Study the Distribution of Physical Properties on the P-Pdot Diagram for the Magnetar Stars

Sundus A. Abdullah Albakri[1], Marwa M. Yasseen[2]

[1,2]Baghdad University, College of Science, Department of Astronomy and Space, Baghdad, Iraq

Abstract: ***Neutron stars are excellent subjects for unveiling more about the physical laws in nature. In this work some of the physical properties will be studied. Halo cone model will be considered within light cylinder limits. Neutron stars types like Milliseconds and Normal stars with Magnetar stars samples adopted in this work. Magnetic fields, luminosity, spin down and characteristic age will be calculated. P-Pdot diagram will be indicating the start of the trajectory a neutron star with follow along its life: going to the lower right where a big population lies before fading out in the graveyard. The ages, magnetic field strength, the spin and its spin down rate are read from this diagram. The results showed that find that magnetar stars will be located at the top right of the diagram and the high-energy at high-derived long period. They are young stars compared to the stars of the millisecond second, which lies in the center of the diagram. This is also the region where we find those pulsars which are still associated with supernova remnants. These remnants fade and are not detectable anymore after a few hundred thousand years or so. Therefore, older pulsars with typically ages of a few million years can be found in the center of the diagram. If pulsars slow down further, conditions to create radio emission apparently cease, and the longest period known for Magnetar stars is just about 11 seconds.***

Keywords: Neutron Stars; Magnetic field; Age stars; Magnetar stars.

1. Introduction

Neutron stars are one of three known endpoints of stellar evolution, the other two being white dwarfs (formed by stars with masses less than 8 solar masses) and black holes (formed by stars with masses greater than 15-20 solar masses [1]. Figure 1 shows a theoretical neutron star structure and composition [2].

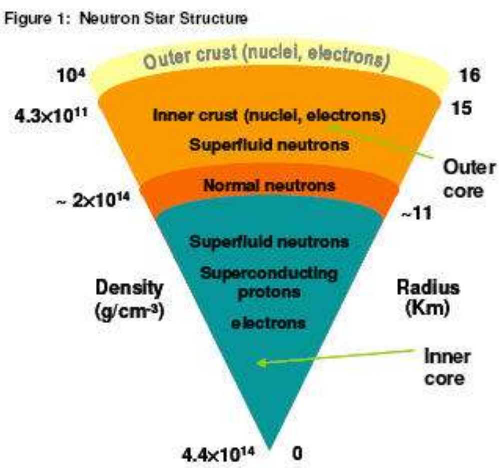


Figure 1: A typical structure of neutron star interior. (Source) [2].

During stellar nuclear fusion processes governed by gravity and pressure leading to supernova explosion, the Chandrasekhar mass limit is reached whereby electron degeneracy pressure at the stellar core can no longer support a gravitationally collapsing star. At this point of extreme density, relativistic electrons combine with protons in and around the stellar core via a process called neutronization resulting in neutrons and electron neutrinos being greeted i.e. e-+ p to n + νe [3].

2. Neutron Star Life

Appear in the upper left corner of the pulsar **P-$\dot{P}$ diagram** as shown in Figure 2. If magnetic field B is conserved and they age as described later, they gradually move to the right and down, along lines of constant B and crossing lines of constant characteristic age. Pulsars with characteristic ages $<10^5$ yr are often found in or near recognizable supernova remnants (SNRs). Older pulsars are not, either because their SNRs have faded to invisibility or because the supernova explosions expelled the pulsars with enough speed that they have since escaped from their parent SNRs. The bulk of the pulsar population is older than 10^5 yr but much younger than the Galaxy ($\sim10^{10}$ yr). The observed distribution of pulsars in the P$\dot{P}$ diagram indicates that something changes as pulsars age [4] [5]. One controversial possibility is that the magnetic fields of old pulsars must decay on timescales $\sim10^7$yr, causing old pulsars to move almost straight down in the P$\dot{P}$ diagram until either their magnetic field is too weak or their spin rate is too slow to produce radio emission via the normal, and as yet still highly uncertain, emission mechanism. **Rotating Radio Transients (RRATs)** are pulsars that emit so sporadically that they are more easily detected in searches for single pulses rather than for periodic pulse trains [5]. RRATs with measurable periods usually have P>1sP>1s. Neutron stars can be divided into three types depending on rotation periods as Normal and Millisecond with Magnetar types [5] [6].

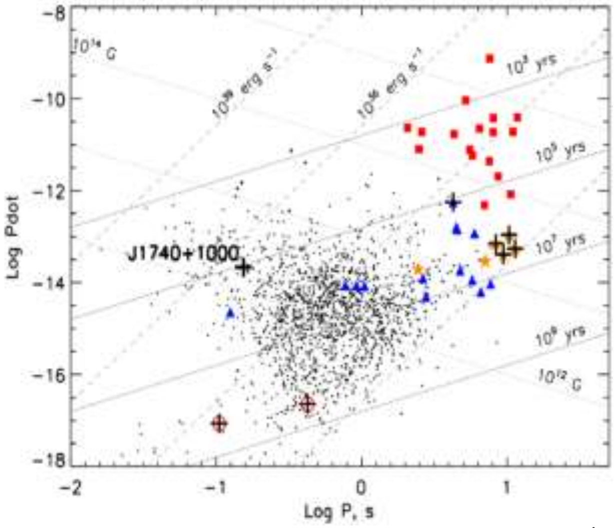


Figure 2: The observed distribution of pulsars in the P$\dot{P}$ diagram indicates that something changes as pulsars age [5]

3. Magnetar properties

In all neutron stars, the crust of the star is locked together with the magnetic field so that any change in one affects the other. The crust is under an immense amount of strain, and a small movement of the crust can be explosive. But since the crust and magnetic field are tied, that explosion ripples through the magnetic field. In a magnetar, with its huge magnetic field, movements in the crust cause the neutron star to release a vast amount of energy in the form of electromagnetic radiation. A magnetar called SGR 1806-20 had a burst where in one-tenth of a second it released more energy than the sun has emitted in the last 100, 000years [3] [6].

Recent observational developments indicate that isolated neutron stars also manifest themselves as other species1, among which soft gamma-ray repeaters (SGRs) and anomalous X-ray repeaters (AXPs) have attracted growing attention in the neutron star community [6]. These two types of objects originate, respectively, from the anomalous species of two distinct classes of phenomenon, i.e., gamma-ray bursts and accreting X-ray pulsars, but share many common features. SGRs/AXPs are neutron stars with super strong magnetic fields ($\sim 10^{14} - 10^{15}$ G at the surface). Other models either have troubles to interpret some observations. The precise measurements of the pulsar rotation period P and its time derivative $\dot{P}$ provide accurate knowledge of the energy reservoir and the total released power. A significant fraction of the spin down power (typically 1-10%) is converted to high-energy gamma-rays, as clearly demonstrated by the FermiLAT observations in the 0.1-10 GeV band [6] [7]. Thus pulsars must be efficient particle accelerators. Understanding their mechanism is a difficult task, because it involves a complex interplay between electrodynamics, high-energy radiative processes, and electron-positron pair creation [8].

4. Magnetic field

The Sun and many other stars are known to possess approximately dipolar magnetic fields. Stellar interiors are fully ionized and hence good electrical conductors. Charged particles are constrained to move along magnetic field lines, and magnetic field lines are tied to the charged particles. When a star collapses from a radius $\sim 10^6$ km to $\sim$10km, its cross-sectional area is divided by $\sim 10^{10}$, The emission from radio-pulsars was soon interpreted in terms of rotating neutron stars with large dipolar magnetic fields: the periodic emission would then be explained as the beamed radiation emitted by a rotating (i.e., accelerated) dipole. This is the so-called "lighthouse model" (see Figure 3 and 4) [4] [5].

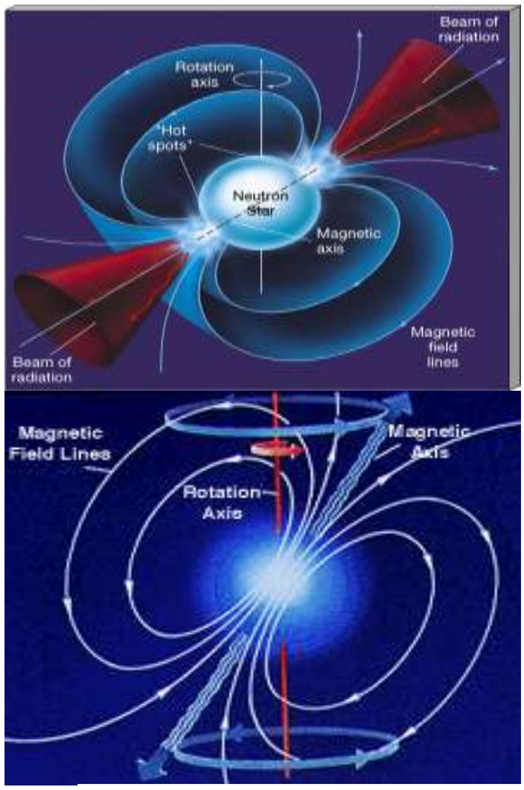


Figure 3: A pulsar is a neutron star that emits beams of radiation The "pulses" of high-energy radiation we see from a pulsar are a misalignment of the neutron star's rotation axis and its magnetic axis. The lights have been described like a lighthouse with its rotating lights. The lights from pulsars can only be seen when they past Earth [7]

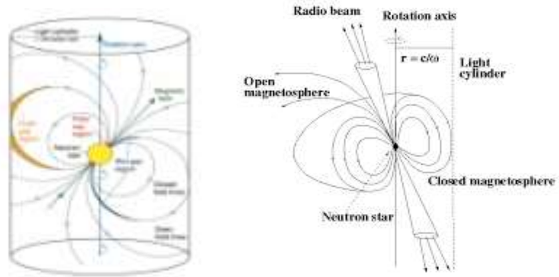
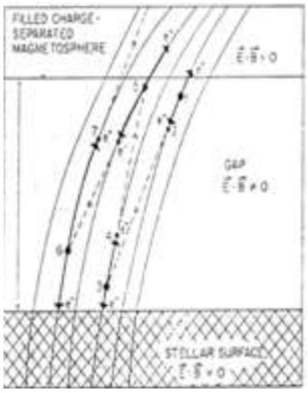


Figure 4: Pulsar model this diagram of the 'lighthouse model' of neutron stars emission accounts for many of the observed properties of pulsars [8].

4.1The Adopted Model

Gold suggest that pulsar are rotating magnetic neutron stars that formed in Super Novae explosion. In this model the magnetic dipole moment is aligned with the rotation axis [9]. The electromagnetic radiation emitted by pulsars is taken from the rotational energy of the neutron star. From the observations of the Crab nebula, Gold deduced that the pulsar must be highly magnetised. Therefore, most of the electromagnetic radiation takes the form of low frequency magnetic dipole radiation. We can equate the power of magnetic dipole radiation with the loss in rotational energy, from the early vacuum model to recent numerical experiments with plasma- filled magnetospheres. Significant progress became possible due to the development of global particle-in-cell simulations which capture particle acceleration, emission of high-energy photons, and electron-positron pair creation [7] [9].



5. Basic Considerations and Results

Goldriech and Julian model indicated the characteristic of the co-rotating magnetosphere surrounding an axisymmetric neutron star with aligned magnetic moment and rotation axes [9]. The accelerating electric fields were essentially taken as those which would obtain if there were no co rotating magnetosphere at all on open field lines. The associated accelerating voltages are then much greater than those from space change effects in the co rotating magnetosphere associated with bringing the emitted electrons to relativistic speeds, these give for (P=1s) less than a 10^{10} V potential drop above the surface. The main goal of studying the pulsars stars is to maintain the behavior of those unique stars for showing their strong magnetic field and other factors, by some samples of Magnetar stars and comparing it with other samples pulsars by using data from "ATNF Pulsar Database" catalogue, [6, 10].dipolar magnetic field aligned with the rotation axis. the magnetosphere is separated from the star by a spherical gap of height (h) as shown in figure5, The magnetic field (B) equation is given by [8] [11]:

$$B=(\mu/4\pi)\int(J\times r)/r^3 dv \tag{1}$$

Where, B: is the magnetic field induction produced a current density J at point P.r the vector that directed from the point of integration (source point of J) toward the field point P. dv is the volume element that content the source J. In cosmical bodies the magnetic field generally derives from currents induced by rotation in such a body.

B: the magnetic field of neutron star which is given by, [9]

$$\mathbf{B} = (a/r^3)\,[1+3\sin^2\lambda]^{1/2} \tag{2}$$

Where r: the magnetic line of force has the form:

$$r = re\cos^2\lambda \tag{3}$$

Where re: the distance from the origin of star

a: The dipole magnetic moment was estimated to be (2×10^{20} Tm^3).

λ: The position angle of particle as shown in figure5-B) and the position angle λ is:

$$\lambda=\frac{1}{2}\pi-\theta$$

Where θ: the angle between magnetic axis and x-axis.

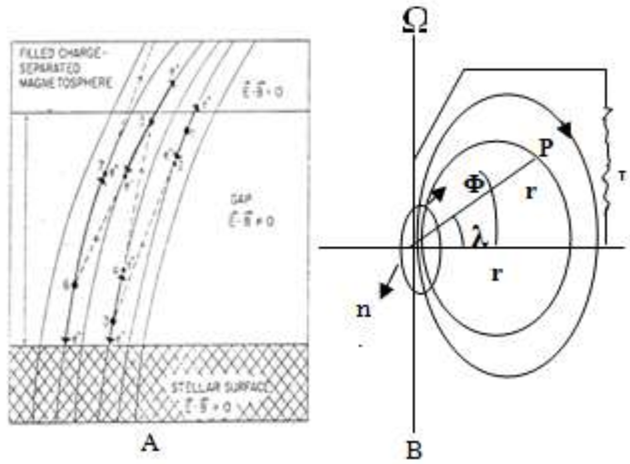


Figure 5: A: The magnetosphere is separated from the star by spherical gap of height h, also this cascade pair production acceleration of electrons and positrons along field lines as B [11].

5.1 Spin down and Equilibrium Period of Pulsar Stars:

The spin down decay of Pulsars around its axis is given by [8]:

$$\text{Spin down} = P \times \dot{P} \tag{4}$$

Where: P:is Pulsar's period, $\dot{P}$ is Pulsar's period derivative.

Relation can estimate the Equilibrium period of Pulsar and accretion rate as [8] [11]

$$P_{Eq}=(1.9)B^{6/7}M^{-5/7}(\dot{M}_{Edd}\,\dot{M})^{-3/7}R^{18/7} \tag{5}$$

Where:

B: is the Magnetic field in G unit

M : is the mass of Neutron star = 1.4 $M_{\odot}$

$\dot{M}$: is accretion rate of pulsar star = LR/GM

R: Radius of Neutron star = 10^6cm

G: gravitation constant = 6.670 $\times10^{-8}$,

$\dot{M}_{Edd}$ = The critical eddingtor = 1.5 $\times$ $10^{-8}M_{\odot}$

The relation can estimate the magnetic field of pulsar as [7]:

$$B=\sqrt{IP\dot{P}C^3}/(2\pi)^2R \tag{6}$$

Relation can estimate the Spin down Luminosity of Pulsar as [11]

$$L_{sp}=\frac{-4\pi^2 IP^{\cdot}}{P^3} \tag{7}$$

Where: I is the moment of inertia $=10^{45}$ $g.cm^2$

C= the light velocity

5.2 The potential drop (ΔΦ) along field line traversing the gap:-

The potential drop across the gap for different values of magnetic field [9] [12]]:

$$\Delta\Phi = \Omega\, Bh^2 / c \qquad (8)$$

Where:
ΔΦ: The potential drop.
B: the Magnetic field of Pulsar
Ω : angular frequency (Ω=2 π).
h : The height of the polar gap(cm).

Or the potential drop relate to period derivative is [11]

$$\Delta\Phi = B/\dot{P} \qquad (9)$$

Characteristic age can be determined by using the relation [8]

$$T_{ch} = P/2\dot{P} \qquad (10)$$

It is known that neutron star rotation drastically distorts the magnetic field near and beyond the light cylinder radius RLC = c/Ω (where Ω = 2π/P is the neutron star angular velocity; P is the period), and that magnetic field lines crossing the light cylinder remain open all the way to 'infinity'. Field lines will also open up in the presence of a powerful wind of particles emitted from the neutron star. Near the surface of the star, dipole magnetic field pressure is high enough to completely dominate the wind stresses. However, the magnetic energy density drops much faster with distance than that of a quasi–isotropic particle wind of kinetic luminosity at infinity [12] [13]

By using the relations that adopted, equations (2) and (5) with equation (6), the magnetic field and equilibriums period are calculated for adopted sample of magnetars. We review electrodynamics of rotating magnetized neutron stars, spectra, corresponding to huge magnetic fields of order. The dipole model determines the age, and magnetic field of a pulsar from the measured values of period (P) and period $\dot{P}$ for example as illustrated in table 1 and for adopted sample for magnetar stars. Although model dependent, observations yield the ranges and, with some of the youngest objects having the largest magnetic fields (magnetars) and the oldest ones having the fastest rotation (millisecond pulsars); the large majority of pulsars, however, can be found in the range and as shown in Figures (6;A, B and C) which illustrate that magnetar stars had strong variation in magnetic field comparing with the tars a Millisecond stars (MSPs both mix and High energy(HE)). These different classes of stars are generally explained in terms of stellar evolution. The magnetic field of magnetars may so strong as to reach two orders of magnitude above the quantum critical threshold, 10^{14}-10^{15} gauss. These results can be interpreted by that the ultra –strong field strength of magnetars, by the collapse process alone.

The neutron star spins down because the electromagnetic torque generated at the surface of the polar cap opposes its rotation. Inside the neutron star surface, this current flows horizontally towards the edge of the polar cap, where it flows out in a current sheet along the interface between open and closed field lines. We present two simple, physically equivalent, estimates of the electric current flowing in the magnetosphere. One is to consider particles (electrons/positrons) with Goldreich–Julian charge densities $\rho GJ \approx B0/2\pi R_{LC}$ flowing outwards at the speed of light from the polar cap [13] [14].

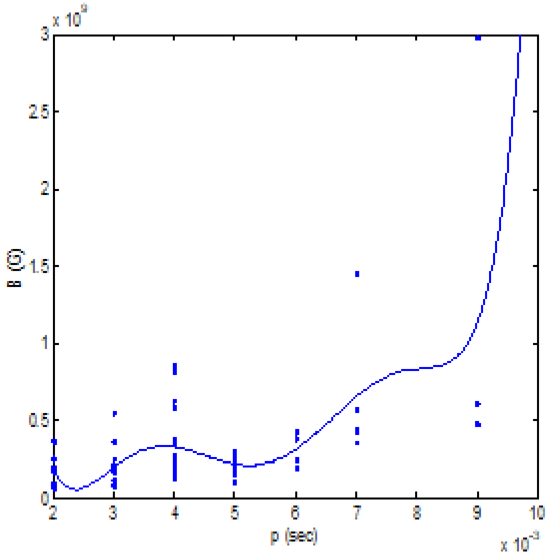
Using the above relations for the polar cap current in equations (4) and (10) we obtain the expression for the spin down associated with the characteristic age as equation (10). Table 2 and Figure 6, the conflicting goals of preserving the magnetar stars (B>∼ 10^{14} G), spin down and characteristic age were be estimated for the magnetar stars. The potential drop will increases at periods ≤11 s for Magnetar stars as shown in figure (7;C) and bringing the characteristic age within a factor of 2 of the 10^4yr age with maximum spin down at 10^{-9}s. Millisecond pulsars will have maximum spin down at (10^{-22}-10^{-20}s) as shown in figure (8; A, B).

Figure 9 in such a diagram we plot the period derivative (the rate of change of the period in units of seconds per second - commonly called Pdot after the mathematical notation for rates of change in which a dot is placed over the relevant symbol, in this case a P) versus the pulse period on a logarithmic scale. (Similarly, one can plot the magnetic field versus period as we will do later.) Since both characteristic age and surface magnetic field with luminosity are functions of period and period derivative, lines of constant age and magnetic field are straight lines in such a P-Pdot diagram.

According to the diagram (9) of the period and the derivative period we find that magnetar stars will be located at the top right of the diagram and the high-energy at high-derived long period. They are young stars compared to the stars of the millisecond second, which lies in the center of the diagram. This is also the region where we find those pulsars which are still associated with supernova remnants. These remnants fade and are not detectable anymore after a few hundred thousand years or so. Therefore, older pulsars with typically ages of a few million years can be found in the centre of the diagram. If pulsars slow down further, conditions to create radio emission apparently cease, and the longest period known for Magnetar stars is just about≥ 11 seconds.

Table 1: Represents the values of magnetic field, Drop potential, Equilibrium period and radius of light cylinder with the period and period derivative for Adopted sample of magnetar pulsar star.

Name	P (s) [10]	$\dot{P} \times 10^{-11}$ (s.s^{-1})	B$\times 10^{15}$(G)	$R_L \times 10^8$ (m)	Drop potential $B/P^{\cdot} \times 10^{27}$	$p_{eq} \times 10^{10}$
SGR J1086-20	7.6	75	2.4159	3.8000	0.0032	3.4586
SGR J0526-66	8.05	3.8	0.5597	4.0250	0.0147	3.8170
SGR J1900+14	5.19	9.2	0.699	2.5950	0.0076	1.7986
SGR J1627-41	2.59	1.9	0.2245	1.2950	0.0118	0.5463
SGR J0418+5729	9.07	0.0006	0.0075	4.5350	1.2442	4.6832
SGR J1833-0832	7.56	0.43	0.1825	3.7800	0.0424	3.4274
1E 1547-5408	2.06	2.31	0.2207	1.0300	0.0096	0.3690
XTE 1547-5408	5.54	0.77	0.2090	2.7700	0.0271	2.0115
1E 1048-5937	6.45	2.70	0.4223	3.2250	0.0156	2.6106
1E 2259+586	6.97	0.04	0.0534	3.4850	0.1336	2.9818
CXOU J010043.72134	8.02	1.88	0.3929	4.0100	0.0209	3.7927
4U 0142+61	8.68	0.19	0.1300	4.3400	0.0684	4.3433
CXO J164710.2455216	10.61	0.08	0.0932	5.3050	0.1165	6.1277
1RXS J170849.0-400910	10.99	1.94	0.4673	5.4950	0.0241	6.5088
1E 1841-045	11.77	4.15	0.7072	5.8850	0.0170	7.3206
PSR J1622-4950	4.32	1.7	0.2742	2.1600	0.0161	1.3132
CXOU J171405.7381031	3.82	6.40	0.5003	1.9100	0.0078	1.0635
RX J1856	7.05	0.003	0.0147	3.5250	0.4906	3.0407
RX J0720	8.39	0.0069	0.0243	4.1950	0.3529	4.0975
RX J1605	6.88	0.006	0.0206	3.4400	0.3427	2.9161
RX J0806	11.37	0.011	0.0358	5.6850	0.3253	6.8993
RX J1308	10.31	0.004	0.0205	5.1550	0.5137	5.8337
RX J2143	9.44	0.0002	0.0044	4.7200	2.1985	5.0155
RX J0420	3.54	1.88	0.2611	1.7700	0.0139	0.9334
4U 0142+61	5.76	3.8	0.4734	2.8800	0.0125	2.1504
1RXS J170849.0−400910	7.54	0.77	0.2438	3.7700	0.0317	3.4119
SGR 1806−20	8.43	0.79	0.2611	4.2150	0.0331	4.1311
Swift J1834.9−0846	2.48	4.09	0.3223	1.2400	0.0079	0.5071
SGR 1935+2154	11.78	0.01	0.0347	5.8900	0.3473	7.3313
J1001-5939	11.55	9.2	1.0431	5.7750	0.0113	7.0876
J0100-7211	3.24	0.04	0.0364	1.6200	0.0911	0.8020



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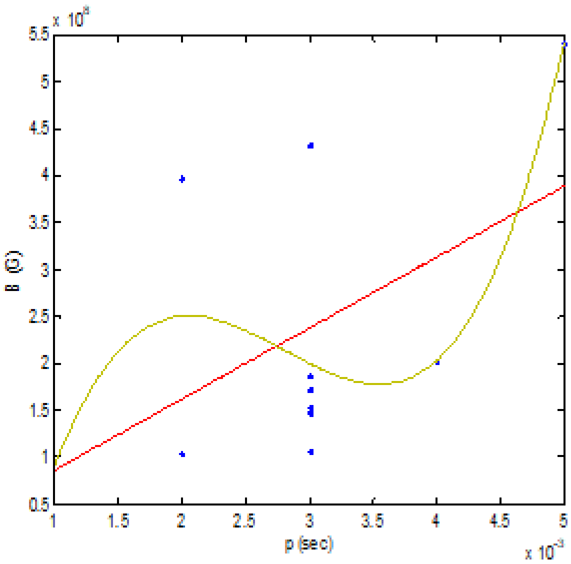

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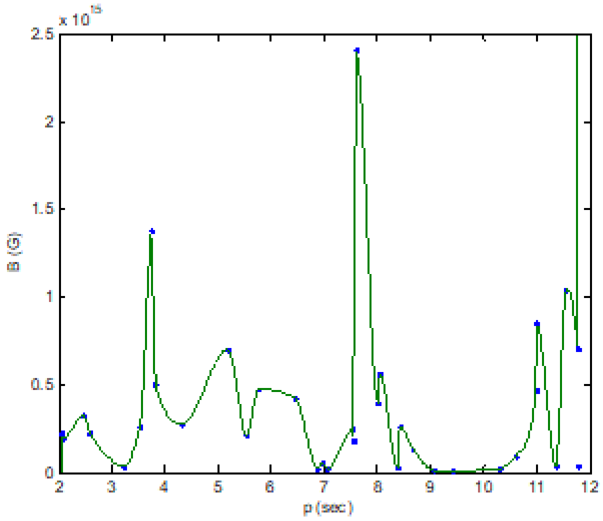


C

Figure 6: Represents the relationship between the Pulsar period and the magnetic field for: (A) mix MSPs, (B) HE MSPs and (c)

Table 2 : Represents the values of Luminosity, Spin down and characteristic age for Adopted sample of magnetar pulsar star

Name	L_{sp} (erg/sec)	**Spin down** $(P \times P^{\cdot})$ *(sec)*	$T_{ch} \times 10^{8}$ **(year)**
SGR J1086-20	0.6745×10^{35}	0.5700×10^{-8}	0.0002×10^{6}
SGR J0526-66	0.0288×10^{35}	0.0306×10^{-8}	0.0034×10^{6}
SGR J1900+14	0.2598×10^{35}	0.0477×10^{-8}	0.0009×10^{6}
SGR J1627-41	0.4317×10^{35}	0.0049×10^{-8}	0.0022×10^{6}
SGR J0418+5729	3.1746×10^{29}	5.442×10^{-14}	2.3995×10^{7}
SGR J1833-0832	0.0039×10^{35}	0.0033×10^{-8}	0.0279×10^{6}
1E 1547-5408	1.0432×10^{35}	0.0048×10^{-8}	0.0014×10^{6}
XTE 1547-5408	0.0179×10^{35}	0.0043×10^{-8}	0.0114×10^{6}
1E 1048-5937	0.0397×10^{35}	0.0174×10^{-8}	0.0038×10^{6}
1E 2259+586	4.663×10^{31}	0.0003×10^{-8}	0.2766×10^{6}
CXOU J010043.1-72134	0.0144×10^{35}	0.0151×10^{-8}	0.0068×10^{6}
4U 0142+61	0.0011×10^{35}	0.0016×10^{-8}	0.0725×10^{6}
CXO J164710.2-455216	2.644×10^{31}	0.0008×10^{-8}	0.2105×10^{6}
1RXS J170849.0-400910	0.0058×10^{35}	0.0213×10^{-8}	0.0090×10^{6}
1E 1841-045	0.0100×10^{35}	0.0488×10^{-8}	0.0045×10^{6}
PSR J1622-4950	0.0832×10^{35}	0.0073×10^{-8}	0.0040×10^{6}
CXOU J171405.7-381031	0.4533×10^{35}	0.0244×10^{-8}	0.0009×10^{6}
RX J1856	3.3800×10^{30}	0.0211×10^{-11}	3.7302×10^{6}
RX J0720	4.6124×10^{30}	0.0579×10^{-11}	1.9301×10^{6}
RX J1605	7.2735×10^{30}	0.0413×10^{-11}	1.8201×10^{6}
RX J0806	2.9544×10^{30}	0.1251×10^{-11}	1.6407×10^{6}
RX J1308	1.4409×10^{30}	0.0412×10^{-11}	4.0913×10^{6}
RX J2143	0.0939×10^{30}	0.0019×10^{-11}	7.4921×10^{7}
RX J0420	0.1673×10^{35}	0.0067×10^{-8}	0.0030×10^{6}
4U 0142+61	0.0785×10^{35}	0.0219×10^{-8}	0.0024×10^{6}
SGR 0418+5729	0.7567×10^{35}	0.0035×10^{-8}	0.0019×10^{6}
SGR 0526−66	0.0190×10^{35}	0.0704×10^{-8}	0.0027×10^{6}
SGR 1627−41	3.6762×10^{35}	0.1861×10^{-8}	0.0001×10^{6}
1RXS J170849.0−400910	0.0071×10^{35}	0.0058×10^{-8}	0.0155×10^{6}
SGR 1806−20	0.0052×10^{35}	0.0067×10^{-8}	0.0169×10^{6}
Swift J1834.9−0846	1.0586×10^{35}	0.0101×10^{-8}	0.0010×10^{6}
SGR 1935+2154	2.415×10^{30}	0.1178×10^{-11}	1.8698×10^{6}
J1001-5939	0.0236×10^{35}	0.1063×10^{-8}	0.0020×10^{6}
J0100-7211	0.0046×10^{35}	0.1296×10^{-11}	0.1286×10^{6}

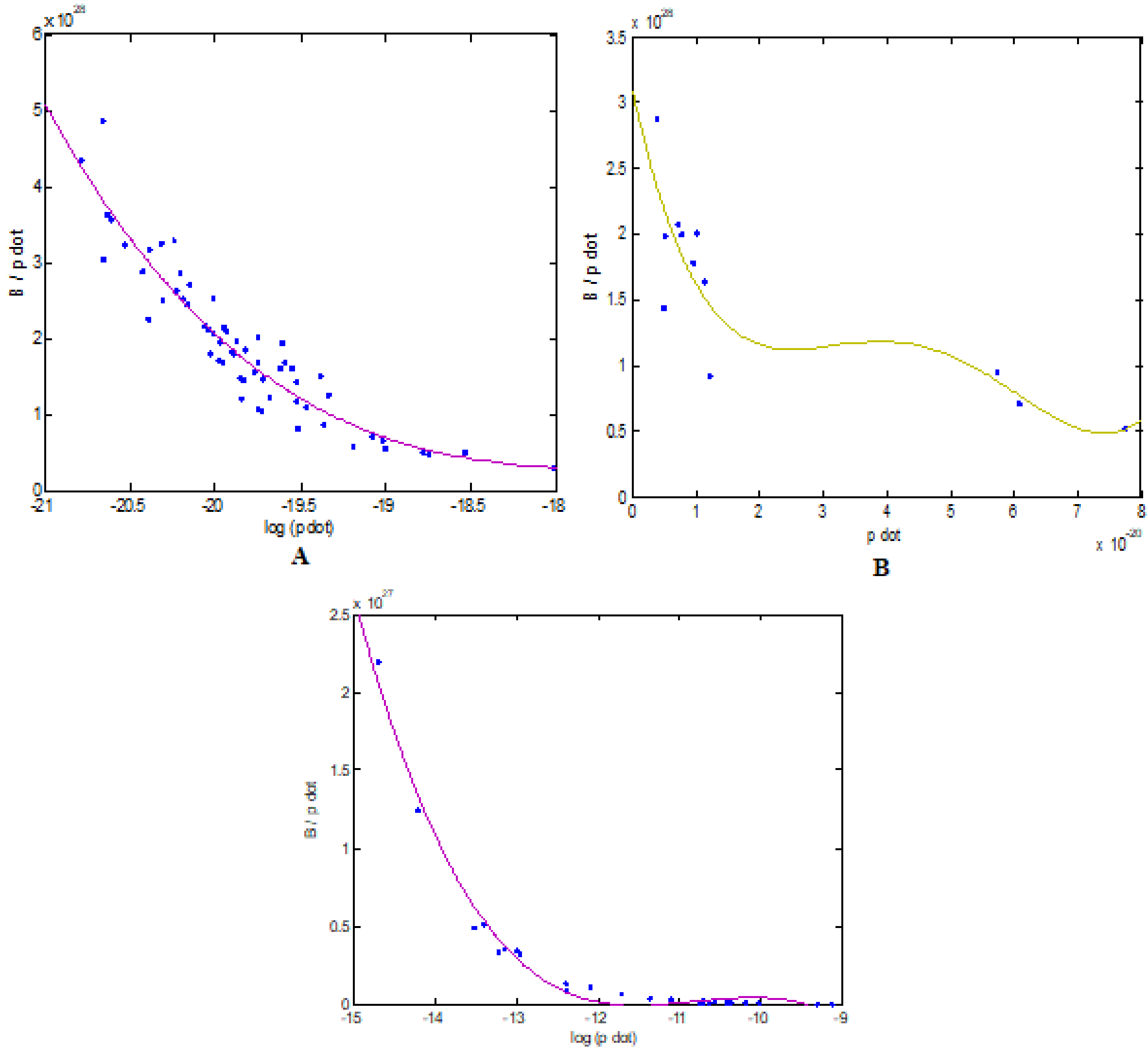
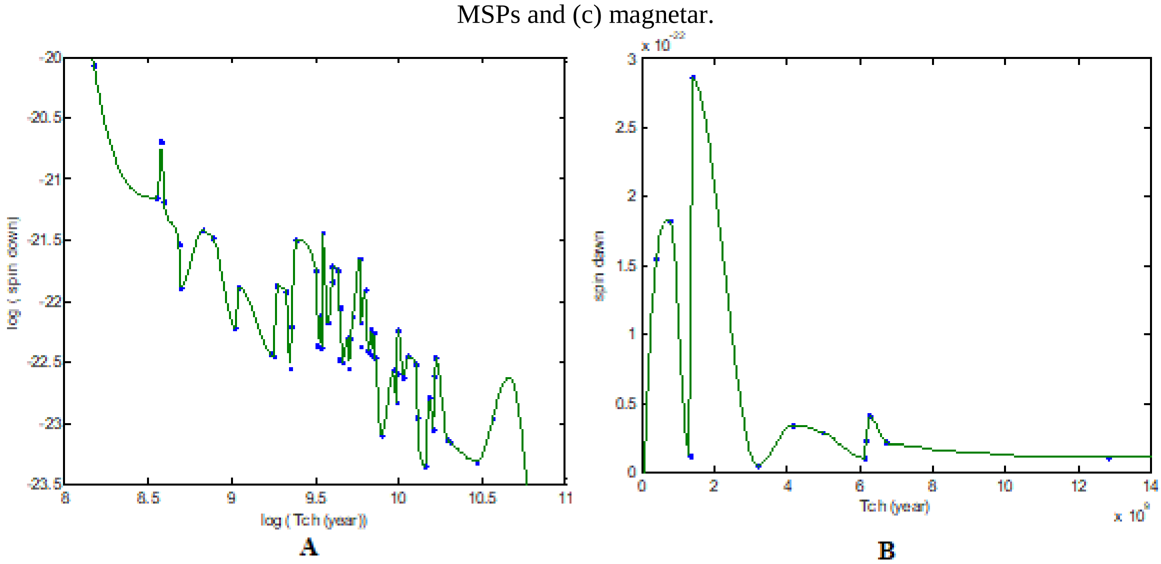


Figure 7: Represents the relationship between the Pulsar period and the $^{B}/_{P^{\bullet}}$(drop potential) for: (A) mix MSPs, (B) HE MSPs and (c) magnetar.



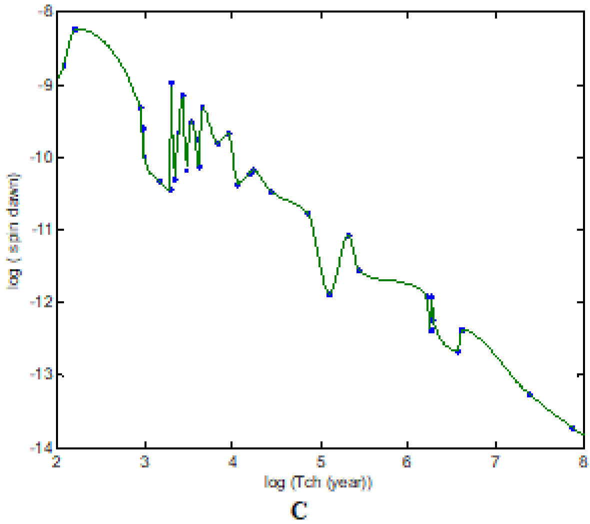


Figure 8: Represents the relationship between thecharacteristic age and the Spin down for: (A) mix MSPs, (B) HE MSPs and (C) magnetar

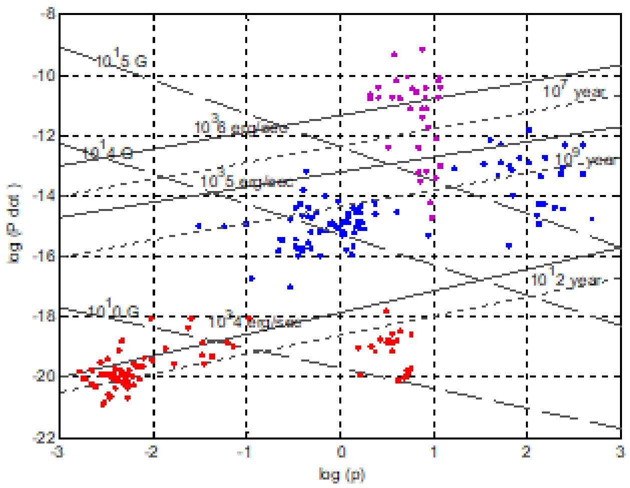


Figure 9: Shows the distribution physical properties for the Magnetarpulsar P-Pdot diagram as a comparison with others types of Neutron stars. P – P˙ diagram of all known pulsars with measured period and period derivatives. Data are from [13].

6. Conclusions

- The older millisecond pulsars defined as having greater ages, because P/P` specifies how long pulsars lives at that age.
- As the field begins to decay, the tracks of pulsars will be swing downwards and eventually become vertical that is could be due to field decay. That is indicate the field decay comes from the recycled pulsars. The spin-down toque (PP) decay versus the characteristic (p/p) for periods (Magnetar pulsars) has been detected and their numbers are rapidly growing. In a good agreement with recently discovered pulsars in gLobular clusters, which must surely be old
- The results indicated that the potential drop (B/P2) will increase at periods ≤11 s for Magnetar stars.
- The characteristic age within a factor of 2 of the 10^4yr age with maximum spin down at 10^{-9}s while Millisecond pulsar will have maximium spin down at (10^{-22}-10^{-20} s).
- Find that magnetar stars will be located at the top right of the diagram and the high-energy at high-derived long period. They are young stars compared to the stars of the millisecond second, which lies in the center of the diagram.
- Magnetar stars had strong variation in magnetic field comparing with the Normal stars and Millisecond stars (MSPs). These different classes of stars are generally explained in terms of stellar evolution. The magnetic field of magnetars may so strong as to reach two orders of magnitude above the quantum critical threshold, 10^{14}-10^{15} gauss.

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Author Profile

Dr. Sundus A. Abdullah A. Albakri, University of Baghdad-College of Science, Dept. of Astronomy and Space. She has Ph.D in Astrophysics and Remote sensing. Her interest includes planetary Nebulae fields, pulsars and plasma space. She has published more than 25 papers in local and International journal. She is a reviewer in IJAA, China.