Comparative Study of Pulsars Based On Emission Mechanism

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Abstract

Using the database obtained from the Australian Telescope National Facility (ATNF), an attempt to analyse different types of pulsars based on emission mechanism was made. Twenty-eight pulsars are taken from the catalogue and are categorised into groups for comparison. A few cases of pulsars with unique characteristics are considered. Precise observational data on parameters (with respect to J2000 coordinates) is obtained from the ATNF database. Few parameters are obtained from empirical relations and are used for analysis. In an attempt to understand the behaviour of pulsars from observational data, pulsars that have high parametric values, distinguished properties and surroundings are included. It is observed that for some pulsars, that the surroundings affect them more than their interior properties. Comparative analysis of different pulsars provides us an understanding of existing data and to explore and examine non categorised objects.

Keywords: ATNF database, parameters, J2000 coordinates, empirical relations, analysis.

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Introduction

The existence of neutron stars was theoretically proposed by **Walter Baade** and **Fritz Zwicky** in 1934[1]. About 30 years later, in 1967, **Jocelyn Bell Burnell** and **Antony Hewish** observed pulsating radio sources or **pulsars** which are also known as "rotating neutron stars"[6]. Most neutron stars are observed as pulsars. Currently, there are more than 2000 known neutron stars[7] and more are yet to be discovered.

Neutron stars are formed due to the **gravitational collapse** of a massive **progenitor star** in a **supernova explosion**. Their theoretical masses are in the range of $1.4 - 3M_{\odot}$[2] with its radius in the range of about $10 - 20$ km, making them one of the densest objects in the universe. They exhibit extreme physical conditions such as strong magnetic fields, typically of the order of 10^{13} Gauss, critical temperature of the order of 10^{10} kelvin, superfluidity and superconductivity[2]. These dense and exotic objects thus act as laboratories to study and understand dense matter physics, nuclear physics, particle physics, high energy physics, and the co-relation among them[2].

1.1 | Formation of Neutron Stars

Every star forms from dense molecular clouds which are also known as **"nebula"**. Due to gravity, the molecular clouds begin to collapse[3]. The clouds get fragmented into smaller clumps and these clumps continue to collapse till they reach the critical temperature necessary to initiate nuclear fusion[4]. For nuclear fusion to take place, the temperature required is of the order of 10^6 kelvin. The star fuses the lighter nuclei into heavier nuclei, starting from hydrogen ($_1\mathbf{H}^1$) and then gradually forming all other elements in the periodic table over millions of years. On reaching iron ($_{26}\mathbf{Fe}^{56}$), the fusion stops. As iron sits at the peak of the **nuclear stability curve**, it requires a very high temperature to overcome the **electron-electron repulsion** and form any other heavier elements[3]. The core starts to cool and eventually, the radiation pressure and gas which balances the gravitational pressure break equilibrium. The star collapses under its own gravity initiating **neutronization**, a process where the electrons and the free protons fuse to form neutrons with the release of **neutrinos** and **gamma rays**[3].

$$p + e = n + \gamma$$

These neutrinos are temporarily trapped inside the core[2]. The neutrons get closely packed in the core until their density is equivalent to the density of the atomic nucleus. At this stage, the core collapse stops and the central portion of the core rebounds generating a shock-wave from the outer edge of the core which propagates radially outwards for 100 to 200 km. Due to rotation, convection and magnetic field, the neutrinos escape from the core at the speed of light which expels the stellar mantle[2]. The remaining portion of star's core is a neutron star. No fusion takes place inside the core and the gravity is balanced only by the neutron degeneracy pressure. The size of a neutron star is determined by the balance between neutron degeneracy pressure and its gravity. Neutron stars have densities ranging from 10^{17} to $10^{18} kg/m^3$. The theoretical mass limit for neutron stars is in range $1.4M_{\odot}$-$3M_{\odot}$, which is popularly known as the **Tolman−Oppenheimer−Volkoff (TOV) limit**. There are some neutron stars which have masses less than $1.4M_{\odot}$. In order to conserve angular momentum, the neutron stars have high spins[3]. As a neutron star spins, it emits electromagnetic radiation, which are emitted from the **magnetic poles/ magnetosphere** of the neutron star.

2

ATNF Catalogue

2.1 | The ATNF Pulsar Catalogue

The ATNF Pulsar catalogue was first published in 2005 with data for 1509 pulsars[8]. Currently (version 1.64) it has data for about 2000 different pulsars. It was developed by the **CASS Pulsar group**, which is a part of **ATNF** (Australian Telescope National Facility), a division of **CSIRO** (The Commonwealth Scientific and Industrial Research Organization) **Astronomy and Space Science**. The catalogue has classified the pulsars based on the source of the electromagnetic radiation emitted by them and includes all **spin-powered pulsars** as well as **anomalous X-ray pulsars** and **soft gamma-ray repeaters** showing **coherent**, **pulsed emissions** but excludes **accretion-powered systems**. The CASS group has also developed a web interface to make the catalogue available to a wider community. The web interface has an option to display tabular form of data and plots for the objects chosen. It allows us to select from a wide range of parameters which includes Name and Position parameters, Timing and Profile parameters, Binary Systems parameters, Distance parameters, Association and Survey Parameters, Derived parameters, etc[8]. All the objects in the catalogue are named based on their position in the **J2000 coordinate system**.

2.2 | Basis for the classification of pulsars

Pulsars are generally classified into three distinct categories based on the source of the electromagnetic radiation emitted by them[9]. They are:

1. **Rotation (Spin-powered) pulsars** are those in which the loss in the rotational energy of the pulsar gives rise to the radiation.

2. **Accretion-powered pulsars** (binary systems) are those in which the gravitational potential energy of the accreted matter from the companion is the source of radiation. Example, most of the X-ray pulsars.

   In case of **High mass X-ray Binary** (**HMXB**), the mass-losing star has a mass which is $\geq 10M_{\odot}$ and is an early (age) **O-Type or B-Type** star. The mass transfer takes place by the capture of matter from **stellar wind** and not by the accretion disk because they do not have a very distinct accretion disk. The X-ray emission is from the magnetic poles of the pulsar[14].

   In case of **Low mass X-ray Binary** (**LMXB**), the mass-losing star has a mass of about $1M_{\odot}$, which are mostly late type (age) stars, **Type A**. These stars do not have strong stellar winds. These late type stars fill their Roche lobe and hence mass transfer takes place by the accretion of matter through the **inner Lagrangian point** as a result of **Roche lobe overflow**. LMXBs have a very distinct accretion disk and most of the X-rays are produced at the inner part of the disk and at the surface of the neutron star. X-rays are also produced from accretion disk corona (the region above and below the disc) - **Accretion powered** system[14].

3. **Magnetars** are pulsars with extremely strong magnetic fields and the decay of these fields produce electromagnetic radiation.

2.3 | Pulsar Types

The pulsar types as listed by the catalogue are:

1. **AXP** - Anomalous X-ray Pulsar or Soft Gamma-ray Repeater with detected pulsations.
2. **Binary** - Pulsar with one or more binary companion(s).
3. **HE (Objects with High Energy emissions)** - Spin-powered pulsar with pulsed emission from radio to infra-red or higher frequencies .
4. **NRAD (Non-Radio pulsars)** - Spin-powered pulsar with pulsed emission only at infra-red or higher frequencies .
5. **Radio** - Pulsars with pulsed emission in the radio band.
6. **RRAT (Rotating Radio Transient Sources)**- Pulsars with intermittently pulsed radio emission.
7. **XINS (X-ray Isolated Neutron stars)**. Isolated neutron stars with pulsed thermal X-ray emission but no detectable radio emission.
8. **NaN** - Object type not yet defined.

1. **AXP - Anomalous X-ray Pulsar:**
   Most X-ray pulsars are in Binary systems, in which the X-rays are produced due to the gravitational potential energy released during the accretion of matter from the massive companion[9],[10]. But AXPs are young, isolated and highly magnetized. Absence of a companion shows that their radiation is not powered by accretion of matter. The pulse periods of AXPs are long in the range of 6 - 12 seconds[10]. Their rotation rates are too slow to power the X-ray emission[10],[11],[12].

   Until recently, the radiation emission mechanism of AXPs was completely unknown. Current models propose that AXPs are a type of magnetar (a neutron star with very strong magnetic fields), and X-rays are produced as their magnetic fields decay over time. Observations also show that AXPs have very similar properties to that of Soft gamma-ray repeaters (SGRs) which are also thought to be magnetars[10],[11],[12]. AXPs and SGRs have similar pulse periods, spin down rates and strong magnetic fields but the main difference is that AXPs are less active than SGRs. It is considered that SGRs evolve into AXPs when their rotation slows and magnetic field weakens[10],[13].

2. **Binary Pulsar Systems:**
   A Binary pulsar system has a pulsar with a companion which is usually a star of any type and sometimes even a planet. X-ray Binary systems emit X-ray radiation which originates as a result of gravitational potential energy released during accretion of matter from the companion[9],[10]. The main classes of the Binary pulsar systems are,[13]

   High-mass Eccentric Binaries, in which the pulsar has a main sequence (**B or Be**) star of around $10M_{\odot}$ as its companion. They have highly eccentric orbits with very long orbital periods of several weeks to several years.
   Example: PSR B1259-63.

   Circular White Dwarf Binaries have degenerate white dwarf companions of mass approximately equal to $0.1M_{\odot}$ - $1.2M_{\odot}$. Sometimes, the pulsar is a millisecond pulsar born from a previous episode of recycling. These systems have exceptionally circular orbits. Example, PSR J0437-4715 (we have chosen this object for our study).

   Neutron Star - Neutron Star Binary Pulsars have short orbital periods and eccentric orbits. Example, Hulse-Taylor binary system, which consists of a pulsar and a neutron star, viz, PSR J1915+1606 and PSR B1913+16, the first binary pulsar system to be discovered in 1974 by Russel Alan Hulse and Joseph Hooton Taylor Jr.[49].

   Eccentric White Dwarf + Pulsar Systems have a non-recycled, young pulsar in orbit around a white dwarf companion. In this case, the white dwarf is formed before the pulsar and their evolution is special. This system requires special initial conditions and mass transfer to have taken place. They have eccentric orbits.
   Example, PSR J1141-6545.

Double Pulsars have two visible pulsars. This system is very important to test the theory of general relativity. Example, PSR J0737-3039.
The 'Black widow' pulsars have short orbital periods which is less than a day and contain feeble, low-mass non-degenerate star companion. Example, PSR J2051-0827.
The Planet Pulsars System is debatable as to if it is a true binary system or not. Example, PSR J1300+1240 which has three planets orbiting it.

3. **HE, NRAD (Spin-Powered Pulsars):**
   HE pulsars, i.e, pulsars with high energy pulsations and NRAD pulsars, i.e, Non-radio pulsars are both Spin-Powered Pulsars. In Spin-powered pulsars, the loss of the rotational kinetic energy gives rise to pulsed emissions. The pulsed emission occurs in a range of frequencies. For HE pulsars, the pulsed emission is in the radio to infra-red or higher frequencies of the electromagnetic spectrum, where as for NRAD pulsars, the pulsed emission is only at infra-read or higher frequencies of the electromagnetic spectrum[8],[9].

4. **Radio Pulsars**:
   Radio pulsars are considered to be highly magnetized, rapidly rotating neutron stars exhibiting light-house effect with pulsed emissions. Majority of these pulsars spin at a rate of about once per second, some pulsars spin up to approximately 650 times per second and are generally referred to as millisecond pulsar (a pulsar spinning faster than about 50 milliseconds). Some Radio pulsars are associated with supernova remnants[15].

5. **RRAT - Rotating Radio Transient Sources:**
   RRATs are sources of short radio pulses which last for only a few milliseconds and are moderately bright. They emit pulses, for perhaps, every 100 - 1000 rotation periods of the neutron star[16]. They spend much of their time invisible in quite different ways and have underlying periodicities which are attributable to rotating magnetic neutron stars[17].

6. **XINS - X-ray Isolated Neutron Star:**
   It is a Non-radio Isolated Neutron Star. They produce thermal radiation and have high magnetic fields but not as high as that of magnetars. They are visible in some parts of the electromagnetic spectrum particularly in X-rays and gamma-rays[18].

2.4 | Objects

Objects and their categories (as per catalogue): We have selected 28 objects of the following categories,

1. HE
2. NRAD
3. RRAT
4. AXP-HE
5. AXP-NRAD
6. NaN(Object type not yet defined)

Object Description:

1. PSR J0205+6449[19],[52]:

1. It is a young, high energy pulsar (HE) and a supernova remnant that is possibly associated with supernova 1181 (SN 1181), which is a supernova in the Milky Way Galaxy .
2. Its common name is 3C-58.
3. The pulsar is significant for its high rate of cooling which cannot be explained by standard theories of neutron star formation.
4. It can be detected in radio and X-ray energies. It has the third-largest spin down flux among known spin- powered pulsars.

2. PSR J0218+4232[20]:

1. It is a high energy (HE) binary millisecond pulsar with a helium white dwarf companion (He). The radiation source is due to the loss in rotational kinetic energy, as accretion from white dwarf companions do not occur.

2. It is a 2.3 ms radio pulsar in a two day orbit around its low mass white dwarf companion.

3. PSR J0437-4715[21],[22]:

1. It is a high energy (HE) binary millisecond pulsar (MSP) with a low mass helium white dwarf companion (He) and an orbital period of 5.7 days. Accretion of matter from the white dwarf companion does not occur and hence the radiation emission is powered by the loss in rotation energy.
2. It is the closest and one of the brightest millisecond pulsar.
3. It is the first MSP to be detected in X-rays.
4. It exhibits the greatest long-term rotational stability of any pulsar, with accuracy that beats Earth-based atomic clocks.
5. The pulsar period is 5.75 ms.

4. PSR J0534+2200 (crab pulsar)[23]:

1. It is a high energy (HE) young neutron star located at the centre of the Crab Nebula, a remnant of the supernova 1054 (SN 1054).
2. It is one of the very few pulsars to be verified optically.
3. It has a period of 33 ms.
4. The radiation is observed from radio to gamma-rays.

5. PSR J1124-5916[24]:

1. This pulsar is associated with the supernova remnant G292.0+1.8.
2. It has a period of 135 ms.
3. It is a very young HE pulsar.

6. PSR J1617-5055[25]:

1. The young energetic pulsar has a X-ray PWN (Pulsar Wind Nebula - nebula that is found inside the shell of a supernova remnant and is powered by the winds generated by the central pulsar).

7. PSR J1930+1852[48]:

1. It is in a Double Neutron Star System (DNS).

2. DNS systems have rapid spin periods, eccentric orbits and short orbital periods. But PSR J1930+1852 has the longest spin period of approximately 185 ms and an orbital period of about 45 days.

3. It is partially recycled (neutron stars that spin-up by accreting matter are called recycled pulsars) and might have formed before its neutron star companion.

8. PSR J2124-3358[26]:

1. It is an isolated HE MSP with a pulsar period of 4.9 ms.

9. PSR J2229+6114[27]:

1. HE pulsar which is significantly more luminous than the Vela pulsar.

2. It has radio and X-ray pulsations at a pulsar period of 51.6 ms.

10. PSR J0633+1746[28]:

1. It is a HE pulsar, commonly called as Geminga which is at a distance of approximately 800 ly from the Sun.

2. The pulsar period is approximately 237 ms.

3. It is a gamma-ray source.

11. PSR J0537-6910[29]:

1. One of the most unusual NRAD pulsar which is losing its energy faster than any other known pulsar.

2. It also has a prolific glitch activity (a phenomenon during which the pulsar experiences a sudden change in its rotation rate).

3. It is observed only in X-ray.

12. PSR J1811-1925[30]:

1. A young NRAD pulsar which has a characteristic age greater than its supernova remnant approximately by 10 times. The reason might be its spin period. It is assumed that its spin period (65 ms) has not changed much after its birth. The reason for this might be due to the accretion from its surroundings which made it rotation-powered X-ray pulsars (from the paper cited).

13. PSR J1846-0258[31]:

1. NRAD pulsar located at the centre of the supernova remnant Kes-75.
2. It is in the boundary between magnetars and rotation powered pulsars.
3. It is young with one of the highest surface magnetic field strengths.

14. PSR J0628+0909[47]:

1. It is a millisecond rotating radio transient source.

15. PSR J1809-1943[32]:

1. It is an AXP-HE pulsar.
2. It is the first magnetar found to be emitting radio pulses.
3. The radio emission is in the form of strong, narrow bursts.
4. It has properties that are different from ordinary rotation powered pulsars including extremely variable flux densities.

16. PSR J1745-2900[33],[52]:

1. It is an AXP-HE pulsar.
2. It is the first discovered magnetar orbiting the black hole Sagittarius A* in the centre of the Milky way.
3. The magnetar period is 3.76 s and its magnetic flux density is of the order 10^{14}G.
4. The magnetar is at a distance 0.33 ly from the central black hole.

17. PSR J0100-7211[34]:

1. It is an AXP-NRAD pulsar located in the Small Magellanic Cloud.

2. This is the first abnormal extra-galactic X-ray pulsar to be discovered.

3. Its characteristic age is 6800 years.

18. PSR J1708-4008[53]:

1. It is an AXP-NRAD pulsar.

2. It is observed to have weak magnetic field than others.

19. PSR J1808-2024[31]:

1. It is an AXP-NRAD pulsar located in the constellation of Saggitarius, about 15 kpc (about 48923.45 ly) from earth.

2. It is one of the few known SGRs in our own galaxy.

3. It has a surface temperature of 1,36,000 K and is around 12.39$M_\odot$.

20. PSR J1841-0456[35]:

1. It is an AXP-NRAD pulsar associated with the supernova remnant of Kes 73.

2. It is an X-ray source with a pulsar period of approximately 11.8 s.

3. Its rotational energy is far too small to produce X-rays and other proposed mechanisms for the production of X-rays are:

   a) Accretion from a high mass X-ray binary, a low mass companion or a fossil disk or a merged white dwarf.

   b) Intrinsic energy loss, such as initial cooling or decay of magnetic fields.

21. PSR J1907+0919[36]:

1. Associated with SGR 1900+14, it has a pulsed radio emission of period 5.16 s.

2. It has a super strong magnetic field in the order of 8.1×10^{14}G.

22. PSR J2301+5852 & 23. PSR J0525-6607:

1. It is an AXP-NRAD pulsar.

24. PSR J1105-6107[37]:

1. The object category is not defined in the catalogue (NaN), but it is a radio pulsar (Rotation-powered) with a period of 63 ms (from the paper cited).

2. It is a young and energetic pulsar and is possibly associated with the nearby supernova remnant G290.1-0.8.

3. This pulsar can be observed at higher energies.

25. PSR J0543+2329:

1. Its category is not defined by the catalogue, but it is an X-ray source[38]

2. This pulsar was in a close binary system with J0528+2200 which was later disrupted by a supernova explosion[39].

26. PSR J0636-4549:

1. It might be a radio source[40].

27.PSR J1811-4930 & 28. PSR J1812-1718:

1. Object type unknown.

2.5 | Parameters:

In order to understand the properties of all the pulsars in detail, we chose the following few parameters from the catalogue and studied them. We also derived some other parameters such as the moment of inertia and radius from period and period derivative of the pulsars. Parameters from the catalogue[8],[42],[43]:

1. P - Barycentric period of the pulsar in second (s): The period of the pulsar (the interval between pulses) with respect to its barycentre is known as the barycentric period of the pulsar.

2. $\dot{P}$ (dimensionless): is the time derivative of the barycentric period. It is an observational value, but the measurements are difficult to perform as it demands extremely long and precise rows of observations.

$$\dot{P} = \frac{P_2 - P_1}{T_2 - T_1} = \frac{\partial P}{\partial t} \tag{2.1}$$

where P_1, P_2 are the pulsar periods and T_1,T_2 are the time intervals.

3. R_{Lum} - Radio luminosity at 400 MHz in milli-Jansky kpc^2 (mJykpc^2) : Radio luminosity is an intrinsic property of radio pulsars related to the properties of a magnetospheric plasma and the beam geometry. It is inversely proportional to the

observing frequency. It is also considered as a function of the spin parameters of the pulsar.

4. τ - Characteristic age (or spin down age) of the pulsar in year (yr):
   The characteristic age of a pulsar is calculated from its spin down rate. It provides an approximate measure for the pulsar's true age. The characteristic age is given as in equation 2.2,
   $$\tau = \frac{P}{2\dot{P}} \tag{2.2}$$
   where P is the period of the pulsar and $\dot{P}$ is the first derivative. Calculation using this formula is valid under the following three assumptions:
   a) The pulsar's initial spin period was much smaller compared to the spin period observed today.
   b) There is no magnetic field decay
   c) The magnetic braking can be approximated by the energy loss, as spinning dipolar magnet would experience in a perfect vacuum [in this case, the braking index($n = 3$)].[41]
5. F - Barycentric rotation frequency in Hertz (Hz).
6. B_S - Surface magnetic flux density in Gauss (G) : It is the magnetic flux (the total number of magnetic field lines passing through the area) at the surface.
7. $\dot{P}$ - Spin down energy loss rate (erg/s): Pulsars have high spin, due to which it loses energy, causing the spin to reduce. The rate of loss of rotational kinetic energy is expressed in $\dot{E}$.
8. B_{LC} - Magnetic field at light cylinder in Gauss (G).
9. PX - Annual parallax in milli-arcsecond (mas).
10. D - Distance in kiloparsec (kpc): Best estimate of the pulsar distance using the YMW16 DM-based distance as default (kpc).
    Distance from barrycenter to target (pulsar): D = 1/PX, where PX is annual parallax.

2.6 | Derived Parameters:

These parameters are deduced from empirical relations based on **moment of inertia (I)**, **spin-period (P)**, **rate of change of spin-period ($\dot{P}$)**, **surface magnetic flux density (B_s)**, etc. In order to calculate the values for surface magnetic flux density (B_s), the catalogue has made two assumptions and generalised the values for radius and moment of inertia [54] where the radius of the objects is considered to be,
(R = 10^6 cm) and moment of inertia (I = 10^{45} g.cm^2) .

The following parameters were calculated using empirical relations:

1. Radius of the neutron star: Most of the objects in our data (table) have almost equal radius values. (write the equations systematically). On rearranging 2.3, the equation for radius is given by,

$$R_{NS} = (\frac{IP\dot{P}}{B_s^2})^{1/6} \tag{2.3}$$

2. Luminosity:

$$L = \frac{I\dot{P}}{P^3} \tag{2.4}$$

3. Moment of Inertia(I):

$$I = \frac{\dot{E}P}{4\pi^2\dot{P}} \tag{2.5}$$

4. Magnetic moment (m): Magnetic moment can also be defined as dipole moment or the characteristic magnetic filed of a pulsar. Through the magnetic dipole inclination we can determine the electromagnetic radiation at a particular rotational frequency.

$$m = \sqrt{\frac{3P\dot{P}Ic^3}{8\pi^2}} \tag{2.6}$$

Rotating pulsars have extremely strong magnetic fields, this creates an angle between the rotation axis and magnetic axis. When a pulsar loses it energy, rotational energy compensates for the loss by emitting electromagnetic radiation, which in turn leads to a decrease in the angular velocity. If we consider the neutron star as a magnetized rotating body, we can define the spin down torque as:

$$\tau = \frac{2m^2\omega^3\sin^2\beta}{3c^3} \tag{2.7}$$

3

Analysis

3.1 | Distribution of Data:

The ATNF database, version 1.64, lists more than 2000 pulsars. However, we selected 28 candidates of different categories for analysis. There are ten high energy pulsars in which two of them are binary millisecond pulsars with Helium White Dwarf companion (PSR J0218+4232 and PSR J0437-4715) and one object is an isolated MSP (PSR J2124-3358). There are three NRAD pulsars, one RRAT pulsar, two AXP-HE pulsars, seven AXP-NRAD pulsars, two X-ray sources and three NaN objects (objects whose types are not yet defined in the catalogue).

Note: The **'-'** and **'NaN'** represent the **"Unknown Type"** category.

The distribution of data with respect to categories of pulsar types is shown in the above /textbfFigure 3.1. They include the following pulsar categories:

1. HE: High energy pulsar.
2. He-hwd : High Energy pulsar with binary companion helium white dwarf.
3. X_{ray} : X-ray pulsars.
4. NRAD : Non-Radio pulsars detected in high frequency like gamma.
5. RRAT :Rotating Radio Transient.
6. "-" : Unknown pulsars whose types are not yet defined (NaN).
7. AXP - NRAD : Anomalous X-ray pulsars observed in both X-ray and Gamma-ray.

Table 3.1: (1)

Name of pulsar(J2000)	Period(P) sec	Spin-Rate($\dot{P}$)	D(Kpc)	Age(yrs)
J0205+6449	0.06571592849	1.94E-13	3.2	5370
J0218+4232	0.002323090532	7.74E-20	3.15	476000000
J0437-4715	0.005757451937	5.73E-20	0.157	1590000000
J0534+2200	0.0333924123	4.21E-13	2	1260
J1105-6107	0.06320213092	1.58E-14	2.36	63200
J1124-5916	0.1354768544	7.53E-13	5	2850
J1617-5055	0.069356847	1.35E-13	4.743	8130
J1930+1852	0.136855047	7.51E-13	7	2890
J2124-3358	0.004931114943	2.06E-20	0.41	3800000000
J2229+6114	0.05162357393	7.83E-14	3	10500
J0537-6910	0.01612222202	5.18E-14	49.7	4930
J0543+2329	0.2459836833	1.54E-14	1.565	253000
J1811-1925	0.064667	4.40E-14	5	23300
J1846-0258	0.3265712883	7.11E-12	5.8	728
J0628+0909	3.76373308	5.48E-16	1.771	35900000
J0633+1746	0.2370994417	1.10E-14	0.19	342000
J0636-4549	1.984597367	3.17E-15	0.383	9910000
J1811-4930	1.432704197	2.25E-15	1.447	10100000
J1812-1718	1.205374441	1.91E-14	3.678	1000000
J0100-7211	8.020392	1.88E-11	59.7	6760
J1708-4008	11.0062624	1.96E-11	3.8	8900
J1808-2024	7.55592	5.49E-10	13	218
J1809-1943	5.540742829	2.83E-12	3.6	31000
J1841-0456	11.7889784	4.09E-11	9.6	4570
J1907+0919	5.198346	9.20E-11	NaN	895
J2301+5852	6.97907097	4.71E-13	3.3	235000
J1745-2900	3.76373308	1.76E-11	8.3	3400
J0525-6607	8.047	6.50E-11	NaN	1960

Name of pulsar(J2000)	B_s(G)	$\dot{E}$(erg/s)	B_{Lc}(G)	I(gcm^2)	R_{Ns}(km)
J0205+6449	361E+10	2.70E+37	119000	1.00E+45	9.965951693
J0218+4232	429E+6	2.40E+35	321000	9.86E+44	9.937420138
J0437-4715	429E+6	1.20E+34	28500	1.01E+45	11.04616289
J0534+2200	379E+10	4.50E+38	955000	1.01E+45	9.979321103
J1105-6107	101E+10	2.50E+36	37600	1.01E+45	9.985829419
J1124-5916	102E+11	1.20E+37	38500	1.01E+45	9.975170757
J1617-5055	31E+11	1.60E+37	87000	1.00E+45	9.961065114
J1930+1852	103E+11	1.20E+37	37500	1.04E+45	10.01010109
J2124-3358	322E+6	6.80E+33	25200	1.01E+45	9.971865167
J2229+6114	203E+10	2.20E+37	139000	9.81E+44	9.934604859
J0537-6910	925E+9	4.90E+38	2070000	1.01E+45	9.968171155
J0543+2329	197E+10	4.10E+34	1240	1.00E+45	9.967652442
J1811-1925	171E+10	6.40E+36	59200	9.97E+44	9.950232304
J1846-0258	488E+11	8.10E+36	13100	1.01E+45	9.967961401
J0628+0909	835E+9	1.10E+31	4.09	2.71E+46	20.76965512
J0633+1746	163E+10	3.20E+34	1150	9.86E+44	9.940989183
J0636-4549	254E+10	1.60E+31	3.05	1.00E+45	9.95872678
J1811-4930	182E+10	3.00E+31	5.8	9.92E+44	9.945216014
J1812-1718	485E+10	4.30E+32	26	1.00E+45	9.96381375
J0100-7211	393E+12	1.40E+33	7.14	9.74E+44	9.91671133
J1708-4008	47E+13	5.80E+32	3.3	1.00E+45	9.961209485
J1808-2024	2.06E+15	5.00E+34	44.8	9.96E+44	9.955833236
J1809-1943	127E+12	6.60E+32	6.98	1.01E+45	9.962802699
J1841-0456	703E+12	9.90E+32	4.02	1.01E+45	9.968236292
J1907+0919	7E+14	2.60E+34	46.7	1.01E+45	9.970565369
J2301+5852	58E+12	5.50E+31	1.6	1.01E+45	9.972322439
J1745-2900	26E+13	1.30E+34	45.7	1.00E+45	9.963810035
J0525-6607	732E+12	4.90E+33	13.2	9.96E+44	9.953254432

Name of pulsar	Category	Magnetic moment(ergs/G)	$\ddot{P}$	lum(ergs/s)
J0205+6449	HE	3.62E+27	4.36E-74	6.85E+35
J0218+4232	HE-hwd	4.26E+23	1.44E-77	6.09E+33
J0437-4715	HE-hwd	5.86E+23	1.65E-78	3.04E+32
J0534+2200	HE	3.81E+27	3.59E-73	1.14E+37
J1105-6107	X-ray	1.02E+27	3.77E-75	6.34E+34
J1124-5916	HE	1.03E+28	3.98E-74	3.04E+35
J1617-5055	HE	3.10E+27	2.73E-74	4.06E+35
J1930+1852	HE	1.05E+28	3.60E-74	3.04E+35
J2124-3358	HE	3.23E+23	8.23E-79	1.72E+32
J2229+6114	HE	2.02E+27	2.85E-74	5.58E+35
J0537-6910	NRAD	9.28E+26	2.01E-73	1.24E+37
J0543+2329	X-ray	1.98E+27	2.47E-76	1.04E+33
J1811-1925	NRAD	1.71E+27	1.02E-74	1.62E+35
J1846-0258	NRAD	4.90E+28	6.67E-74	2.05E+35
J0628+0909	RRAT	7.58E+27	3.76E-80	2.79E+29
J0633+1746	HE	1.62E+27	1.92E-76	8.11E+32
J0636-4549	-	2.54E+27	7.66E-79	4.06E+29
J1811-4930	-	1.81E+27	1.45E-81	7.61E+29
J1812-1718	-	4.86E+27	1.32E-77	1.09E+31
J0100-7211	AXP-NRAD	3.88E+29	2.84E-76	3.55E+31
J1708-4008	AXP-NRAD	4.71E+29	1.57E-76	1.47E+31
J1808-2024	AXP-NRAD	2.06E+30	9.86E-75	1.27E+33
J1809-1943	AXP-HE	1.27E+29	9.02E-77	1.67E+31
J1841-0456	AXP-NRAD	7.05E+29	2.86E-76	2.51E+31
J1907+0919	AXP-NRAD	7.03E+29	3.34E-75	6.59E+32
J2301+5852	AXP-NRAD	5.83E+28	9.20E-78	1.39E+30
J1745-2900	AXP-HE	2.60E+29	1.21E-75	3.30E+32
J0525-6607	AXP-NRAD	7.31E+29	9.56E-76	1.24E+32

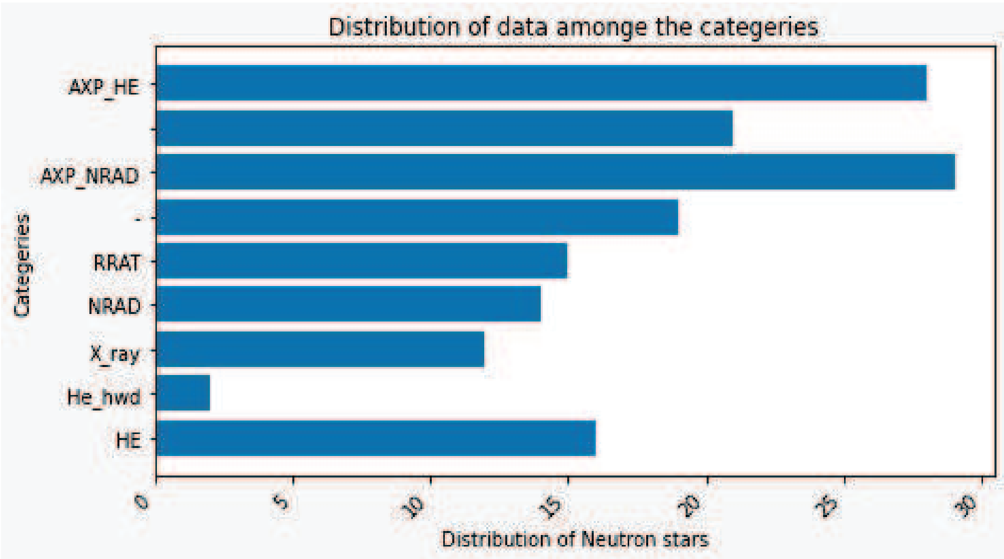


Figure 3.1: Number density distribution of pulsars graph based on ATNF data collected.

3.2 | Magnetic field at Light Cylinder and Period of Rotation:

There are two types of pulsar models[a] proposed and observed so far.

1. Polar cap or surface model: The pulses are generated above the magnetic poles of neutron star and are beamed out along the magnetic field lines.
2. Relativistic Beaming or Light cylinder model : The pulses are formed in the magnetosphere of NS, and they account for relativity.

Thomas Gold proposed that the pulsar emission would come from plasma magnetically trapped in co-rotation of NS at nearly speed-of-light velocity radius(R_{Lc}).

Note: Radius at light cylinder does not mean radius, but in fact it refers to the angular velocity at which the beam is being processed along the direction of emission.

Co-rotating field lines emerging from the polar caps across the light cylinder, an imaginary cylinder is centered on the pulsar and aligned with the rotation axis whose radius at co-rotating speed is equal to the speed of light, so these field lines cannot close. Electrons in the polar cap are magnetically accelerated to high energies along the open but curved field lines, where the acceleration resulting from the curvature causes them to emit curvature radiation that is strongly polarized in the plane of curvature.

Period(p) of a pulsar is the time interval between the two pulses received by an observer from the source(Neutron star). Each pulse is calculated from the pulse arrival time data. ATNF uses pulsar timing to generate intrinsic period and frequency with respect to the barycentric frames. Magnetic field lines at light cylinders(B_{LC}) are the locus of magnetic field lines that reach out to the light cylinder. Assuming that inertia(I) is 10^{45} g.cm^2.

3.2.1 | HE & HE-Binary:

10 pulsars were grouped into one set and were plotted respectively. Each set of category is analyzed separately using color coded plotting with the help of **seaborn** library.

The magnetic field strength at light cylinder in Gauss vs spin period in seconds for high energy pulsar were plotted using a logarithmic scale. Taking log10 on both sides changes the nature of the graph(figure 3.2).

The spin period is negative because high energy pulsars have a period of less than one second(1-10 milliseconds) as a result of the logarithmic scale, it is scaling down to the negative y axis. i.e. for example: $\log_{10} 0.01 = -2$.
The following are the inference made from the plot:

1. **J0633+1746** or **Geminga** has high period and low angular velocity. It is a high energy emission source as well as gamma source, unlike the other HE pulsars it behaves different due to its weak pulsar magnetosphere, it has less magnetic field lines at the light cylinder.

2. **J1930+ 1852** and **J1124-5916** are young pulsars that have similar periods, first derivative periods, and age, and hence these points overlap in the graph(figure 3.2). The reason for the similarities are, they are from similar types of nebula. **J1930+ 1852** is from **SNR G054.1+00.3** which is a Supernova remnant. **J1124-5916** is from **SNR G292.0+01.8** which is a wind nebula.

3. These two are young and energetic, hence B_{LC} is less when compared to **J167-5055**. **J1930+ 1852** has a companion neutron star which hasn't been discovered yet, but it has a higher spin period.

4. **J1617-5055, J0205+6449** and **J2229+6114** are in the same line than other HE, though periods are almost the same their B_{LC} is in an increasing order due to its age which

is directly proportional to the magnetic field at the light cylinder. For this type of HE pulsar(upper part of the graph(figure 3.2))their ages are in increasing order.

5. **J0534+2200 or crab pulsar** has a low period and fast spin compared to the previous one because of its lower age, it is highly energetic when compared to the previous one but it has an exceptionally high B_{Lc} than the rest of the pulsars because of its second derivative frequency. The second derivative frequency was observed for decades. The slow spin-down rate of the pulsar leads to loss of kinetic energy in the form of electromagnetic radiation. This results in exceptionally high B_{LC} as shown in graph(figure 3.2).

6. The second graph(figure 3.2) also involves HE-pulsars with a white-dwarf companion, which is the reason for their peculiar position in the plot.

7. The relationship between the two parameters B_{Lc} and P is in the form of linear relation $y = mx + c$ since they are log-scaled parameters. Although when cross checked with existing theories we can infer that they are inversely proportional which on scaling into log-scale gives the same relation that was observed with the data.

3.2.2 | Comparing to **ATNF** from the Catalog:

From the graph(figure 3.3), we can confirm that millisecond pulsars and binary millisecond pulsars with a companion(white helium dwarf) are not anomalies but are at lower regions of plot due to their unique conditions of surroundings caused by their companion.

Binary-Systems in Plot:

1. PSR J0437-4715: This pulsar has a white dwarf companion. The mass range for the pulsar and it's companion are $m_c = 0.254 \pm 0.018 M_s$ and $m_p = 1.76 \pm 0.2 M_s$. This pulsar has been said to be the highest in mass-range[b].From this paper, we can infer the reason why this binary system is acting as an anomaly in the plot. It is due to the high mass and anomalous accretion from the companion. Hence the more spin-power and magnetic-field generation or emission of energy from the magnetosphere is high also known as Light cylinders.

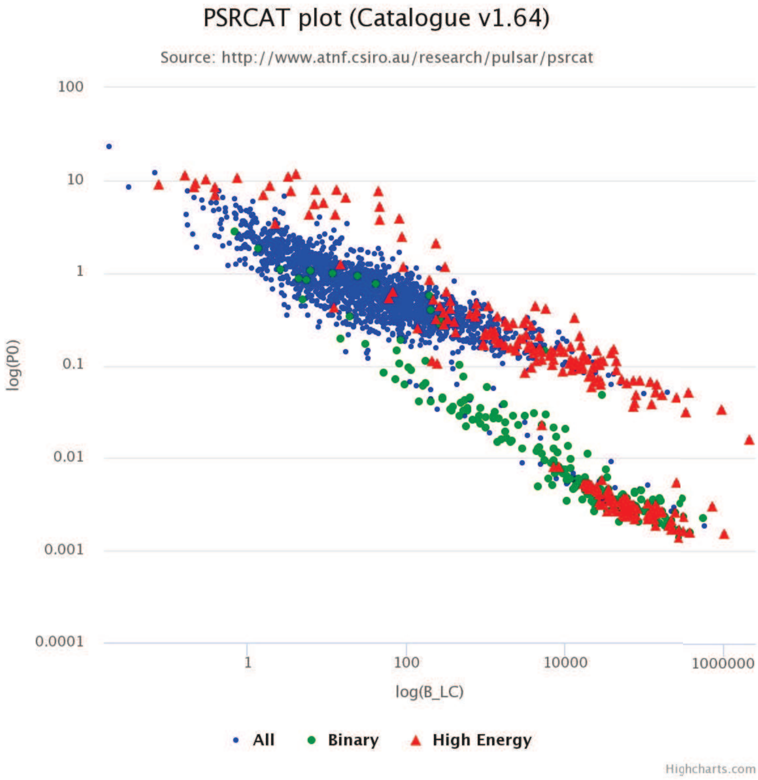
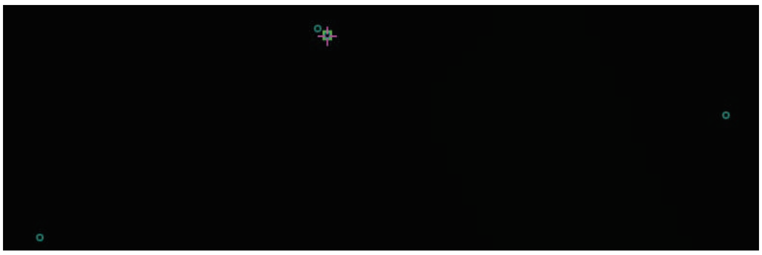
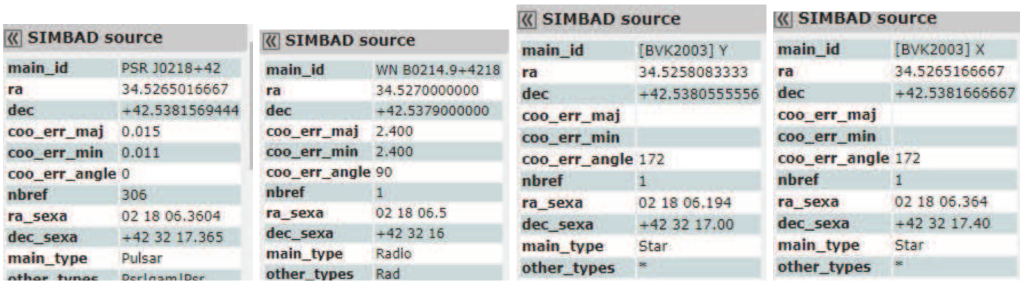


Figure 3.2: PSRCAT plot between magnetic field at light cylinder and spin-period.

2. PSR J0218+4232: From the data and paper[c] It has period of 0.002323s. It has the companion **[BVK2003] X – Star** which is a **low mass G-type star** of mass around $1M_s$. There are two more objects which are close to this binary system among them one of it is a **radio source** which could be a neutron-star and the other is a star of unknown type.

   This could be the cause for such high spin-period of the pulsar **J0218+4232** and the high B_{LC} value in the plot can be assumed due to the **accretion** from it's companion-star gaining rotational KE and hence being able to produce high energy emissions through the magnetosphere also known as the flux from B_{LC}.





SIMBAD source		SIMBAD source		SIMBAD source		SIMBAD source	
main_id	PSR J0218+42	main_id	WN B0214.9+4218	main_id	[BVK2003] Y	main_id	[BVK2003] X
ra	34.5265016667	ra	34.5270000000	ra	34.5258083333	ra	34.5265166667
dec	+42.5381569444	dec	+42.5379000000	dec	+42.5380555556	dec	+42.5381666667
coo_err_maj	0.015	coo_err_maj	2.400	coo_err_maj		coo_err_maj	
coo_err_min	0.011	coo_err_min	2.400	coo_err_min		coo_err_min	
coo_err_angle	0	coo_err_angle	90	coo_err_angle	172	coo_err_angle	172
nbref	306	nbref	1	nbref	1	nbref	1
ra_sexa	02 18 06.3604	ra_sexa	02 18 06.5	ra_sexa	02 18 06.194	ra_sexa	02 18 06.364
dec_sexa	+42 32 17.365	dec_sexa	+42 32 16	dec_sexa	+42 32 17.00	dec_sexa	+42 32 17.40
main_type	Pulsar	main_type	Radio	main_type	Star	main_type	Star
other_types	[illegible]	other_types	Rad	other_types	*	other_types	*

Figure 3.3: Data from SIMBAD source on stars-χ, G,neutron-star, J0218+4232.

3. **J2124-3358** has an unnatural position in the plot, this is due to the **bow shock** which in turn suggests that the MSP **gained** significant mass during **recycling** and then lost its companion. Hence it has high angular velocity and low period compared to all other HE-Pulsars despite it's old age, and high Luminosity due to the accretion from it's lost companion.

   From the paper[d], we can infer the following:

   1. Both the pulsars **J2124-3358** & **J0437-4715** are having binary companion of **NS(predicted)** and a **WD** respectively. Both of them have produced **bow-shocks** at detection through the **NASA Hubble Telescope**.
   2. This could be the reason for both of them having a similar range of period and position in the plot as shown.

   The properties for the bow-shock formation and characteristics can be extracted from the paper "The Asymmetric Bow Shock/Pulsar Wind Nebula of PSR J2124–3358"[e].

3.2.3 | AXP & AXP-Binary:

J1841-0456 is one of the high period pulsar and low speed rotating pulsar which is located in center of supernova remnant **4C -04.71**(not yet confirmed to be supernova remnant). It has a high period due to high magnetic field rather than because of loss of kinetic energy due to rotation. Even glitch activities are less.

J1808-4008 and **J1841-0456** have relatively same period and low magnetic field lines at light cylinder because **J1808-4008** because of its characteristic age, it exhibits same properties as **J1841-0456**. The minute difference in the magnetic field at light cylinder is because of the number of glitches(**J1808-4008** - 3, **J1841-0456** - 4).

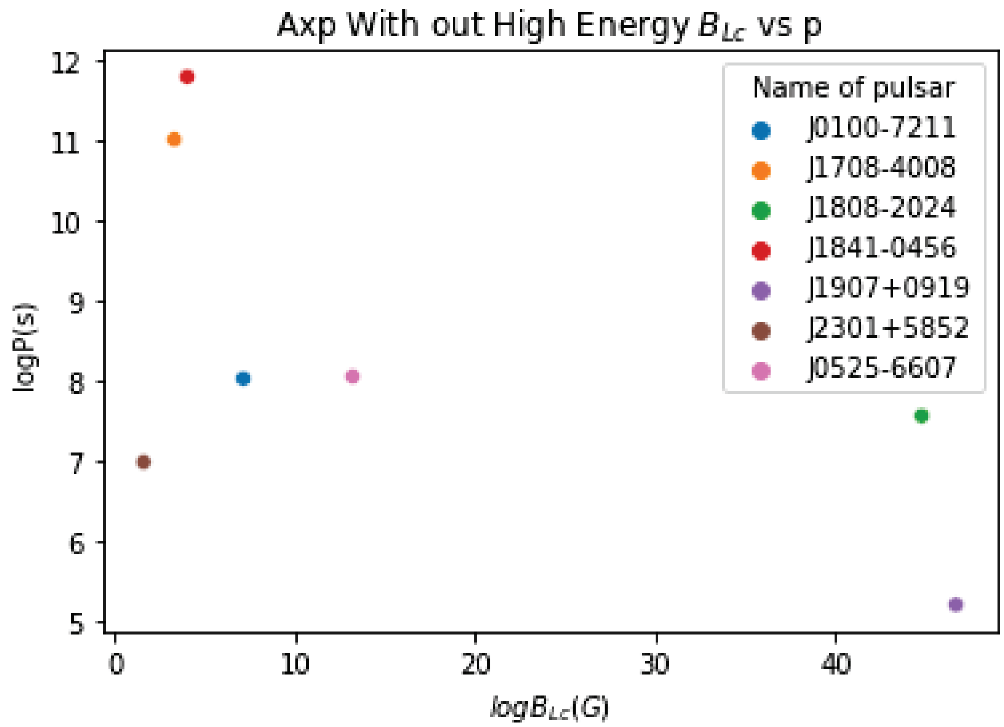


Figure 3.4: Plot between spin-period and magnetic field at light cylinder radius in logarithmic scale.

J0100-7211 - due to its surroundings, which is in a Small Magellanic cloud. It has high spin down rate when compared to **J1808-4008**, **J1841-0456** which resulted in high rotational velocity, because of the nearby stars **[DV2005] Z**, **[DV2008] 5**,**GSC2 S01020208968** within the **1 arcsec** distance to the pulsar they are lying because of which light cylinder radius is significantly compared to theoretical value.

J0100-7211 and **J0525-6607** are exhibiting same period and has a small difference in magnetic field at light cylinder. **J025-6607** is found in outer galaxy Super-Nova remnant **052566.1**, which is also known as **N49**. Though the surface Magnetic field is high but the inside light cylinder, it significantly less. Here in the case of **J0525-6607**, there are continuous burst outs and flares. In both of the pulsars the surroundings are effecting significantly high compare to age, Magnetic field at surface.

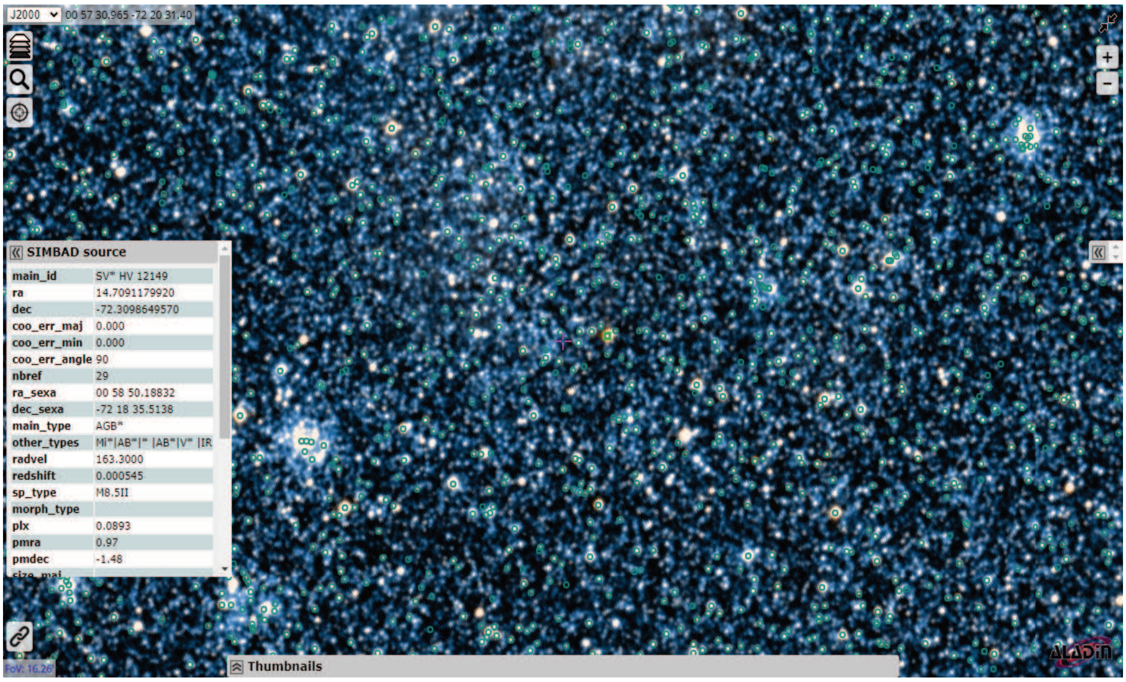


Figure 3.5: Optical image of J0100-7211 with it's surroundings(very dense cloud). green square is a pulsar in it's host nebulae.
Source : Aladdin Lite

3.2.3.1 | Anomalies Observed:

J1808-2024 is binary with very massive companion as **[KMN95] Star A** , which is a supergiant star because of which it is exhibiting low period and has good magnetic dipole at light cylinder. It is not a anomaly in reality because of lack of binary AXP-NRAD pulsar in our data, it is acting as anomaly. Similar to HE binary pulsars, they are following lower region of logarithm graph.

J1907+0919 is a counterpart of pulsar **1900+14** , which is in open cluster, that's the indication of ultra high magnetic field and high spin down rate because of which is having high B_{LC} values compared to others.

The reason for **J1808-2024** and **J1907+0919** are having a bit same derived parameters(because of log-log scale period is not noticed as same in our graph but are similarly acting for good amount of data) is that **J1907+0919** is not confirm to be binary but it has similar conditions as binary . It might be orbiting but involved in accretion yet or Pulsar **1900+14** has burst out might be effecting the this pulsar.

J2301+5852 (IE 229+586) is a one among three pulsars which are detected in galactic supernova remnant, this one is **SNR G109.1-01.0** which is actual anomaly, though it is not seems to be acting like that in our graph but it is a anomaly in reality because of **anti-glitch** mechanism is reducing the spin down rate and due to near by high mass binary X-rays it might be acting as anomaly.

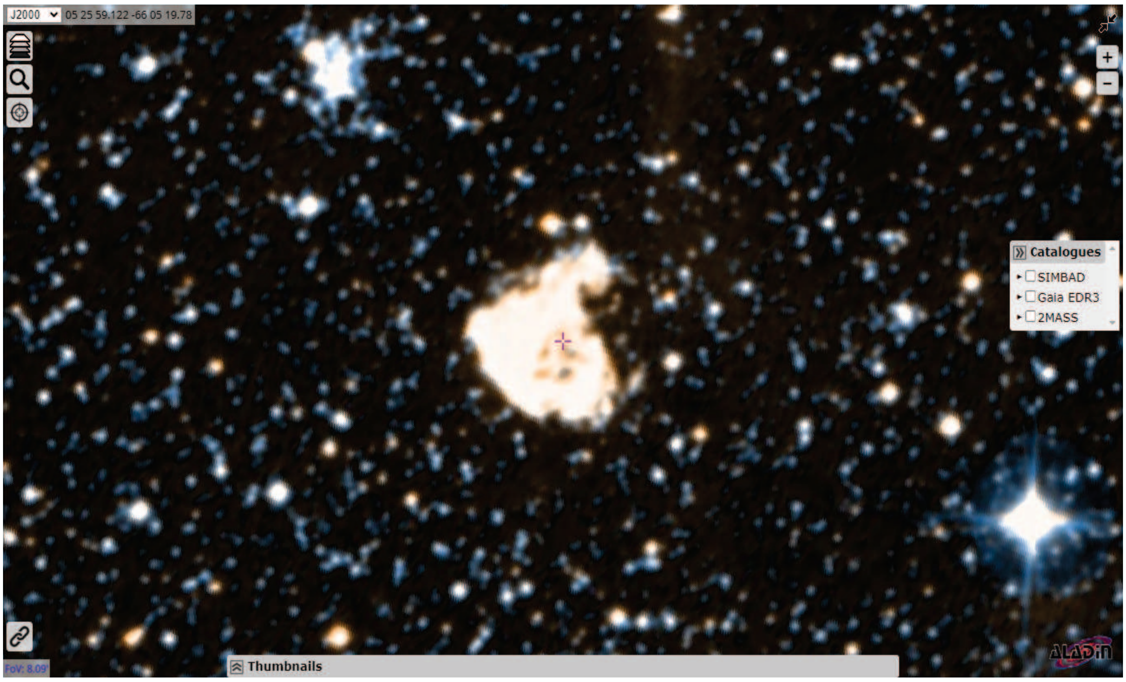


Figure 3.6: DSS2 colored in optical band image of J0525-6607(name changed to SGR 0525-66)
Source : Aladdin Lite

From figure 3.7:

a) **J1809-1943**[f] and **J1745-2900** are **AXP-HE pulsars**.

b) **J1809-1943** is a young pulsar, there are no significant role of glitches or burst outs. There very few reason for it to have low period compared to other normal AXP-NRAD one is it is a from young supernova remnant **G11.2-0.3**.The other reason is it having high energy and x ray burst outs may be because of environmental conditions.

c) **J1745-2900** is a magnetar which is orbiting around the black hole Sagittarius A. B_{LC} is high because of presence of Black hole but the reason why it is not having high as binary AXP-NRAD is the pulsar is orbiting the black hole,

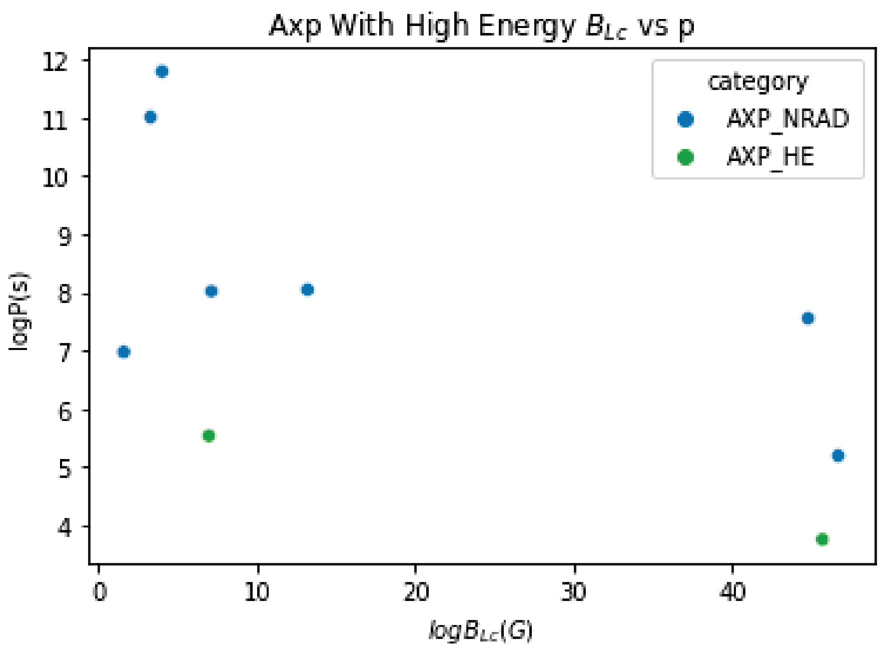


Figure 3.7: Plot of magnetic field at light cylinder radius and spin-period for AXP.

the rate of change of period or first derivative of period changes while rotating, during each Epoch in orbit, the total temperature changes which in turn effects the period.

3.3 | Radius & Luminosity:

Most of the objects in the data have comparably equal radius values. This is maybe considered due to the assumption of constant moment of inertia(as I = $10^{45} gm/cm^2$) of the pulsars. The R_{NS} values are calculated using an empirical relation (equation 3.1) using the known parameters.

$$R_{NS} = (\frac{IP\dot{P}}{B_s^2})^{1/6} \tag{3.1}$$

This relation is obtained by using the equation 3.2

$$\dot{\omega} = -\omega^3 [\frac{(2|m|^2 \sin^2 \alpha}{3Ic^3}] \tag{3.2}$$

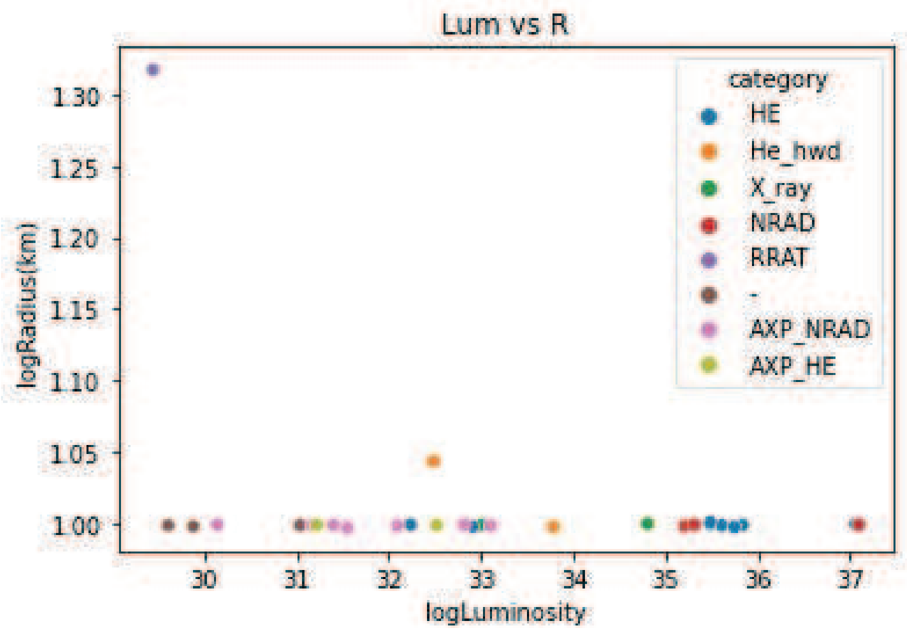


Figure 3.8: Plot between radius of pulsars and luminosity in logarithmic scale.

Luminosity:

We have used the known parameters to determine the luminosity values by developing an empirical relation as shown in equation 3.3

$$L = \frac{I\dot{P}}{P^3} \tag{3.3}$$

The relation from the graph and empirical relation:

The radius values for various pulsars are approximately similar and the luminosity values are distributed as on the same line (parallel to the x-axis) because the calculated values for radius are similar. These values (radius) were calculated using inertia, which in turn was calculated using equation 3.4 which solely depends on the known parameters:

$$\Delta L/\Delta E = \omega^{-1} \tag{3.4}$$

Since, the moment of inertia(I) is mostly constant for the neutron star, the angular velocity decreases in accordance with decrease in rotational kinetic energy. And this loss of energy is mostly released from the magnetosphere of the neutron stars or pulsars in the form of EM-emissions along the direction of magnetic field lines(magnetosphere) for the pulsars which follow the light cylinder model of pulsars, and for canonical model of pulsars or neutron stars, the energy is released along the same direction as directed by the magnetic polar caps or poles. This energy release in form of EM-emissions through magnetic field lines, accelerates the particles producing high energy beams of photons due to high magnetic field intensity.

Hence, the rate of rotational kinetic energy loss($\dot{E}$) explains the relation with change in angular velocity which indirectly relates that lower the spin-period(*P), higher the rotational KE loss which means they are producing High energy beams(mostly X-ray Gamma). These pulsars are known as High Energy pulsars. Although most of the neutron stars release X-ray beams, they are considered as **ordinary** neutron stars. And the objects which are mostly having very low spin-period(P) can produce High Energy emissions(mostly millisecond timescale objects). This explains the indirect reason for luminosity.

We have direct relationship for $\dot{E}$ and I(indirectly proportional to Period), and from the figure 3.9 we can infer the following:

1. $\dot{E}$ is less for the AXP_NRAD compare to High energy pulsar and NRAD because AXP_NRAD has high period and slow rotation. Minute changes in AXP_NRAD is because of difference in first derivate period, which in turn changes the characteristic age. $\dot{E}$ is high for for HE pulsars because spin-period is low and they have high angular velocity(ω) in turn resulting in high kinetic energy loss due to spin. The reason why binary HE pulsars are loosing less kinetic energy than the High energy pulsars is because of accretion with it's companion white dwarf.

2. $\dot{E}$ of J0218+4232 has higher value than J0437-4715 relatively because relatively high period may be due to surrounding Radio source which is 1.61 arcsec distance from the pulsar.
3. RRAT is observed to be not exhibiting the characteristics of millisecond pulsar because of quasar which 40 degrees away from pulsar in polar coordinate. Due to no proper research done on this pulsar, the data which we received alone with inseparable quasar data, it is acting as an anomaly in our graph

Anomalies:

J0537-6910 is a NRAD having high E because of the rapid spin-down period excep-

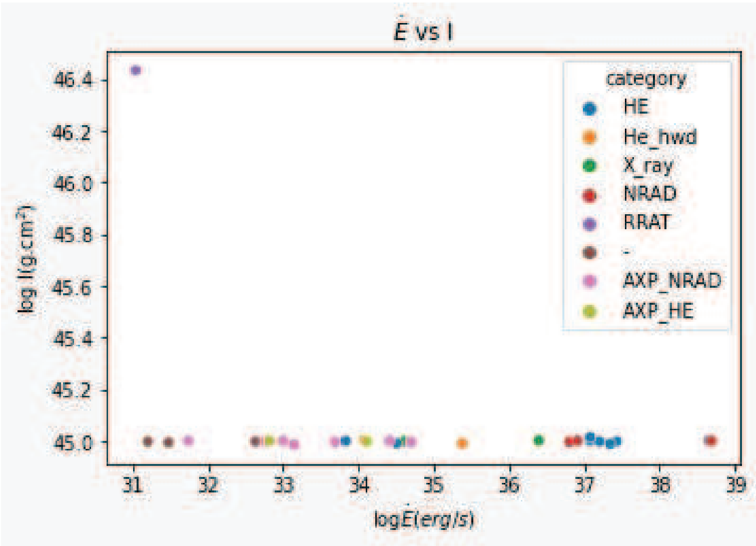


Figure 3.9: Plot between spin-down luminosity(loss of rotational KE) and moment of inertia.

tionally because of high density. I strongly say this an anomaly because it is losing energy faster than any other pulsars detected, it is even having high spin-down luminosity conformed by LIGO. The reason for this pulsar to have high E dot is constant glitch activities. Pulsar glitch is a phenomenon where pulsar suddenly increases its spin rate.

Based on paper from [LIGO Scientific Collaboration - The science of LSC research] on **Diving below the spin-down limit: Constraints on gravitational waves from the energetic young pulsar PSR J0537=6910**[h].

J0633+1746 is middle age neutron which was observed to emit electron-positron pair, now it is in stage between the HE and Non radio emission. According to updated version of ATN version it is High Energy, We conclude from graph that it is acting as anomalys because of it's transit state.

J212-3358 is a millisecond pulsar which lost the companion which was a neutron star recently, due to which spin down of this pulsar is very low though period is similar to other HE pulsar. Due to **less spin down** the loss of kinetic energy is low for this middle age star.

3.4 | Rate of Change of Spin and Magnetic Moment:

Magnetic Moment(m):

Magnetic moment can be also be defined as dipole moment or the characteristic magnetic filed of a pulsar. Through the magnetic dipole inclination we can determine the electromagnetic radiation at a particular rotational frequency.

Rotating pulsars have extremely strong magnetic fields, this creates an angle between the rotation axis and magnetic axis. This causes electromagnetic radiation. when a pulsar loses it energy, rotational energy compensates for the loss by emitting electromagnetic radiation, which in turn leads to a decrease in the angular velocity.

If we consider the neutron star as a magnetized rotating body. We can define the spin down torque as shown in equation 3.5:

$$\tau = \frac{2m^2\omega^3 \sin^2\beta}{3c^3} \tag{3.5}$$

here:

a) τ = torque due to spin-down
b) m = magnetic moment
c) β = inclination of magnetic axis w.r.t rotational axis

The Moment of inertia forces the magnetic moment to remain stable. The relation between moment of inertia and Period($\dot{P}$) can be explained by equation 3.6

$$\dot{P} = \frac{mP^2}{2\pi I} \tag{3.6}$$

Torque can be defined as the rotational analogue of force. By co-relating the above two equations we can deduce equation 3.7 for magnetic moment of a neutron star.

$$m = \sqrt{\frac{3P\dot{P}Ic^3}{8\pi^2}} \tag{3.7}$$

The magnetic moment and the first derivative of AXP-NRAD are high compared to HE and NRAD because the magnetic field of magnetars is very high with rapid spin-down. In AXP-NRAD, AXP-HE there is a minute difference because of the difference in magnetic field lines.

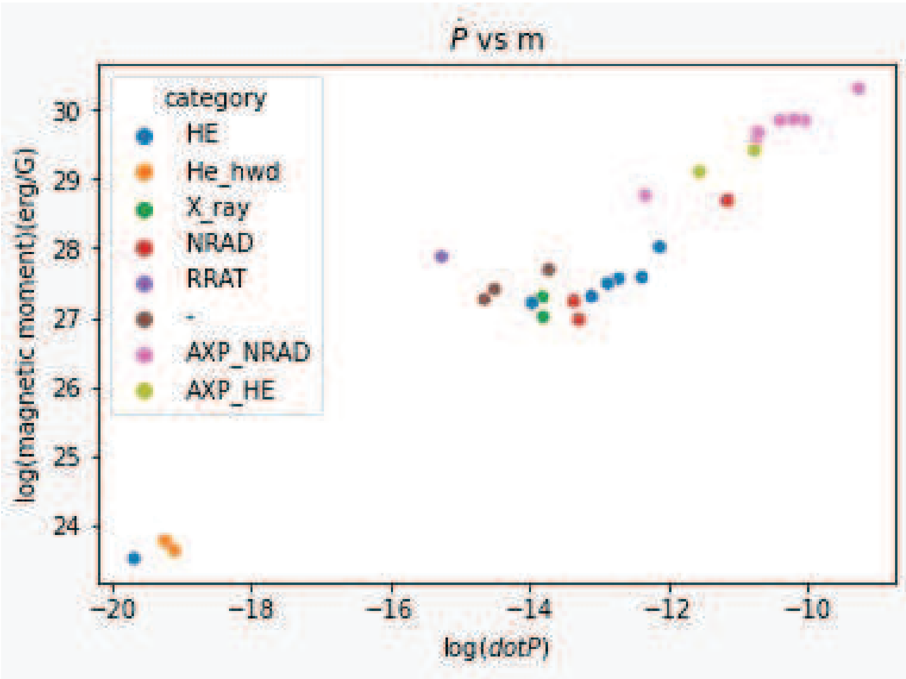


Figure 3.10: Plot between rate of change of spin-period and magnetic moment of pulsar.

Anomalies:

a) **J0628+0909** is a RRAT is between the HE and AXP-NRAD which is a anomaly in reality because of it's less spin down though it is a millisecond pulsar.

b) **J18460258** has different moment values compared to other two NRAD pulsars because of the high spin-down period caused by its glitch activities, which is comparable to loss of kinetic energy property.

c) Last three pulsars are having very less moment and spin down period because one **J2124-3358** is a millisecond pulsar with lost companion, so it is having less spin down rate[i] then other two millisecond pulsar with binary companion.

d) **J0218+4232** is having low magnetic moment than **J0437-4715** due to change in companion mass[j], the radius changes that in turn results in minute difference in two binary HE with helium white dwarf.

3.4.1 | Attempt to categorize NaN Type Pulsars:

From High energetic pulsar analysis,it has high spin compared to other type of classifications from the observations made. The test for high energy pulsars is period , rate of change of period ,loss of kinetic energy due to spin and other derivable parameters.

From observations made using figure 3.11 & 3.12, it seems to be following in the HE and NRAD region with respective to graphical or data analysis. The test for magnetars is Magnetic field at surface, Magnetic field at light cylinder, characteristic age, if the objects fall in the region AXP and RNAD, it might be a AXP-NRAD .

For analysis, we assume that surroundings are not effecting the neutron star.Unknown pulsars- J1812-1718, J0636-4549, J1811-4930. These are classified as 'NaN' in ATNF Catalog.
Due to semi-logarithmic nature, it is adding exponential nature to graph, From graph the unknown may be HE but not AXP-NRAD pulsars. It approximately exhibits the properties of High energy pulsar. It can be HE or NRAD .
B_{LC} and Age graph, the unknown pulsars seems to lie in AXP region than in HE region, we can conform from ATNF database.

The upper region of figure 3.13 & 3.14, we can infer them as AXP-NRAD, from ATNF graph we can conform unknown pulsars exhibit the magnetar properties.

From our analysis, unknown pulsars may exhibit both HE and AXP-NRAD properties. I reason, i took all three are in category is they have similar observed parameters and surrounding conditions.

From Parkers high altitude survey[50],[51], the **J0636-4549** is observed to be a Rotating Radio transient and fast radio burst which indeed exhibits both properties such as high flux density for single pulsar. It maybe a RRAD pulsar. FRB may explain about high magnetic field. **J0636-4549** may be a RRAD with extremely high magnetic property. **J1812-1718**, **J1811-4930** might also be RRAD with high **B**-field.

Plot between rate of change of spin w.r.t spin-period

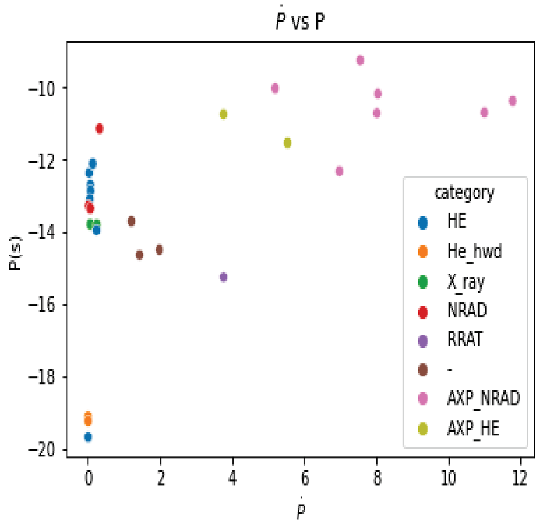


Figure 3.11: For all categories

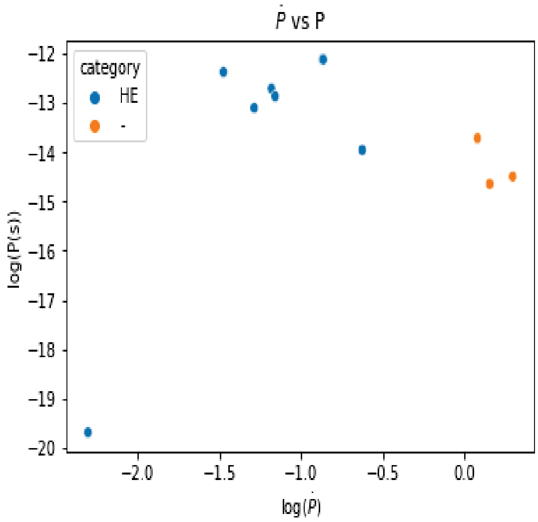


Figure 3.12: For High Energy and unknown category pulsars.

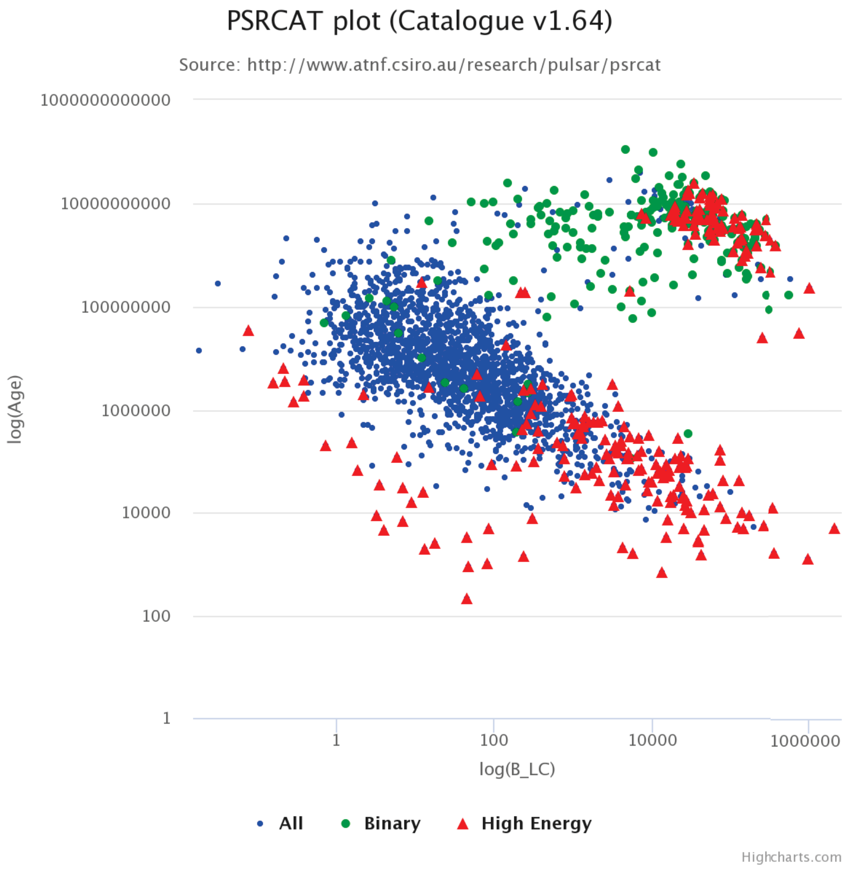


Figure 3.13: PSRCAT plot of magnetic field at light cylinder radius and age in logarithmic scale.

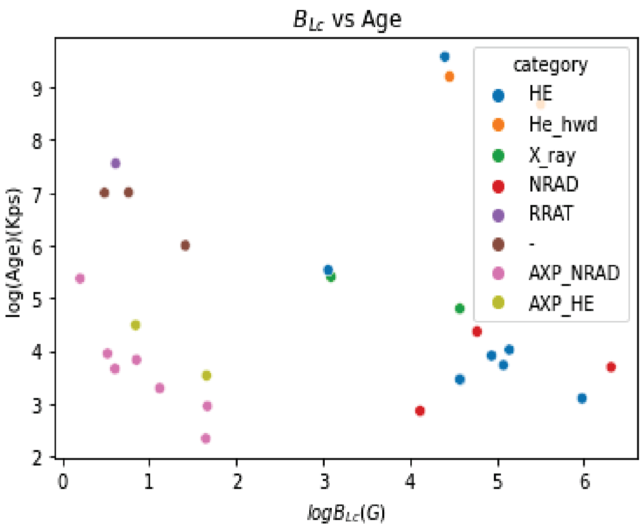


Figure 3.14: Observed plot of magnetic field at light cylinder radius and age in logarithmic scale.

4

Conclusion

1. J0628+0909 is acting abnormal compared to the other observed pulsars, it is due to the compact steep-spectrum **Quasar 3C 147** which is impacting the observation of pulsar.

2. From the graphs High Energy pulsars are lying in two regions:
a)Region-1 : High energy with no millisecond pulsar and binary companion.
b)Region-2: High energy pulsar with millisecond pulsar and binary companion.

3. J0218+4232 has a low mass companion when compared to J0437-4715 but most of the properties and behavior is similar because of surrounding objects- [BVK2003] X, WN B0214.9+4218 which might be the double degenerate system NLTT 11748 affecting the pulsar and might be a quadrupole system with two binary systems affecting each other.

4. J2124-3358 is a millisecond pulsar with lost neutron star companion which is one of the major reason for this pulsar to be in second region of High energy than in first region.

5. J0537-6910 is an NRAD pulsar behaves like the HE pulsar because of high spin rate due to glitch, from LIGO's data this pulsar turns out to have rapid spin-down rate ever noted from any other pulsar.

6. J0633+1746 is a HE pulsar but behaving like NRAD pulsar because of it's less spin rate than other HE pulsar, It might be intermediate stage of accretion and ejection of energy. The reason why we arrived at this conclusion is it is observed to be emitting positron and electron pairs but the first derivation period is less than

7. Unknown pulsars **J1812-1718, J0636-4549,J1811-4930** might be a Rotating radio transient pulsar with high magnetic field, it exhibits both AXP and HE properties.

5

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