School of Physics

The Fast Transient Sky

Stage Transfer Report

Owen Johnson†
Astrophysics Group
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Abstract

The abstract is a short concise outline of your project area, **of no more than 100 words**.

Supervisor: Assoc. Prof. Evan Keane

†ojohnson@tcd.ie

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Declaration

I hereby declare that this report is entirely my own work and that it has not been submitted as an exercise for a degree at this or any other university.

I have read and I understand the plagiarism provisions in the General Regulations of the University Calendar for the current year, found at http://www.tcd.ie/calendar.

Signed: ____________________ Date: ____________________

Publications and Presentations

Publications

Johnson, O.A., Gajjar, V., Keane, E.F., et. al (2023). Simultaneous dual-site SETI with LOFAR international stations. Manuscript accepted for publication to AJ. arXiv:2310.15704

Presentations

1. Low Frequency's Place in SETI, January, 2024, PSETI Symposium, Penn State. **[Invited]**

2. Technosignatures with NenuFAR, December, 2023, Science at Low Frequencies IX, UvA.

3. SETI Science at 30 - 190 MHz, November, 2023, BLUK Workshop, SKAO. **[Invited]**

4. Technosignature Science at Low Frequencies, November, 2023, NASA Goddard Flight Center.
   [Invited]

5. Dual Site SETI Searches, 2023, International Astronautical Congress, Baku.

Physical Constants

Constant	Symbol	Value
Speed of Light	c	2.99792458×10^{8} m/s
Gravitational Constant	G	6.674×10^{-11} m^3 kg^{-1} s^{-2}
Planck's Constant	h	6.626×10^{-34} m^2 kg s^{-1}
Boltzmann Constant	k_B	1.381×10^{-23} m^2 kg s^{-2} K^{-1}
Stefan-Boltzmann Constant	σ	5.670×10^{-8} W m^{-2} K^{-4}
Electron Charge	e	1.602×10^{-19} C
Electron Mass	m_e	9.109×10^{-31} kg
Proton Mass	m_p	1.672×10^{-27} kg
Neutron Mass	m_n	1.675×10^{-27} kg
Solar Mass	$M_\odot$	1.989×10^{30} kg
Solar Radius	$R_\odot$	6.957×10^{8} m
Solar Luminosity	$L_\odot$	3.828×10^{26} W
Solar Temperature	$T_\odot$	5772 K
Jansky	Jy	10^{-26} W m^{-2} Hz^{-1}

1 A Prelude to Pulsars

When stars with a mass of at least $8\,\mathrm{M}_\odot$ reach the end of their evolutionary stage and experience a depletion of nuclear fuel will undergo a core collapse and explode as a Supernovae. Depending on the mass of the host star the Supernova will form a Black Hole or a Neutron Star. Based on the electron degeneracy pressure limit (Chan 1967) stars that fall in the range of 20 - 30 $\mathrm{M}_\odot$ form neutron stars (need citation).

Neutron stars are supported against further collapse by the presence of neutron degeneracy pressure which arises from the Pauli exclusion principle. Strong Nuclear forces between the neutrons also provides additional support against gravatational collapse. With these two opposing forces a stable equilibrium is formed.

In turn, this makes neutron stars exceptionally dense, they become the densest known objects in the universe that emit light. The average density of a neutron star is $10^{17}\mathrm{kg/m}^3$ (need citation). The radius of neutron stars are comparable to the size of cities, with radii of 10 - 20 km.

During collapse the conservation of magnetic flux plays a crucial role in the large strength magnetic fields that are observed in neutron stars along with contributions from the dynamo effect and frozen-in magnetic fields. The magnetic field of a neutron star are of the order of 10^{12} - 10^{15} Gauss (Need citation).

Charged particles accelerate along the magnetic field lines in the magnetosphere of the neutron star. The particles emit electromagnetic radiation in a cone shape along the magnetic axis. If the magnetic axis is not aligned with the rotational axis of the neutron star, the radiation beam will sweep across the sky. This is known as a pulsar and are analogus to cosmic lighthouses.

1.1 The Population of Pulsars

As of writing there are currently more than 3380 known pulsars. Since their discovery in 1967 by Jocelyn Bell Burnell the population has grown immensely but there remains many questions about pulsar evolution and the subclasses that lie within the population as a whole. Similarly to how exoplanet popilations are shown using the mass-radius diagram and stellar populations are shown using the Hertzsprung-Russell diagram, pulsar populations are shown using what is known as the $P - \dot{P}$ diagram.

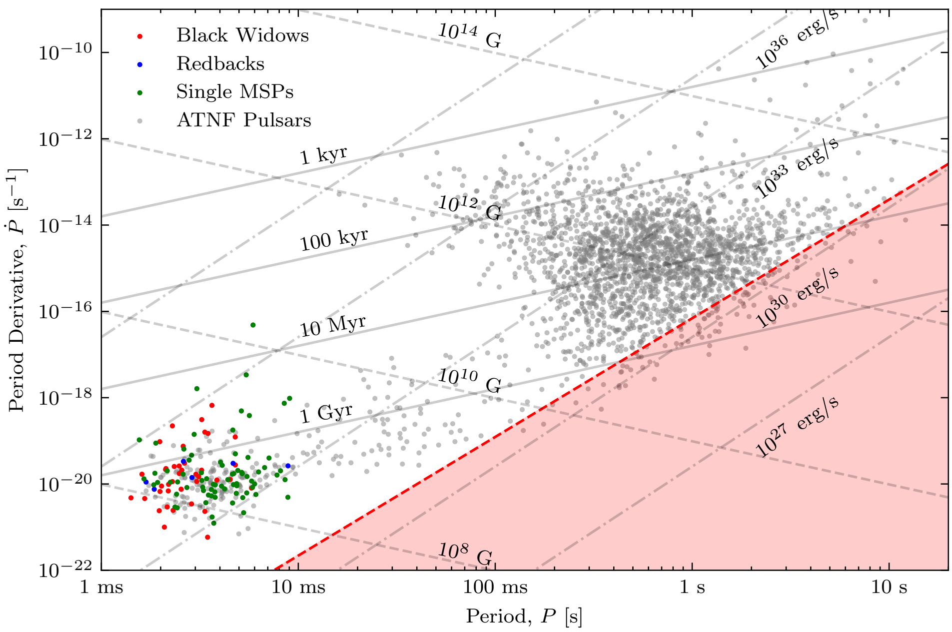

Figure 1: The $P - \dot{P}$ diagram showing the population of pulsars. The the milisecond pulsar subclasses are colour coded. The red region represents the death line, where pulsars are theortically no longer able to emit radio waves.

P representing the Pulsar's rotational period and $\dot{P}$ it's derivative. These are key ways that pulsars are classified and study in context of their evolution. An example of a $P - \dot{P}$ diagram is shown in fig. 1. Different values on the plot indicate the roughly the Pulsars age and magnetic field strength. Figure 1 shows the vastly different values bettween pulsars in the milisecond range and pulsars in the second range.

Theoretically it has been shown that pulsars exhibit a death line in the $P - \dot{P}$ diagram. This is the line where pulsars are no longer able to emit radio waves. This is due to the fact that the pulsar's magnetic field is no longer strong enough to accelerate particles along the magnetic field lines. However it has been shown that pulsars do exist below this line. The area below this line is commonly referred to as the "graveyard".

1.2 The Properities of Pulsars

Understanding the mass of pulsars are important for understanding their evolution and equation of state. Oppenheimer and Volkoff (1939) derived a canonical mass limit of neutron stars to be 1.4 $M_\odot$, but expermientally this has been shown to be higher with the largest mass of a pulsar being $\sim 2.35\,M_\odot$ (Romani et al., 2022). The mass-radius relationship of a pulsar is defined by an equation of state and a maximum mass limit. Redshifts and gravatational effects observed in pulsars exhbit the observed temperture and flux to be smaller than the actual value. The observed radius R_{obs} can be described as follows (Lorimer and Kramer, 2004),

$$R_{\text{obs}} = \frac{R}{\sqrt{1 - \frac{2GM}{Rc^2}}} \tag{1}$$

1.3 Pulsar Subclasses

The population of pulsars can be broken down into subclasses based on unique patterns in their properities. The main subclasses[1] are as follows:

1. Normal Pulsars: These are the most common type of pulsars. They are characterized by their regular pulses and are often observed in radio wavelengths. They are also known as radio pulsars.

2. Rotating Radio Transients (RRATs): These are a subclass of pulsars that were initially discovered through their sporadic radio bursts rather than regular pulses. They exhibit irregular and infrequent radio emission.

3. Magnetars: While not exclusively pulsars, magnetars are highly-magnetized neutron stars that can also emit pulsed radiation. They are characterized by extremely strong magnetic fields, much more intense than typical pulsars.

4. Binary Pulsars: These are pulsars that are in orbit around another star, usually a normal (non-neutron) star. The interaction with the companion star can have significant effects on the pulsar's behavior, and studying binary pulsars has provided important tests of theories of gravitation.

5. Millisecond Pulsars (MSPs): These are pulsars with very short rotation periods, typically less than 10 milliseconds. They are believed to be old pulsars that have been spun up by the accretion of mass from a companion star in a binary system.

6. Gamma-ray Pulsars: Pulsars that emit pulsed gamma-ray radiation are known as gamma-ray pulsars. These are often detected by space-based telescopes like the Fermi Gamma-ray Space Telescope.

7. X-ray Pulsars: Pulsars that emit pulsed X-ray radiation fall into this category. These pulsars are typically observed in binary systems where the pulsar accretes matter from its companion star, leading to X-ray emission.

[1] This is a non-exhaustive list.

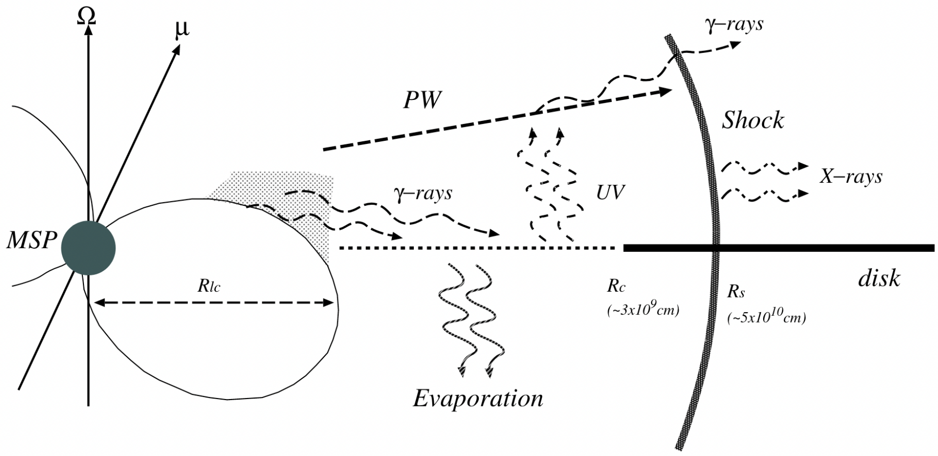

Figure 2: Figure taken from Takata et al. (2014). Multiwavelength emission from a Redback pulsar.

8. Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs): These are closely related to magnetars and are characterized by their intense and variable X-ray and gamma-ray emission. They are believed to be neutron stars with extremely strong magnetic fields.

1.4 Spider Pulsars

The type of pulsar that is of interest to this project is a subclass of transional miliscond pulsars known as Spider Pulsars. Spider pulsars fall into two categories depending on their orbiting companion. The first category are known as Black Widow pulsars segreated based on their companion mass falling in the range of 0.01 - 0.05 $M_{\odot}$ with a compantion orbital period (P_B) of less than 10 hours (citation). The second category are known as Redback pulsars and have a companion mass of 0.2 $M_{\odot}$ or greater with a P_B of less than 1 day (citation).

It is thought that most milisecond pulsars are formed through the accretion of matter from a evolved compact binary system, the $\sim 30\%$ found in isolation are thought to have ablated their companion star to the point of dissapaction (citation). Matieral being thrown off the pulsar causes the radio emission to be eclipsed via scattering and absorption, for a segment of the companion's orbit.

The wind the host pulsar emits causes heating of the companion star, causing the emittance of varying optical radiation (citaiton).

1.4.1 4FGL J0523-2529

1.4.2 4FGL J2054-6904

2 Work This Far

2.1 Search for Extraterrestrial Intelligence

2.2 M-dwarf Radio Flares

3 Summary

References

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J. R. Oppenheimer and G. M. Volkoff. On Massive Neutron Cores. *Physical Review*, 55 (4):374–381, Feb. 1939. doi: 10.1103/PhysRev.55.374. URL https://link.aps.org/doi/10.1103/PhysRev.55.374. Publisher: American Physical Society.

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