Determination of the Magnetogyric Ratio and Death line for the Neutron stars

Marwa M.Yaseen
Department of Astronomy and space
University of Baghdad, College of Science, Baghdad, Iraq

Sundus A.Abdullah Albakry
Department of Astronomy and space
University of Baghdad, College of Science, Baghdad, Iraq

Abstract- In this research some Physical properties of Neutron stars will be studied like , residual of magnetic field, potential drop, Magnetogyric Ratio of particles and death line for sample pulsar stars that adopted in this paper. Halo cone model will be considered within light cylinder limits. Neutron stars types like Milliseconds, Normal and Magnetar stars samples adopted in this paper. The Magneto Ratio (γ) will be determined to understand the distribution of pulsar properties for the samples that adopted in the $\gamma - P$ diagram, and the death line will be calculated for these pulsars. The data were obtained from Australian Telescope National Facility (ATLNF). The results showed that Magnetar stars don't have death line, the actual reason for that is not known, but it preponderated to strong magnetic field. The results estimated the γ and death line for Pulsars that Pair production from the polar cap is believed to be a main condition for pulsar radio emission.

Keywords – Magnetic field, Potential drop, Neutron Stars, Pulsars, Radio emission

I. INTRODUCTION

Neutron stars are objects formed by the collapsing cores of massive stars at the end of their evolution as shown in Figure (1). The energy released by the collapsing core that ejects the outer Layers of the progenitor star in a so called supernova explosion. Neutron stars are the densest massive objects in the universe; the masses of Neutron stars are in the range M $\sim$ 1 - 3$M_{\odot}$. The radii of Neutron stars are in the range R $\sim$ 9 - 15 km [1].

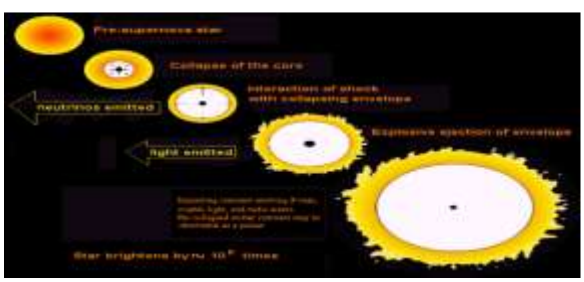


Figure 1. Sequence of events Ne*0 utron Stars- Supernovae [1].

The internal structure of a Normal Neutron star is depicted in Figure (2 A, B). The star can be viewed as having 4 regions [2, 3]:-

●The outer crust (the outer envelope), is liquid and has density (1 gm.cm^{-3}). Its matter consists of ions *Z* and electrons *e*.

●The inner crust (the inner envelope); the density range up to about (10^{14}) g.cm^{-3}, the crust is mainly populated with nuclei and electrons. The matter of the inner crust consists of electrons, free Neutrons *n*, and Neutron-rich atomic nuclei, and has density (4. 10^{11} g. cm^{-3}), a sea of (likely super fluid) Neutrons accompanies the nuclei and becomes more abundant at higher densities.

●the outer core consists of nucleons (Neutrons with several percent mixture of protons *p*), electrons and muons μ (the so called *npeu* composition). Protons in the outer core may be superconducting.

●The inner core, depending on the stellar mass, which occupies the central regions of massive Neutron stars and the relative strength of matte.

There are different types of young isolated Neutron Stars (NSs): radio pulsars, compact central X-ray sources in supernova, magentas: Anomalous X-ray Pulsars (AXPs) and Soft Gamma-Ray repeaters (SGRs) .Another large class of observed systems with NSs is formed by X-ray binaries. They are subdivided into High Mass X-ray Binaries (HMXB) and Low Mass X-ray Binaries (LMXB) .The most numerous class of HMXBs are X-ray binaries. Now there are about 70 objects of this type known in the Galaxy, 78 in the Small Magellan Cloud (SMC), and 16 in the Large Magellan Cloud [4].

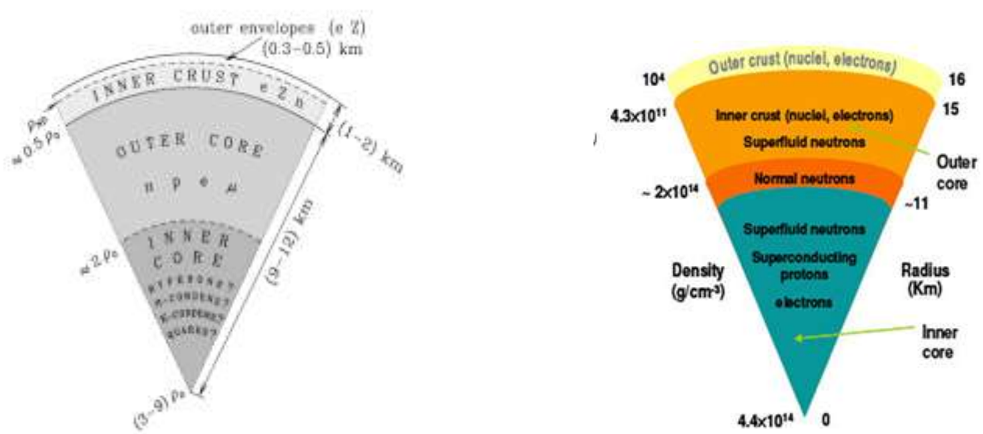


Figure 2. A: Internal structure of a Neutron star, B: A typical structure of Neutron star interior [3].

Magnetars are expected to be some kind of X-ray Pulsars. Currently, four kinds of X-ray Pulsars are known [5,6]:

- Rotation-power X-ray pulsars. The X-ray emissions of the Crab pulsar and the Vela pulsar are assumed to be originated from their rotational energy.
- 2. Accretion powered X-ray pulsars. They are accreting Neutron stars in X-ray binaries.
- 3. Magnetars. Observationally, anomalous X-ray pulsars and Soft Gamma-ray Repeaters are thought to be Magnetar candidates. The persistent and burst energy of Anomalous X-ray pulsars and Soft Gamma-ray Repeaters may originate from the Neutron star's magnetic energy.
- 4. If the above three kinds are out of reach, then the central Neutron star can still emit X-rays due to its remain thermal energy.

II. The Residual Magnetic Fields

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). Appear in the upper left corner of the pulsar P-$\dot{P}$ diagram as shown in Figure (3). 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 ($\sim 10^{10}$ yr) [4,5]. The observed distribution of pulsars in the P$\dot{P}$ diagram indicates that something changes as pulsars age. One controversial possibility is that the magnetic fields of old pulsars must decay on timescales $\sim 10^7$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. RRATs with measurable periods usually have P > 1sec. Neutron stars can be divided into three types depending on rotation periods as Normal and Millisecond with Magnetar types [5, 6].

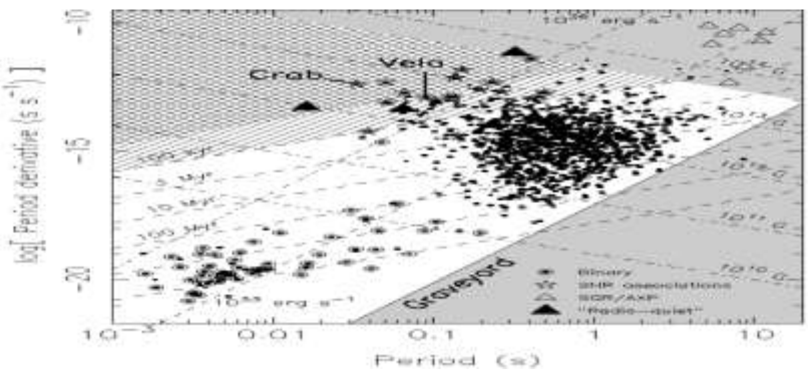


Figure 3. P- ˙P diagram for pulsars. The straight lines in the plot indicate the lines of constant age, the dipolar magnetic field strength and the spin-down luminosity. The grey region indicates areas where radio pulsars are not expected. Magnetar candidates, i.e. AXPs and SGRs are indicated with transparent triangles and are clearly separated from the main distribution of pulsars [7]

2.1 The Magnetosphere

The magnetosphere is the region surrounding a star filled with magnetized plasma. Many astrophysical objects, including Neutron stars form highly magnetized magnetospheres. Modeling of the structure of such magnetospheres requires solving for the self-consistent behavior of plasma in strong fields, where field energy can dominate the energy in the plasma. Goldreich & Julian (1969) described the pulsar electrodynamics in the simplest case of a rotating magnetic dipole, aligned with the rotational axis, surrounded by a charge-separated plasma. Most of pioneering models were based on the same underlying assumption: the Magnetic field is arranged in a force-free configuration As shown in figure(4). Under this hypothesis, the electromagnetic forces, much stronger than any other force in the system, are exactly balanced to have no net force on a charge [8].

A B

Figure 4. A: The lighthouse model of the pulsar magnetosphere. B: The region inside the cylinder is filled with high energy plasma [8,9].

2.2 Goldreich & Julian model

Goldreich & Julian (1969) presented the aligned rotator model for pulsars as shown in Figure (5), which is a description of what causes the pulsing behavior in Neutron stars. The model consists of a rapidly rotating Neutron star whose rotation and magnetic axis are aligned. The angle α is the offset between the two axes; in this case, it is zero. One of the significant calculations presented by Goldreich & Julian (1969) is that the dipole magnetic field is not in a vacuum, but that a magnetosphere is produced by the strong parallel electric field at the surface of the star. The magnetosphere co-rotates with the star out as far as the light cylinder, an imaginary cylinder whose boundary is where the velocity of the co-rotating magnetosphere is equal to the speed of light. Radius of the light cylinder is defined as [5.10]:

$$R_L=C/(2\pi/P) \qquad (1)$$

Where: P: Pulsar's period in second, C: speed of light = $3\times 10^{10}\ cm/sec$.

Within the light cylinder, particles are trapped within in the magnetic field and rotate with the star. Outside the light cylinder, particles escape out into the interstellar medium. The electric field potential reaches the same value of that as the interstellar medium at an imaginary line called the critical field line. At small angles between the magnetic pole and the critical line, electrons escape; on the other side of the line, protons escape. The aligned rotator model is a simple model for pulsars because it allows for magnetospheric calculations, like the space charge density which is the number of charges per volume in the magnetosphere [11].

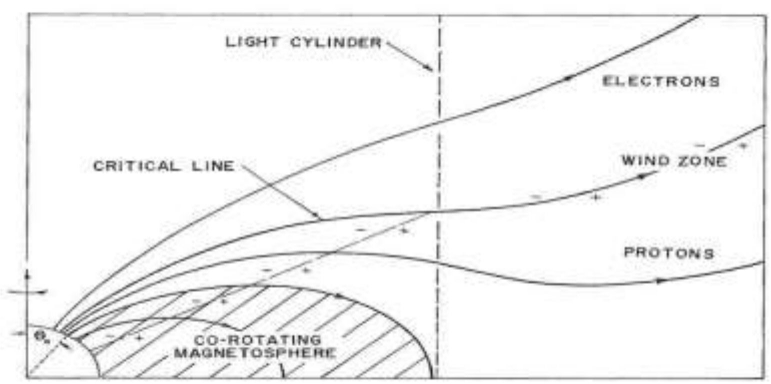


Figure 5. The aligned rotator pulsar model as described by Goldreich & Julian (1969).The Neutron star has a corotating magnetosphere that extends out to the light cylinder [11].

Many pulsars are formed from rotating Neutron stars. Torque exerted by accreting matter can cause the pulsar spin to increase or decrease, and over long times; an equilibrium period (P_{eq}) rate is achieved [7,12].

$$P_{eq} = 1.9\, B^{6/7} M^{-5/7} \left(M^{\bullet}/M^{\bullet}_{Edd}\right)^{-3/7} R^{18/7} \qquad (2)$$

Where: B: is the Magnetic field in G unit.

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

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

L: Luminosity of pulsar star.

G: gravitation constant = $6.670\times 10^{-8} cm^3 . gm^{-1} . sec^{-2}$.

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

The surface magnetic field strength at the poles estimate by [13]

$$B(G) = \sqrt{\frac{IPP^{\bullet}C^{3}}{(2\pi)^{2}R^{6}}} \quad (3)$$

2.3 The potential drop (ΔΦ) along field line traversing the gap

The polar cap region above the Neutron star surface, the charge depletion above the polar cap, which called vacuum gap result from the bounding of positive ions in the surface of Neutron star As a result, a significant part of the unipolar potential drop develops above the polar cap, which can accelerate charge particles to relativistic energies and power the pulsar radiation mechanism. The growth of the accelerating potential drop is limited by the collapse production of electron-positron plasma. The accelerated positrons will leave the acceleration region, while the electrons will bombard the polar cap surface, causing a thermal ejection of ions. This thermal ejection will cause partial screening of the acceleration potential drop, the potential drop across the gap for different values of magnetic field [4,13].

$$\Delta\Phi = \frac{\Omega B h^{2}}{C} \quad (4)$$

Where: Ω: angular frequency (Ω=2 π).

Or the potential drop relate to period derivative is [14]

$$\Delta\Phi = \frac{B}{P^{\bullet}} \quad (5)$$

$P^{\bullet}$: is the period derivative

2.3 Death Line

Pulsar "death" means the stopping of pulsar emission and also called ratio pulsar death. The death defined by Ruderman & Sutherland (1975) is that: a pulsar dead when the maximum potential drop ΔΦ available from the pulsar is smaller than the acceleration potential needed to accelerate particles. Because this death line is model dependent, Contopoulos & Spitkovsky (2006) included the effect of pulsar death when modeling the rotational evolution of pulsars. Considering particle acceleration and pulsar death simultaneously may give a comprehensive interpretation for both short and long-term rotational evolution of pulsars. And death line can calculate by [13,15]**:**

$$\text{Death line} = B/P^{2} \quad (6)$$

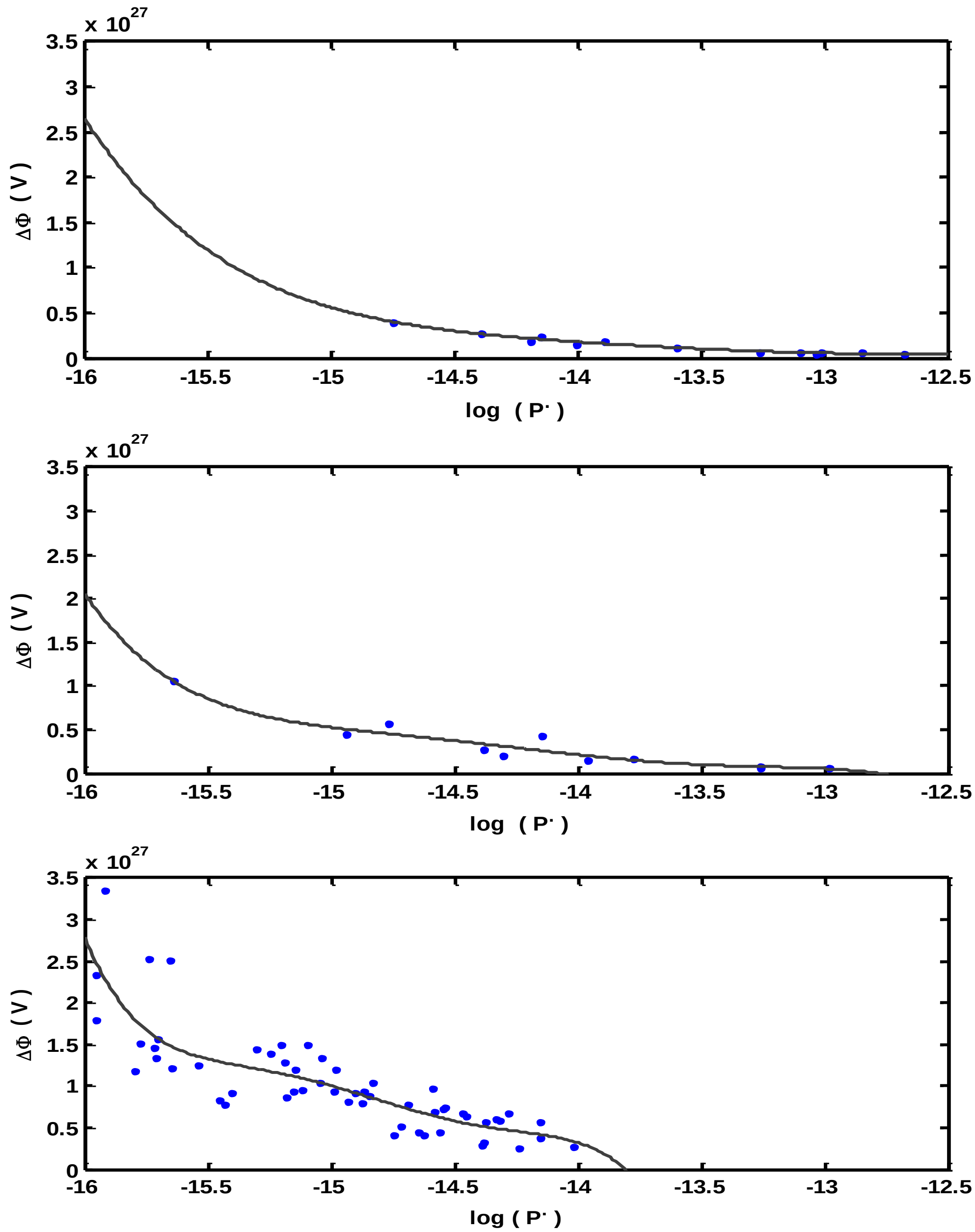
2.4 Magnetogyric Ratio $\boldsymbol{\gamma}$

Magnetogyric ratio it also called gyromagnetic ratio is the ratio of its magnetic moment to its angular momentum. The value of the gyromagnetic ratio determines the effect of magnetic fields on a system that has a magnetic moment. Woodward (1978) has plotted the Magnetogyric ratio of pulsar against their periods to understand the distribution of pulsar in the $\gamma - P$ diagram [13].

$$\gamma = \frac{\text{Magnetic moment}}{\text{Angular moment}} = 10^{8}(P^{3}P^{\bullet})^{1/2} \quad (7)$$

III. Experiment and Result

The potential drop is calculated by using eq. (5), HE have large value of potential drop than NRAD shown in Figures (6 A&B), and the potential drop for Normal is increase at $P^{\bullet} \sim \leq 3 \times 10^{-15}$ as shown in Figure (6, C), while the potential drop will increase at $P^{\bullet} \sim \leq 10^{-19}$ for MSPs as shown in Figure (7, A) and the potential drop increase at $P^{\bullet} \sim \leq 1.5 \times 10^{-20}$ for HE MSPs shown in Figure (7, B), while the potential drop will increase at $P^{\bullet} \sim \leq 10^{-11}$ for Magnetar stars as shown in Figure (7, C), so the older stars have the larger value of potential drop because it have less energy. The data that will be used in this article were obtained from Australian Telescope National Facility (ATLNF) [16].



A B C

Figure 6. Represents the relationship between the Pulsar period and drop potential for: (A) NRAD, (B) HE and (C) mix Normal.

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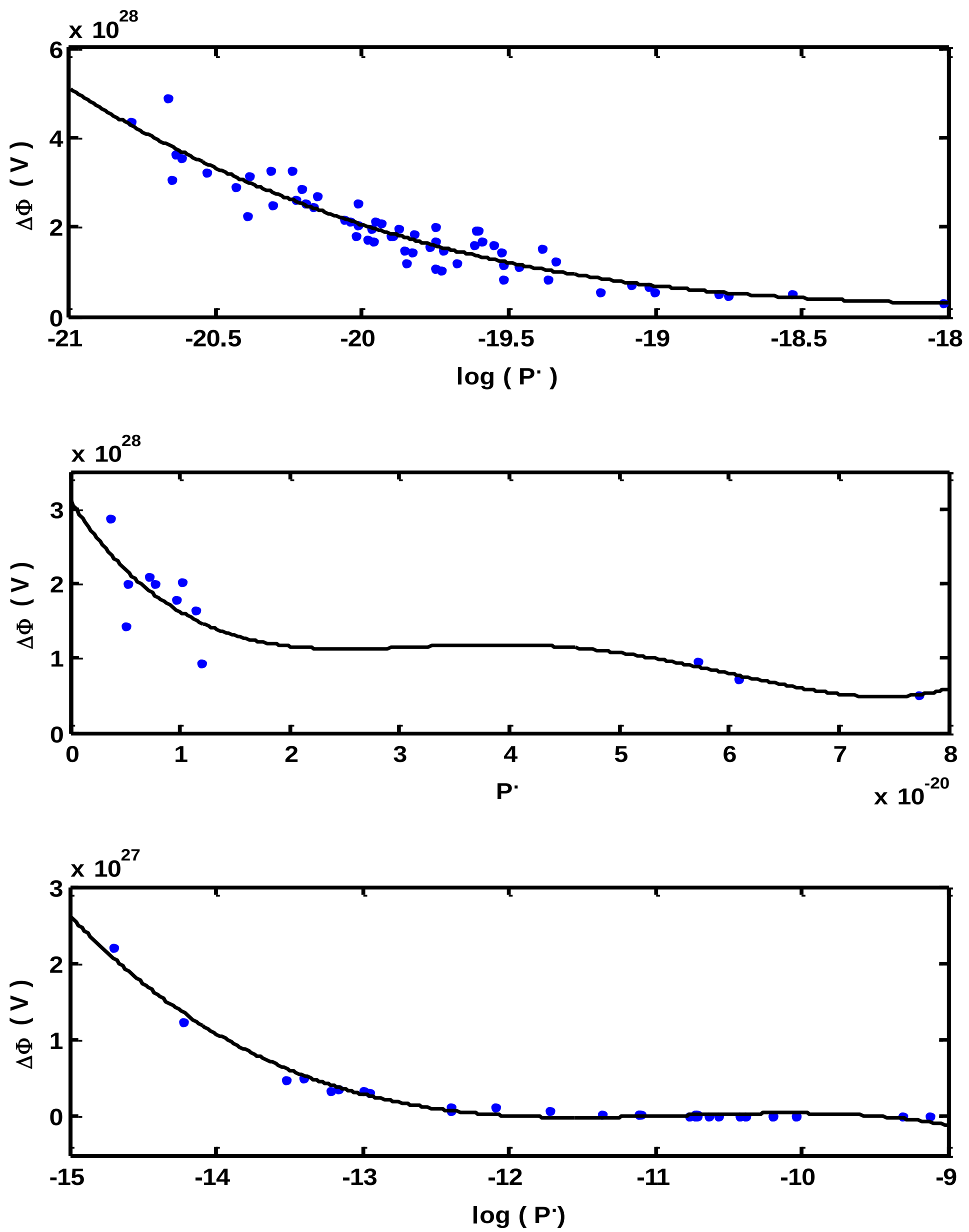


A

B

C

Figure 7. Represents the relationship between the Pulsar period derivative and drop potential for: (A) mix MSPs (B) HE MSPs and (C) Magnetar.

When $\Delta\Phi$ is large enough to ignite the avalanche pair production, then the backflow of relativistic charges will deposit their kinetic energy in the polar cap surface and heat it at a predictable rate. This heating will induce thermionic emission from the surface, which will in turn decrease the potential drop that caused the thermionic emission in the first place. A potential drop proportional to height gap develops along the magnetic field line in gap. The expansion of the polar gap leads to decreases in the magnetic field within the gap. The younger pulsar (Magnetar) the polar gap is near from magnetosphere, because the line of magnetic field is so strong, so it has more energy and the older one (MSPs) the polar gap is far away from magnetosphere.

The results estimated the γ and **death line** for Pulsar by using the equations (6 and 7), Pair production from the polar cap is believed to be a main condition for pulsar radio emission. the Figure (8) shows the relation between γ pulsar period, which is divided pulsar to groups according to its period, $P \sim 0.1 \sim 6$ sec known Normal pulsars as shown in Figure (8 A), P~0.1~1.8 sec known MSPs Pulsars as shown in Figure (8, B), and P~2~12 sec known Magnetar stars as shown in Figure (8, C).

In the Magnetar which have high magnetic field, pulsar death is not uniquely defined, is no strong reason of quit radio emission against high magnetic, may be the energy band of the emission is not in radio; or that the SGRs and AXP are not Magnetars at all. So the Magnetar don't have death line as shown in Figures (9).

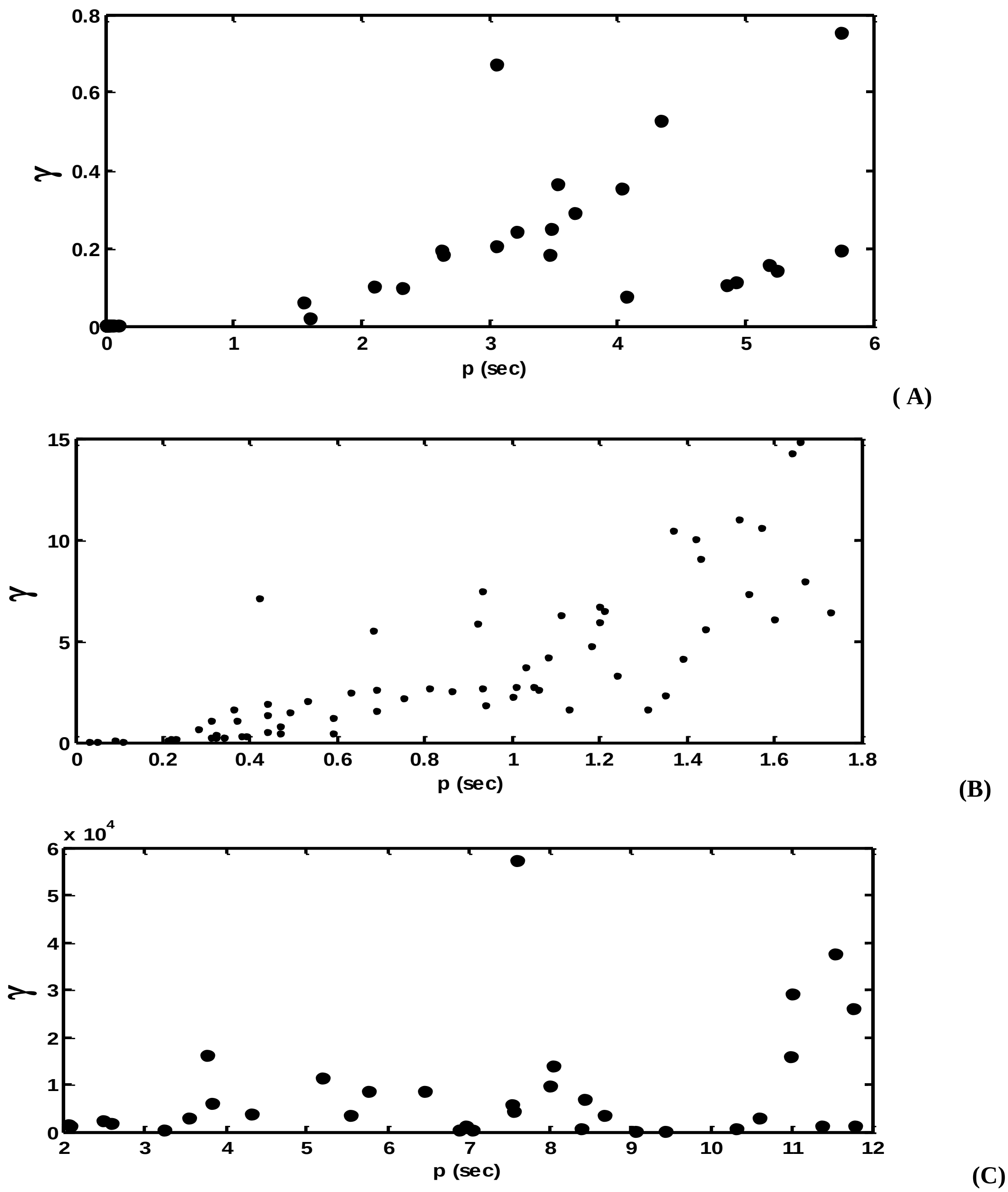
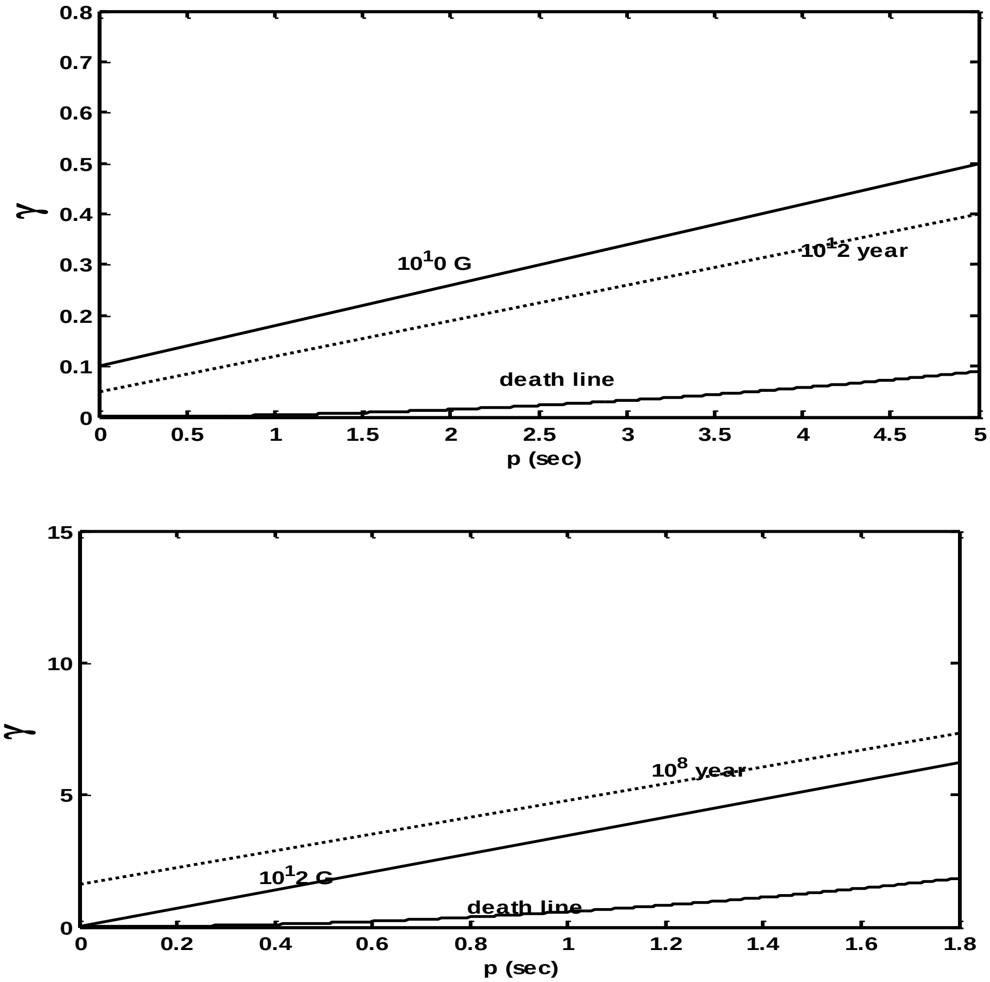


Figure 8. Pulsars in the γ-period diagram for: (A) Normal, (B) MSPs and (C) Magnetar.



(A)

(B)

Figure 9. Pulsars in the Gamma-period diagram with death line for: (A) Normal and (B) MSPs

IV.CONCLUSION

Conclusions can be summarized by the following points:

- Magnetar pulsar is youngest than Normal and MSPs, so it have the strongest magnetic fields and more Luminosity, that is mean it's have more energy and take a long time to disappear in its evolution.
- The polar gap of Magnetar is near the magnetosphere while the polar gap of Millisecond is far away from magnetosphere.
- Pair production from the polar cap is believed to be a main condition for pulsar radio emission.
- In the Magnetar which have high magnetic field, pulsar death is not uniquely defined, is no strong reason of quit radio emission against high magnetic, may be the reasons of radio quiescence of Magnetars are that the main energy band of the emission is not in radio; (Magnetars are well above the death line, so that their spin-down-powered activity is in principle not prohibited).

REFERENCES

[1] Y. Lim , "Theory of nuclear matter of Neutron stars and core collapsing supernovae", Ph.D. thesis, Department of Physics, Stony Brook University, 2012.

[2] J. M. Lattimer, "Neutron Stars as a Probe of the Equation of State", Stony Brook University, 2004.

[3] J. H. Charles, and P. Jorge, "Neutron Star Structure and the Neutron Radius of 208Pb ", the American Physical Society, Vol. 86, N. 25, PP: 5647-5650, 2001.

[4] A. Chashkina .,S. B. Popov, "Magnetic field estimates for accreting Neutron stars in massive binary systems and models of magnetic field decay", Sternberg Astronomical Institute, Moscow State University, New Astronomy, Vol. 17, Issue 6, PP: 594-602, 2012.

[5] W. B. William, "Neutron Stars and Pulsars", Space Sci. Library, Vol. 357, pp:112, 2008.

[6] G. B. Matthew ., K. H. Alice., "Resonant Compton up scattering in anomalous X-ray pulsars", Astrophys Space vol. 308, PP: 109–118, 2007.

[7] Ö. Feryal, F. Paulo, "Masses, Radii, and Equation of State of Neutron Stars", Annual Review of Astronomy and Astrophysics, Vol. 54, NO. 40, PP: 401-440, 2016.

[8] R. Rachel., "A Non-Radial Oscillation Model for Radio Pulsars", PhD thesis, University of North Carolina, Department of Physics & Astronomy, 2007.

[9] R. Milton., P. Vasileios, and L. Stuart Shapiro., " Pulsar spin-down luminosity: Simulations in general relativity", Cornell University Library, Vol.3, PP: 1-12, 2014.

[10] B. Zhang, "Spin-Down Power of Magnetars", International Workshop on Strong Magnetic Fields and Neutron Stars, PP: 83-96, 2016.

[11] A .A. Sundus., "The Spin-down Torque Decay with the Characteristic Age for Binary Millisecond Pulsars (MSPS) Stars", Iraqi Journal of Science, Vol.49, No.1, PP. 239-243, 2008.

[12] A .A. Sundus., "Thermal Emission from Binary Millisecond Pulsar Stars (MSPs) ", Iraqi Journal of Science, Vol. 55, No. 1, pp. 268-275, 2014.

[13] F. Woodward.,' PULSAR MAGNETOGYRO RATIOS AND PULSAR EVOLUTION', The Astrophysical Journal, 225:574-581, 1978.

[14] A .A. Sundus, "Polar Gap Properties for Neutron Star Within Light Cylinder Limits", Um-Salama Science Journal, Department of Astronomy, College of Science, University of Baghdad, Vol.5, No.4, PP:612-618, 2008.

[15] Z. Bing., "Radio Pulsar Death", ACTA ASTRONOMICA SINICA, the Pennsylvania State University, USA, V.44, PP: 215-222, 2003.

[16] R.Manchester, G.Hobes, "The ATNF Pulsar Database, Astronomical Journal, 129, pp.1993-2006, 2005. (http://www.atnf.csiro.au/people/pulsar/psrcat/ and Manchester).

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