosion tend to have high orbital eccentricities, due to a massive kick velocity that results from asymmetric explosions (1), a property that follows through in MS Binary Pulsars. In addition, Main Sequence Binaries have higher spin periods, masses and tend to consist of young pulsars, which would mean (12) that the mass accretion would not have been severe enough to diminish the magnetic dipole braking significantly enough (eq. 2), and a relatively young pulsar would have a higher energy loss rate, as it is inversely proportional to characteristic age (18), explaining the greater changes in spin period shown in Fig. 6 & 7.

An intriguing part of the evolution graph lies in the disappearance of noticeable change in the period evolution of Helium White Dwarf companions from Fig. 6 to Fig. 7. The binary pulsars with low-mass He WD companions are fully recycled MSPs with low periods (5). Due to their formation from low-mass X-Ray emitting Binaries (LMXBs) that generally undergo significant loss in rotational energy, the mass accretion eventually causes the binary to freeze at a period and essentially decelerates any significant evolution in spin period, significantly (19), thus explaining the disappearance of the noticeable change in the plots with smaller scale (Fig. 7).

4.2 Limitations and Future Steps

A necessary limitation of this paper to acknowledge is the size of the dataset ($n=38$). However, this is the number of binary pulsars in the ATNF Catalog that have known eccentricities, and thus, further information regarding eccentricities and orbital properties are required. Moreover, there are binary pulsars with undetermined companions such as PSR J1954+2529, and those with uncertain companions, such as PSRs J1837-0822, J1807-2459B, J1737-0811, J1753-2240, J1755-2550 and J1759+5036. Modern astronomical surveys such as the LSST, or the Vera C. Rubin Observatory has the capacity to aid with this data collection through its capacity to observe and record detailed images of over five billion galaxies (20).

V. Conclusion

In this paper, we have analysed relations between several parameters of binary pulsars, such as their companion mass, total mass, eccentricity, spin period and binary period. Eccentricity shows a positive correlation with the companion mass and the total mass of the binary pulsars in the selected dataset, but a negative correlation with Characteristic Age. Additionally, the spin period of the pulsars show a negative correlation with Characteristic Age, but a statistically insignificant negative correlation with binary period. We have also plotted the spin periods of the 38 pulsars 10 Myr into the future, with regards to their companion type, observing significant changes with MS Companions and He WD Companion, but little to none in other companion types.

There is however, further research needed in order to confirm relations between the parameters of these pulsars, alongside future behaviors of these pulsars, a task for which newer telescopes may be deemed fit. Such telescopes include the LSST, now known as the Vera C. Rubin Observatory, which is capable of capturing panoramic images deep into space.

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Author Contributions

Averi Mukhopadhyay - Data collection, Methodology, Abstract, Results, Discussion and Conclusion.

Parker T. Johnson - Proofreading, Methodology, Results, Discussion and Conclusion.

Conflicts of Interest

The authors declare no conflicts of interest that may have influenced the work in this paper.

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Appendix : Dataset of 38 ATNF Binary Pulsars

Table 1: List of pulsars with their mass, companion mass, and system environment

Name	P0 (ms)	PB (d)	ECC	M1 (M _{sun})	M2 (M _{sun})	Companion Type	Emission Type	Characteristic Age
J0045-7319	926.2	51.17	0.808	1.4	8.0	Main Sequence	Radio	3.29 Myr
J0101-6422	2.57	1.79	0.0000	1.4	0.18	Helium WD	Gamma	7901.0 Myr
J0407+1607	25.7	669.07	0.00094	1.4	0.2	Helium WD	Radio	5154.68 Myr
J0453+1559	45.78	4.07	0.1125	1.56	1.17	Neutron Star	Radio	3897.32 Myr
J0621+1002	28.85	8.32	0.00245	1.7	0.45	Carbon-Oxygen WD	Radio	9665.16 Myr
J0721-2038	15.54	5.46	0.000102	1.4	0.55	Carbon-Oxygen WD	Radio	5596.6906 Myr
J1244-6359	147.3	17.17	0.000179	1.4	0.22	Carbon-Oxygen WD	Radio	530.3229 Myr
J1300+1240	6.22	25.27	0.0	1.4	6.0E-08	Planetary	Radio	861.7437 Myr
J1312+0051	4.23	38.5	0.00024	1.4	0.12	Helium WD	Radio & Gamma	3,822.0413 Myr
J1325-6253	28.86	1.81	0.064	1.4	0.3	Neutron Star	Radio	9562.0763 Myr



J1411+2551	62.45	2.62	0.17	1.4	1.0	Neutron Star	Radio	10307.3585 Myr
J1431-5740	4.11	2.73	4.3E-06	1.4	0.02	Helium WD	Radio	10144.4920 Myr
J1551-0658	7.093	5.21	1.1E-05	1.4	1.1	Helium White Dwarf	Gamma or X-Ray	5482.6233 Myr
J1709+2313	4.63	22.7	1.87E-05	1.4	0.3	Helium WD	Radio	20214.0157 Myr
J1727-2946	27.08	40.31	0.046	1.4	0.25	Carbon-Oxygen WD	Radio	1742.0719 Myr
J1737-0811	4.17	79.5	5.38E-05	1.4	0.2	UL (?)	Radio	8341.6340 Myr
J1740-3052	570.3	231.03	0.578	1.4	11.0	Main Sequence	Radio	0.3543 Myr
J1753-2240	95.14	13.63	0.303	1.4	0.75	Neutron Star (?)	Radio	1553.9872 Myr
J1755-2550	315.2	9.69	0.089	1.4	0.4	Neutron Star (?)	Radio	2.0520 Myr
J1759+5036	176.01	2.042	0.308	1.4	0.2	Neutron Star (?)	Radio	11476.5874 Myr
J1806+2819	15.08	43.87	8.68E-05	1.4	0.35	Helium WD	Gamma & X-Ray	6372.9677



								Myr
J1807-2459B	4.19	9.96	0.75	1.36	1.02	Neutron Star, Carbon-Oxygen WD (?)	Radio & Gamma	805.6651 Myr
J1810+1744	1.66	0.15	4.7E-05	1.4	0.0650	Black Widow (UL in Catalog)	X-Ray & Gamma	5885.7826 Myr
J1811-1736	104.18	18.78	0.828	1.4	1.25	Neutron Star	Radio	1832.0349 Myr
J1822-0848	834.8	286.8303	0.059	1.4	0.35	Helium WD	Radio	97.9795 Myr
J1825-0319	4.55	52.63	0.00019	1.4	0.2	Helium WD	Radio	10609.7495 Myr
J1829+2456	41.01	1.18	0.14	1.3	1.22	Neutron Star	Radio	12376.4085 Myr
J1835-0114	5.12	6.69	1.1E-05	1.4	0.22	Helium WD	Radio	11580.6101 Myr
J1836-2354A	3.35	0.203	0.0000	1.4	0.25	Black Widow (UL in Catalog)	Radio	22927.6308 Myr
J1837-0822	1099.1	98.36	0.0243	1.4	0.2	Helium WD (?)	Radio	144.0505 Myr
J1855-1436	3.59	61.54	0.0002974	1.4	0.28	Helium WD	Radio & Gamma	5224.3070 Myr



J1904+0412	71.1	14.93	0.00022	1.4	0.25	Helium WD	Radio	10240.2789 Myr
J1930-1852	185.5	45.06	0.399	1.4	1.2	Neutron Star	Radio	163.2903 Myr
J1954+2529	931.2	82.72	0.114	1.4	0.2	Undetermine d	Radio	11.7217 Myr
J1959+2048	1.61	0.38	0.00000	1.4	0.02	Black Widow (UL in Catalog)	Radio & Gamma	1511.3042 Myr
J2019+2425	3.93	76.5	0.00011	1.4	0.35	Helium WD	Radio	8875.4890 Myr
J2236-5527	6.91	12.69	5.02E-05	1.4	0.25	Helium WD	Radio	11400.3662 Myr
J2305+4707	106.64	12.34	0.658	1.4	0.28	Carbon-Oxygen WD	Radio	29.6889 Myr