From Ordinary to Recycled Pulsars: An Observational Study of Spin Dynamics and Binary System Evolution

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Abstract

Pulsars are rapidly rotating neutron stars that gradually lose rotational energy and spin down over time. However, neutron stars in binary systems can be spun up through accretion of matter from a companion star, producing recycled pulsars with exceptionally short rotation periods. In this article, I analyze data from the Australia Telescope National Facility (ATNF) Pulsar Catalogue to investigate the differences between ordinary and recycled pulsars and explore how their spin properties relate to binary system evolution. I compare spin periods, period derivatives, inferred surface magnetic fields, characteristic ages, and light-cylinder radii across the two populations. I also examine correlations between spin period, orbital period, and orbital eccentricity in recycled pulsar systems. The results reveal distinct populations in the period–period derivative diagram, with recycled pulsars generally exhibiting shorter spin periods, weaker magnetic fields, larger characteristic ages, and smaller light-cylinder radii. Weak positive correlations are observed between spin period and orbital period (Pearson r = 0.235) and between spin period and eccentricity (r = 0.337). These findings highlight observational signatures consistent with pulsar recycling and provide insights into the relationship between neutron star spin dynamics and binary system evolution.

Introduction

Pulsars are neutron stars that rotate rapidly, emitting beams of electromagnetic radiation that are detected at regular intervals. They appear to pulsate because the radiation beam sweeps across the Earth once during each rotation, similar to the beam from a lighthouse. [6] Pulsars are formed when the cores of massive stars collapse at the end of their lives, producing rapidly rotating neutron stars with strong magnetic fields. Neutron stars are extremely compact stellar remnants, packing more than a solar mass into a sphere only tens of kilometers across. Their strong magnetic fields and rapid rotation produce a magnetosphere containing charged particles, which is responsible for the observed pulsar emission. [4]

As pulsars lose rotational energy through electromagnetic radiation and particle outflows, they gradually spin down over time. Their rotation period therefore increases, while the period derivative $\dot{P}$ provides a measurement of how quickly the pulsar is slowing down. The period and period derivative can also be used to estimate important physical properties of a pulsar, such as its magnetic field strength and characteristic age. Ordinary pulsars generally have rotation periods between tens of milliseconds and several seconds and relatively strong magnetic fields.

Recycled pulsars are a special type of pulsar that usually forms in binary systems. Pulsars naturally spin down over time, and yet some pulsars in binary systems rotate with periods of only a few milliseconds. These are known as millisecond pulsars 1. They are thought to have been "recycled" when matter and angular momentum were transferred from a binary companion onto the neutron star. [2, 1] This accretion can spin the neutron star up to very short periods. Recycled pulsars therefore tend to have much shorter spin periods and weaker magnetic fields than ordinary pulsars. [2]

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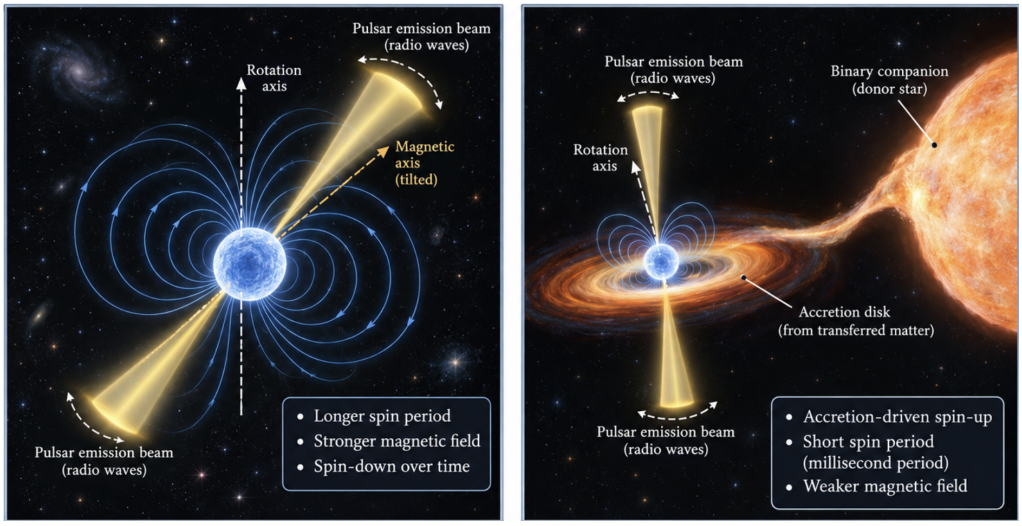


Figure 1: (a) An ordinary pulsar and (b) a recycled millisecond pulsar in a binary system. Ordinary pulsars gradually lose rotational energy and spin down, whereas recycled pulsars gain angular momentum through mass transfer from a binary companion, resulting in shorter spin periods and generally weaker magnetic fields. Image generated using OpenAI's ChatGPT.

The recycling process also changes the orbit of the binary system. During mass transfer, tidal interactions between the two stars tend to circularize the orbit, causing many millisecond pulsar binaries to have very small orbital eccentricities. After mass transfer ends, the companion star is often left behind as a white dwarf. The final orbital period, eccentricity, companion type, and spin period of the pulsar can therefore contain information about how the binary system evolved. Different evolutionary histories may produce different combinations of these observable properties. [5, 1]

In this article, I use data from the Australia Telescope National Facility (ATNF) Pulsar Catalogue[3] to compare ordinary and recycled pulsars and investigate the properties of millisecond pulsar binary systems. I first examine the distributions of spin period, magnetic field, characteristic age, and light-cylinder radius. I then study relationships between the spin period, orbital period, orbital eccentricity, and companion type of recycled pulsars. In particular, I investigate whether the orbital properties of millisecond pulsars contain signatures of the mass-transfer process that caused them to become recycled pulsars.

Methods

I used pulsar data from the Australia Telescope National Facility (ATNF) Pulsar Catalogue[3], which contains measured properties for thousands of known pulsars. I downloaded the spin period P, period derivative $\dot{P}$, orbital period $P_{\rm orb}$, orbital eccentricity e, and binary companion information when available. I separated the pulsars into ordinary pulsars and recycled/millisecond pulsars using the same classification used in my data analysis. Pulsars that were missing the measurements required for a particular analysis were excluded only from that analysis.

I first compared ordinary and recycled pulsars using their spin period and period derivative. I plotted $\log P$ against $\log \dot{P}$ in order to visualize where the two populations lie in pulsar parameter space. I also calculated the surface magnetic field strength using

$$B = 3.2 \times 10^{19} \sqrt{P\dot{P}}\ \mathrm{G}, \tag{1}$$

where P is measured in seconds. This equation estimates the magnetic field by assuming that the pulsar loses rotational energy mainly through magnetic dipole radiation. I then compared the

relationship between spin period and magnetic field for ordinary and recycled pulsars.

I also calculated the characteristic age of each pulsar using

$$\tau_c = \frac{P}{2\dot{P}}, \tag{2}$$

where τ_c is an estimate of the pulsar's age under the assumption that its spin-down behavior has remained approximately constant. Because characteristic age can be inaccurate for recycled pulsars, I used it mainly as a way of comparing the two pulsar populations rather than as the true age of each individual pulsar.

The light-cylinder radius was calculated using

$$R_{\rm LC} = \frac{c}{\Omega} = \frac{cP}{2\pi}, \tag{3}$$

where c is the speed of light and $\Omega = 2\pi/P$ is the angular rotation frequency of the pulsar. I compared the distributions of light-cylinder radii for ordinary and recycled pulsars to examine how the much shorter periods of millisecond pulsars change the size of their magnetospheres.

For recycled pulsars in binary systems, I studied the relationships between spin period, orbital period, and orbital eccentricity. I plotted $P_{\rm spin}$ against $P_{\rm orb}$, and $P_{\rm spin}$ against eccentricity to determine whether the amount of pulsar spin-up is related to the properties of the binary orbit. I calculated both Pearson and Spearman correlation coefficients. Pearson correlation measures the strength of a linear relationship, while Spearman correlation measures whether two variables generally increase or decrease together without requiring the relationship to be linear.

I then examined the relationship between orbital period and eccentricity, $P_{\rm orb}$ vs. e, because the orbit of a recycled pulsar is affected by the mass-transfer process that spins up the neutron star. I compared systems with different types of binary companions when companion information was available. In particular, I examined systems containing white-dwarf companions separately because these systems are expected to have undergone substantial mass transfer and orbital circularization.

All data processing, statistical calculations, and plotting were performed using Python. I used the `pandas` library to organize and filter the ATNF catalogue data, `NumPy` and `SciPy` for numerical and statistical calculations, and `Matplotlib` for visualization.

Results

Pulsars have such strong magnetic fields that the electromagnetic force is the strongest force, far outweighing other forces on the surface. This force can rip charged particles out of the neutron star and force them to follow magnetic field lines. As the magnetic field lines corotate with the neutron star, the particles are also forced to co-rotate. At some point, the speed of said corotation would exceed the speed of light, and at that point the charged particles cannot corotate anymore. This is known as the light cylinder radius. It is given by $R = \Omega/c$, where $\Omega = 2\pi/P$ and c is the speed of light. Because recycled pulsars spin so much faster, their light cylinders tend to be much smaller than those of normal pulsars.

$$R = \frac{\Omega}{c} \tag{4}$$

$$\Omega = \frac{2\pi}{P} \tag{5}$$

Another useful formula that allows for differentiating normal and recyled pulsars is the characteristic age formula. This formula is used to calculate the ages of pulsars. While this formula is innacurate for recycled pulsars, it gives a very specific statistical pattern for them that is easy to infer, being that they are predicted to be far older on average than normal pulsars. The formula for characteristic age is $P/2\dot{P}$.

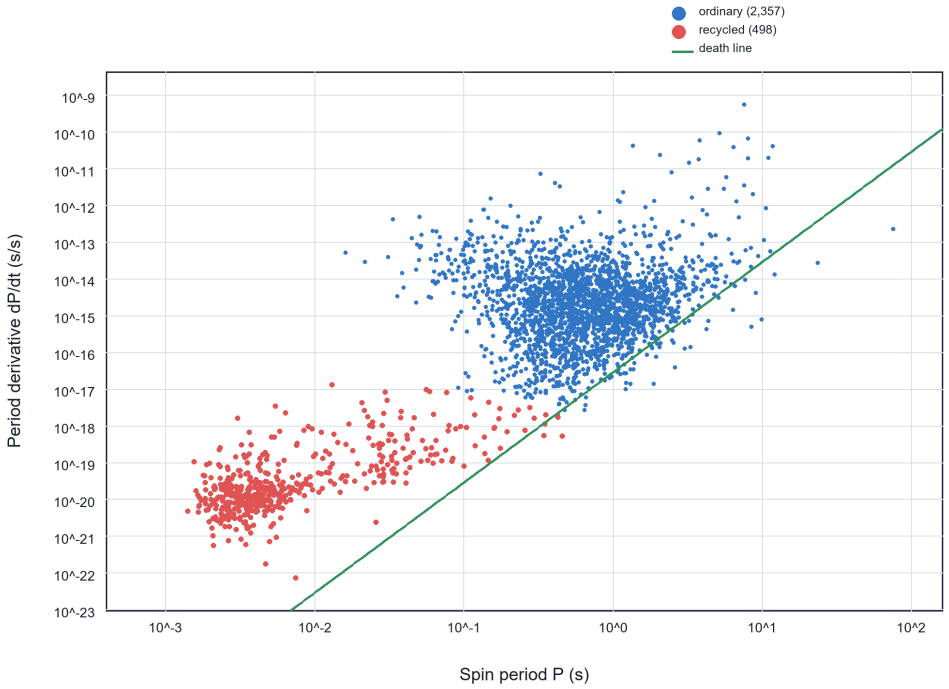


Figure 2: Log P and log $\dot{P}$ for pulsars and recycled/millisecond pulsars. Blue are normal pulsars; red are recycled pulsars.

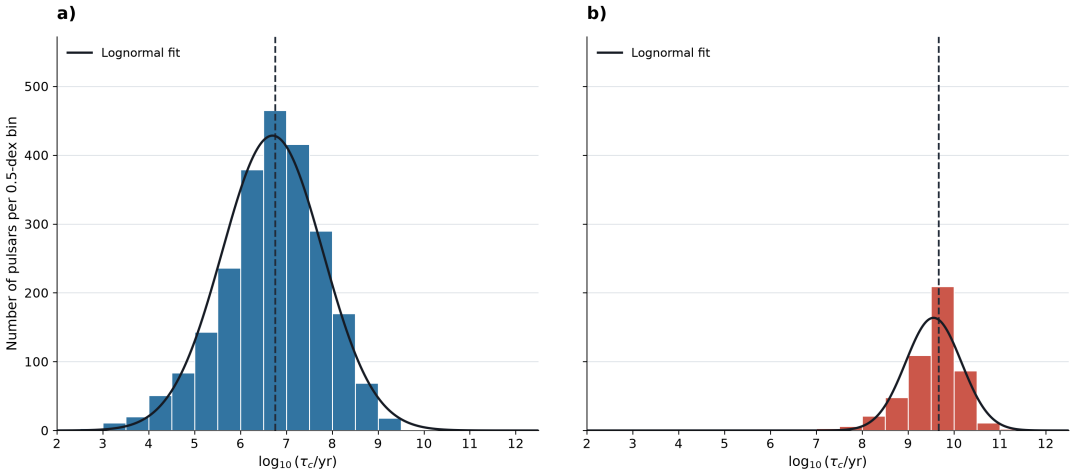


Figure 3: Pulsar Characteristic ages. A) are normal pulsars, B) are millisecond pulsars.

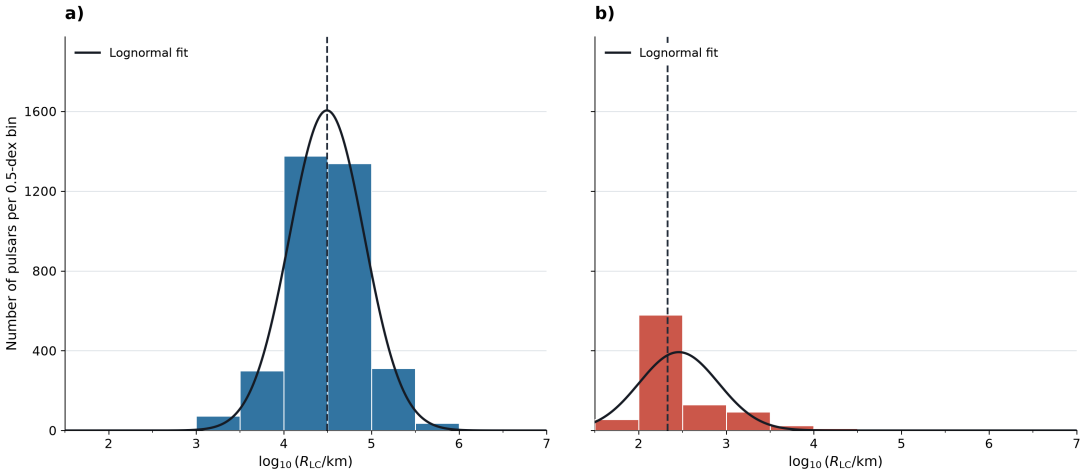


Figure 4: Light Cylinder Radii. A) is normal pulsars, B) is recycled pulsars.

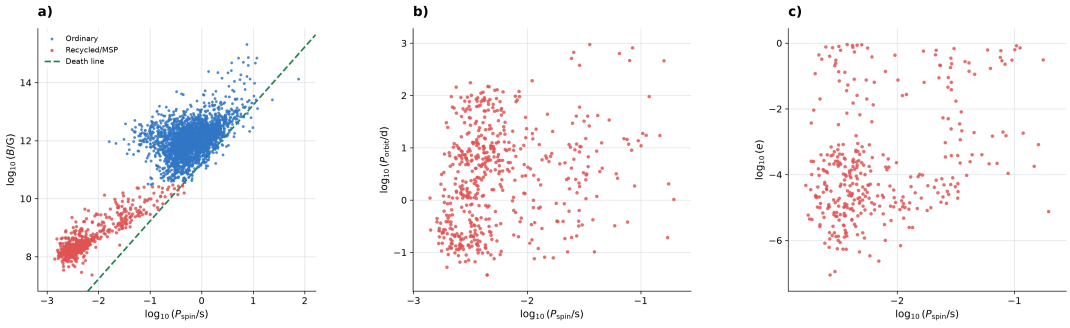


Figure 5: A) is a log P/log B plot of ordinary and recycled pulsars; B) is a plot of recycled pulsars' orbital periods vs spin periods; C) is a plot of recycled pulsars' orbital eccentricities vs spin periods.

Table 1: Table of Pearson correlations of Pulsar populations

Graph	Population	Number	Pearson r
$\log P$ vs. $\log \dot{P}$	All	2,855	0.803
Same graph	Ordinary	2,357	0.094
Same graph	Recycled/MSP	498	0.700
$\log P$ vs. $\log B$	Recycled/MSP	498	0.882
$\log P_{\text{spin}}$ vs. $\log P_{\text{orbit}}$	Recycled/MSP	534	0.235
$\log P_{\text{spin}}$ vs. $\log e$	Recycled/MSP	352	0.337
$\log P$ vs. $\log B$—additional all-pulsar plot	All	2,855	0.897
Same graph	Ordinary	2,357	0.430

Conclusion

I investigated the differences between ordinary and recycled pulsars using data from the ATNF Pulsar Catalogue. The results show that recycled pulsars generally have shorter spin periods, weaker magnetic fields, larger characteristic ages, and smaller light-cylinder radii than ordinary pulsars. I also found weak positive correlations between the spin period and orbital period (r = 0.235) and between the spin period and orbital eccentricity (r = 0.337) of recycled pulsars. These findings are consistent with the theory that mass transfer in binary systems can spin up neutron stars, producing millisecond pulsars.

Future work could investigate how different companion types, particularly white dwarfs, influence pulsar spin and orbital properties. Additionally, comparing recycled pulsars in globular clusters with those in the Galactic field could help identify how different formation environments affect binary evolution. More detailed statistical analysis and numerical simulations of mass transfer could further clarify the physical mechanisms responsible for pulsar recycling.

References

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