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Open Access Journal of Astronomy
ISSN :2996-6701

Cosmic Baby —Does it hint at PSRJ1119-6127 a Triaxial Star?: A possibility

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Research Article

Volume 4 Issue 2

Received Date: July 23, 2026

Published Date: September 28, 2026

DOI: 10.23880/oaja-16000172

Abstract

Discovery of high magnetic radio pulsar PSRJ1119-6127 and its follow up observations after its July'2016 X-ray bursts suggest that it exhibited characteristic of magnetar-like activity. Discovery of Cosmic babylike. Swift J1818.0-1607, in 2020 hints that (a) it is a "triaxial star", (b) triaxiality phase starts from its early phase (i.e. birth) and will continue for a long period of at least 760 years, (c) its core magnetic field strength is ~ 8.924 x 1017G (Parui 2023). Introducing the strong internal magnetic field in nuclear matter equation of state (EoS) Watanabe et al (2022) showed that it is possible for a rotating neutron star (with surface dipole field strength Bsurface = 1012G) may have an ultra-strong magnetic field ~ 2.5 x 1018 G in its interior. Based on these I have estimated the internal magnetic field strength of PSRJ1129-6127 which is ~ 1017 G and ellipticity (ϵ) ~ 5.0091 x 10- 8. These findings show that although PSR J1119-6127 is a pulsar (i.e. rotating neutron star) but its internal strong magnetic field hints PSRJ1119-6127 is a "Triaxial Star" (which will continue for next ~ 212kyr) and can be considered as a magnetar and capable of exhibiting magnetar-like activities. Possible (which nature of other radio pulsar Kyr)18and Canhas been discussed. This author suggests of elf exhibiting to give attention towards the triaxial nature during their observation of radio pulsars.

Keywords: Neutron Star; Pulsar; Magnetar; Triaxial Star

Abbreviations

EoS: Equation of State; RPPs: Rotation Powered Pulsars; DM: Dispersion Measure, RM: Rotation Measure; RPP: Rotation Powered Pulsars; QC: Quantum Chromodynamics; AMM: Anomalous Magnetic Moment; SGR: Soft Gamma Repeaters; AXPs: Anomalous X-ray Pulsars; BAT : Burst Alert Telescope and RRAT: Rotational Radio-transient.

Introduction

A compact star is, basically, a system inside which a continuous struggle between gravity and the degenerate pressure is created by its constituents. One side, gravity tries to crash the star's material by pulling towards the centre of the star while on other side the degenerate pressure due to compactness among the materials tries to overcome

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the gravity pull through counter act. In the year 1969 S. Chandrasekhar [1] theoretically first proposed a new kind of compact star, so called "Triaxial Star". Note that, in 1967 Jocelyn Bell, a Ph.D. Scholar of Cambridge University, UK, detected a peculiar type of rhythmic signal with unknown origin. Later, this unknown origin is identified as "Neutron Star". With the advancement of observational technology various types of neutron stars (such as isolated; rotating neutron star or pulsar; magnetars etc.) have been identified which turns the neutron star as a "gold mine" to the astronomers and scientists.

Triaxial star plays an important role in the evolution of astrophysical compact objects. In the case of "Standard Model" of physics, or precisely particle physics [2-6], a theoretical framework is constructed based on empirical observations and then it is utilized to make prediction and establish correlation between elementary particles and forces — what matter is made and how it holds together by utilizing three of the four fundamental forces. This means that the standard model rests on two basic ideas: "all matter is made of particles" and "these particles interact with each other by exchanging other particles associated with the fundamental forces, i.e. electromagnetic force, strong force and weak force ". So, gravity or gravitational force contributes very little in the standard model. In Einstein's General Relativity gravity is the main most effective force and other three forces have very small contribution. As a result, standard model treats several abstract variables as external inputs, boundary conditions, or "incomplete concept" rather than driving them from the first principle.

This implies that there are the limitations of this standard model regarding the abstract nature of "Mass", "Time", "Temperature" and "Triaxiality" [7-12]. For example:

- In the case of "Mass" → the standard model relies on the Higgs mechanism to generate or create mass for elementary particles, but it cannot predict — why particles have their specific mass value (it is like the case of assigned, not explained). Similarly, other problems.
- In the case of "Time" → 'Time' is treated in the standard model as a classical, absolute background parameter (i.e. a continuous coordinate) rather than a dynamical variable. The other problems are — (i) "The Problem of time" i.e. background dependent view directly makes a clash with the General Relativity in which the time is dynamic, local in the fabric of space-time. The standard model has no required framework to resolve it. (ii) "Arrow of time" — the standard model does not have any explanation why the thermodynamic arrow of time or simply 'time" flows forward.
- In the case of "Temperature" → The problem is "Not Fundamental" i.e. temperature is a macroscopic property arising from statistical mechanics (particle's average kinetic energy). It does not exist as a fundamental property of a single, isolated subatomic particle.
- In the case of "Triaxiality" → "The Problem of Scale Mismatch" i.e. triaxiality refers to the three-dimensional (3D) shape deformation of the system along its three unequal orthogonal axes. In other words, it can be said as a collective, structural property. Such type of property is used in nuclear physics to describe the deformed atomic nuclei, and in astrophysics to describe "elliptical shapes" off galaxy, compacts like high-speed rotating neutron stars, pulsars, highly magnetic neutron star i.e. magnetars. The main problem: "asymmetric macroscopic geometry"— it is phenomenological nuclear collective model emerges purely from fundamental quarks and leptons and to study this triaxial shape scientists use effective field theories, but the standard model is too rigid to handle such type of geometric asymmetry. This asymmetric shapes thus implies that although the triaxiality described an object in which all three principal spatial axes have different lengths but it breaks the traditional axial symmetries and finally exhibit a collective parameter (i.e. ellipticity ϵ) which is used to describe the composite systems rather than a fundamental property of the standard model. It can be said that triaxiality reveals the "true value of a prevailing shape driven by specific components of the strong nuclear forces" However, the triaxial stars were confined in theoretical works only. It was believed that neutron stars could be a good, reliable source of gravitational waves. As a result, in searching the ideal gravitational wave sources the isolated neutron stars, millisecond pulsars became an efficient gravitational wave source. Not only that, but many theoretical studies also [13-15] suggested that the triaxial neutron stars, i.e. triaxially deformed neutron stars, are the most significant gravitational wave sources. So, triaxially deformation in stars (not only for neutron stars, other stars also) gave an impetus to the astronomers, scientists to search for a triaxial star.

More than 50 years have been passed after the proposed theoretical concept of triaxial star but till date it has remained undetectable. The main reason is that these configurations or shape of the star. According to the classical solution of Maclaurin spheroids and Jacobi ellipsoids for self-gravitating and uniformly rotating, incompressible fluids in equilibrium offers two models of rapidly rotating stars. The situation is: When the rotation of an equilibrium configuration is increased, then the sequence of triaxial Jacobi ellipsoids diverges from that of the axisymmetric Maclaurin spheroids,

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and the ratio of kinetic (T) to gravitational (W) energy reaches T/|W| ~ 0.14 [16].

The reason is these configurations are no longer a precise ellipsoidal in relativistic gravity or for compressible fluids the triaxially deformed rotating compact stars (i.e., simply triaxial star) are rather than "ellipsoids". It means that this triaxial star model is very important in relativistic astrophysics because fluid compressibility is included in modelling the relativistic neutron stars as an axisymmetric and uniformly rotating configuration associated with the equation of state (EoS) of high-density nuclear matter [17,18].

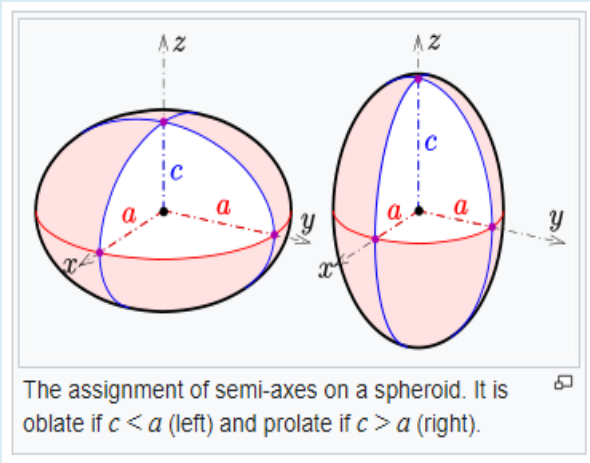
In the year 2000 two high magnetic field pulsars i.e. PSRJ1119-6127 (with surface dipole magnetic field (Bs) = 4.1x 1013 G and characteristic spin down age (τc) of only ~ 1.6 kyr) and PSRJ1814-1744 (with Bs = 5.5 x 1013 G and τc = 85 kyr) were discovered [19,20]. But their apparent normal radio emission in the regime of magnetic field (with some models predict no discernible x-ray emission) as well as their unusual attribution of underwent a magnetar like outburst transition from a magnetar to pulsar make them puzzling creators that remain unsolved till date.

Cosmic babylike. Swift J1818.0 – 1607, was discovered in 2020 through Swift (a space-based satellite X-ray Telescope) Observatory [19]. It is the youngest magnetar (detected so far) with characteristic age (τc) ~ 240 years and surface magnetic field (Bs) ~ 2.7 x 1014 G. Recently, Parui [21] suggested that this cosmic baby is the first detected triaxial star. It offers the astronomers/ scientists as an important probe for studying the magnetar's evolution.

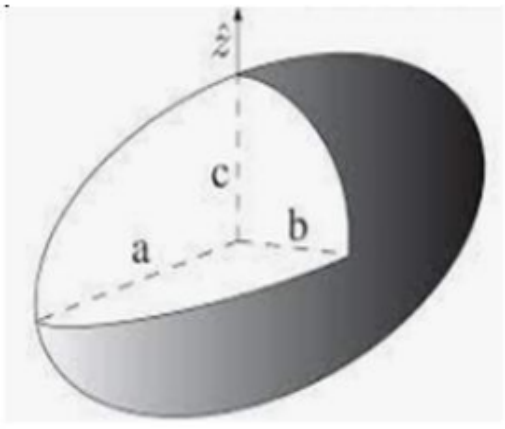
In this paper, I study the unusual behaviour of PSRJ1119-6127 in the light of cosmic baby and other high magnetic pulsars having peculiar properties like that of PSRJ1119-6127. The manuscript is organized as follows: Sec.1 covers the introduction. In Sec. 2 deformation of a star has been explained. Sec.3 deals with the discovery of two high magnetic radio pulsars PSRJ1119-6127 and PSRJ1814-1744 with their observed parameters and unusual behaviours observed so far. In Sec.4 discovery of Cosmic Baby and its observed parameters are mentioned. The significant findings of Watanabe et al for internal magnetic field of neutron stars have been discussed in Sec. 5. The details of possible triaxiality and deformation of PSRJ1119-6127 due strong internal magnetic field are expressed in Sec.6. In conclusion section 7, it is suggested that PSRJ1119-6127 is a Triaxial Star as well as PSR J1814-1744, in realistic case, also exhibiting its triaxiality.

Deformation Due Rotation and Triaxiality of a Star

Deformation of a star in the form of a "Triaxial Star" was first proposed by Chandrasekhar. In fact, it is a deformed phase of a stable star which can be considered as a new type of compact star. This deformation in a stable star may arise due to its high-speed rotation or its internal strong magnetic field [Figures 1A&1B].



(A)



(B)

Figure 1: Schematic diagram showing (A) oblate, prolate and (B) triaxial shape of the star. (Courtesy: Wikipedia)

Now, i)if all the three semi-axes are same, i.e. a = b = c, then it is a sphere;

ii) if the length of two axes of an ellipsoid is same, then the figure is spheroid i.e. an oblate spheroid or a prolate spheroid

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depending on whether c < a or c > a, respectively [figure:1A]; iii) if a ≠ b ≠ c then the spheroid shows its triaxiality [figure:1B].

In Case of Rotation

Classically, the figure of equilibrium of uniformly, rotating homogeneous mass suffers various sequences of ellipsoidal figures under its rotation. Here, Maclaurin sequence is a sequence of oblate spheroids such that along which the eccentricity "e" of the meridional section increases from zero to one. Note that, it was initially thought that the sequence of the square of the angular velocity of rotation (i.e. Ω2) is not the parameter of unrestricted range implying that for each value of Ω2 (except less than a certain determinate maximum value) there are two permissible spheroidal figures of equilibrium. In this context, Jacobi first showed the appearance of a sequence of genuine triaxial ellipsoids of equilibrium diverges from the Maclaurin sequence. For example, in the case of general ellipsoid it's quadratic surface can be expressed in Cartesian coordinates by

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1. \qquad (1)$$

where 'a', 'b', and 'c' are the semi-axes of lengths a, b, c.

Thus, divergence from the Maclaurin sequence means that there is a bifurcation point which clearly distinguishes the permissible sequences of figures of equilibrium from Maclaurin spheroidal sequence to Jacobi ellipsoidal sequence. So, bifurcation of these two models, i.e. the sequence of triaxial Jacobian ellipsoids diverges from that of the axisymmetric Maclaurin spheroids in the case of increasing in rotation of an equilibrium, appears when the ratio of kinetic energy (T) to gravitational energy (W) reaches T / |W| ~ 0.14 [16]. Under this situation, the configurations are no longer a precise ellipsoid in relativistic gravity or for compressible fluids, but a triaxially deformed rotating compact star (or simply "Triaxial Star") rather than the ellipsoids.

In Case of Strong Magnetic Field

Deformation of a star due to its internal strong magnetic field means dominant magnetic field is more effective than the rotation. Instead of kinetic energy magnetic energy will be considered.

Discovery of High Magnetic Radio Pulsars PSRJ1119-6127 and PSRJ1814-1744

The Radio Pulsars PSRJ1119-6127 and PSRJ1814-1744 were discovered on 23rd August'1997 and 24th August 1997, respectively when a survey of the Galactic plane was carried out using the 64m Parkes Radio Telescope in Australia [20]. The observational measured and estimated (i.e. inferred) parameters are shown in Table 1. The radio pulsar PSRJ1119-6127 showed different peculiar behaviours following the magnetar like bursts from the system in July 2016. With the help of advanced radio telescopes and space observatories astronomers have observed the puzzling facts time to time during its evolution. These facts are noted in Table 2.

Parameters	PSRJ1119-6127	PSRJ1814-1744
Spin Period (P)	0.407 s	3.975 s
Spin Period Derivative ($\dot{P}$)	4.0×10^{-12} s s^{-1}	7.4×10^{-13} s s^{-1}
Surface Magnetic Field strength (B_s)	4.1×10^{13} G	5.5×10^{13} G
Characteristic Age (τ_c)	~ 1.6 kyr	85 kyr
Luminosity (spin down)	2.3×10^{36} erg. s^{-1}	4.7×10^{32} erg. s^{-1}
Distance (d)	2.4 – 8 kpc	10 kPc
Radio Luminosity (sd^2)	~ 25 mJykpc^2	~ 80 mJykpc^2
Rotational Frequency (υ)	2.4531601130 s^{-1}	0.251519741
Frequency derivative ($\dot{\upsilon}$)	$-2.4207996 \times 10^{-11}$ s^{-2}	-4.7002×10^{-14} s^{-2}

Table 1: Measured and Estimated Parameters of Discovered Pulsars PSRJ1119-6127 and PSRJ1814-1744 [20]s.

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Period	Observational facts	Inferences/ Implications	Reference
30th, 31st October 1998	At 1384 MHz observed frequency the pulsation was brightest at that time position of the pulsar		Gonzalez et al. [28].
On about MJD51,398 MJD 50850-50940	A small rotation occurred. Another Glitch of similar magnitude occurred with uncertainty. The Glitch appears cubic in shape with much reduced amplitude in comparison to the parabolic residuals.		
23 – 28 February 2006	VLT / NACO observation Infrared (IR) observation of PSR J1119-6127 with the help of NAosCOnica 4th unit telescope of VLT shows the IR flux upper limit can be excluded in the presence of a disk with accretion rate (M•) ≳ 3 x 1016g s-1 but lower limit cannot be rule out with the presence a substantial disk torque on this pulsar. This means that magnetars are intrinsically more efficient IR emitters than rotation powered pulsars.	The possible main reason is the possession of their high magnetic field which makes the relatively low IR emission efficiency of PSR J1119-6127. This implies that having a magnetic field ~ 4.1 x 10^{13} G it is expected to be a magnetar like IR emission from this pulsar, but lower limit suggests the scenario is more similar to the rotation powered pulsar than to the magnetar.	Mignani et al. [24].
	Chandra X-ray Observatory's Observation Analysis of X-ray counterpart (emitted from this pulsar) observed data, obtained through the Chandra Director's Discretionary Time Observation, indicates the magnetar-like activities first observed from a rotational radio pulsar. This fact supports a Pulsar Wind Nebula (PWN) interpretation via the spectral index of PSRJ1119-6127 and suggests the similar one as seen around SGR 1935+2154.	This provides the evidence for a compact pulsar wind nebula of ~ 3" x 6" in angular size. Follow up observations suggest that PWN exhibits an elongated jet like features. The observed change in PWN morphology features shows that it could be somewhat related to a new source of energy powered by the magnetar bursts	Gonzalez, Safi-harb [25], Blumer et al. [26].
26th, 28th July 2016	(a)Timing and energetics of the12 bursts from PSRJ1119-6127 during its burst active phase. (b)In a post burst episode a spectral softer X-ray flux enhancement had occurred.	Nature of this unusual high field radio pulsar firmly take a position within the typical magnetar population. It is evidence that global dipole fields above the quantum critical magnetic field strength are not essential to operate the magnetar rust trigger mechanism.	Göjus et al [22].

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During July 2016	Spin Frequency Evolution a) Analysis of Parkes Observatory's observed data after the x-ray burst it was found a smooth and fast spin down process resulting which a net change in pulsar rotational frequency amounting $\Delta\nu \approx -4 \times 10^{-4}$ Hz and also increase in net spin down rate $(\Delta\nu\bullet) \approx -1 \times 10^{-11}$ Hz s-1. b) Radio pulsations disappeared after the x-ray bursts but reappeared about two weeks later with flux density at 1.4 GHz increased by a factor of 5. As per observation this flux density then decreased but came back to normal following through a slow recovery. c) The integrated profile of the pulsar shows its underwent dramatic and short-term changes in total intensity, polarization and position angle. Multiwavelength observation The first magnetar-like outbursts from PSRJ1119-6127 was observed in July 2016. Considering the 0.5 – 10 Kev X-ray observed data, measured during the period August 2016 , and analysis of these data through phase-resolved spectral process indicates that a) On- and off-pulse spectra show the characteristics of two blackbody component indicating power law component which is similar one to that of hard X-ray spectra of magnetar (in fact this power-law component was non-distinguishable in the earlier data measured from Dec'2016). b) No substantial shift was found between the radio and x-ray pulse peak in X-ray burst after the occurrence of the 2016 x-ray bursts. c) Findings from X-ray data confirm the gamma ray pulsation was occurred after the X-ray outbursts. d) The pulse structure and phase difference between the gamma ray and the peaks (i.e. ~ 0.4 cycle) are also consistent with those available before the X-ray bursts. e) This result show a large lag with a single gamma ray peak of PSRJ1119-6127 means that it is very difficult to reproduce if the origin of gamma ray emission is polar cap region i.e. consistency of the gamma ray emission from the outer magnetosphere of PSRJ1119-6127 with the observed relation between the phase lag and gamma ray peak separation. f) This analysis suggests the reconfiguration of the global magnetosphere model of the high magnetic PSRJ1119-6127 to match the magnetar- like outbursts exhibited from this pulsar during the last 6 months after the 2016.	As per observation, although the evolution of this pulsar is complex but hints a correlation exists between the spin down rate, pulse profile shape and radio flux density. The origin of such peculiar but smooth spin frequency evolution arises due to either (i) reconfiguration of the surface magnetic field, or (ii) the particle winds that was triggered by the x-ray bursts. The facts of the recovery of spin down rate and also in pulse profile normalization suggest a link or connection between high magnetic field pulsar and magnetar. The inferred results from the multi-wavelength observations suggest that (i) the X-ray and radio peaks are from different epochs. (ii) After the X-ray bursts the radio and X-ray emission properties as well as spin-down properties of PSRJ1119-6127 are similar with those of the magnetar XTEJ1810-197	Dai et al. [23]. Wang et al. [27].

Table 2: Important observed facts of PSRJ1119-6127.

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From the above one can suggest that the similarities regarding emission properties (such as X-ray bursts and gamma ray bursts) of the radio pulsar PSRJ1119-6127 and the radio magnetar XTEJ1810-197 support the identification of the 2016 X-ray burst of PSRJ1119-6127 as magnetar-like activity. This implies that although PSRJ1119-6127 is a radio pulsar with high surface dipole magnetic field ~ 4.1 x 1013 G but it exhibits the characteristics of a magnetar having surface dipole magnetic field strength ~ 1014 G with possible internal magnetic field strength ~ 1016 – 1018 G (i.e. magnitude two order more than the surface) or even more.

Discovery of Cosmic Baby

The Swift J1818.0 – 1607 was discovered by the Swift Burst Alert Telescope (BAT) on board the NeilGehrels Swift (a space satellite-based X-ray telescope) Observatory through the detection of a typical characteristics of short burst from magnetar on 12th March 2020 at 21:16:49 UT [29]. This detection of a new un-catalogued X-ray source is presently known as Cosmic Baby. Astronomers coined the term "Cosmic Baby" in the sense that till date all the detected magnetars were almost of million years aged while this Swift J1818.0 – 1607 was only 240 years old which is like a baby compared to other magnetars. Following a series of observations through multiple telescopes (including TMRT and NICER) the confirmed and estimated parameters are shown in Table 3.

Spin period	0.7333920 s
Spin Period derivative	~ 8.2 x 10^{-11} s s^{-1}
Characteristic age	~ 240 years [30]
Surface magnetic field	~ 2.7 x 1014 G
Dipolar magnetic field at poles	~ 7 x 1014 G
Coherent periodicity of X-ray signal	1.36s
Luminosity	~ 8 x 1034 erg. s-1
Spin down Luminosity	~ 1.4 x 1036erg.s-1

Table 3: Various Observed / Measured Parameters of Swift J1818.0-1607 at the Time of Discovery.

Based on the observed data Parui [21,31] estimated the core magnetic field and ellipticity of the cosmic baby and found 8.924 x 1017 G and 9 x10-3, respectively. The estimated ellipticity is within the range of realistic value i.e. ellipticity will be within 10-3 – 10-4 and core magnetic field strength 2 order magnitude more than the surface dipole field. Parui [21] suggested that this cosmic baby provides us with a "Triaxial Star" and will exhibit its triaxiality for next at least 760 years. The significance of this detection is that it is the first detected young magnetar which can be considered as Triaxial Star.

Relevance of Comic Baby

In searching the triaxial star, deformation due rotation is important. i.e. deformation of a stable star will be dominated / prominent with its faster rotation. Cosmic Baby i.e. Swift J1818.0-1607 is the youngest magnetar amongst the so far detected 31 magnetars and its age is 240 years i.e. the youngest comparing with the others whose ages ~ few million years. Astronomers expected that it rotates faster.

As the magnetar's age is ~ 240 years only w.r.t. other magnetars with ages ~ million years, for this reason the Swift J1818.0 – 1607 is called cosmic baby. So, parameters, characteristics of this cosmic baby can be considered as reference. Secondly, it's ellipticity (calculated from the observed parameters) ~ 8.924 x 10-3 which is within the detectable range 10-3 –10-4.

Significant Findings of Watanabe et al. 2000

An isolated pulsar is a rapidly rotating and highly magnetized neutron star with a spin period of ~ 1 ms to ~10 s and a surface dipole field strength (Bs) ~ 108 – 1015 G. More than 2600 pulsars have been detected. Out of these, a small sub-class with only 31 members [31] are so called magnetars having bright and variable emission in the X-ray and gamma ray bands [32]. As the observed radiation emitted from the magnetars is more than the spin-down power of the pulsars, it is suggested that the decay of an ultra-high magnetic field that exceeds the quantum critical magnetic field Bc = me2 c3 / e ħ ~ 4.4 x 1013 G Becomes an important energy source of emission [33]. The only four radio magnetars are PSRJ1745-2900, PSR J1622-4900, XTE J1810-197 and 1E1547.0 – 5408 [34] which are exceptionally rare and constitute only ≲ 0.2% of the pulsar population. Not only that, but they also have large dispersion measure (DM) and Faraday rotation measure (RM) values in comparison to the ordinary radio pulsars implying that they have extreme magneto-ionic environments [35].

The most remarkable characteristic of magnetars is exhibit of short, bright burst, sudden release of energy from star's magnetic field [36], i.e. in particular bursts accompanied by long duration out-burst phase. For example, analysis of observational data confirms that some rotation powered pulsars (RPPs) with their high surface magnetic field strength (i.e. Bs> 1013 G show magnetar –like X-ray bursts indicating a connection between magnetar and normal rotation powered pulsars [37,38].

Neutron star is a unique object of super-dense hadronic matter such that its central density might be several times

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larger than the nuclear saturation density i.e. equation of state (EoS) for the nuclear matter inside the neutron star depends on the energy density of the star. To study the characteristics of neutron star, millisecond pulsars (having short rotation period of less than 10 ms) Watanabe et al. [39] introduced the extremely rapid rotation and strong magnetic field in the EoS. They considered twelve equation of states (i.e. GM1, GM3, TM1-a, TM1-b, TM2 ωρ-a, TM2 ωρ – b, NL3 – a, NL3-b, NL3 ωρ –a, NL3 ωρ – b, DDME2 – and DDM2 – b: for details see the text of the reference [39]) by employing coupling constants of hyperons with meson and fitting the properties of hyper nuclei in the quark model [40].

In fact, neutron stars can be considered as massive because of the pressure produced by the interior magnetic fields. Thus, investigation of neutron stars with a strong magnetic field inside it can be performed with the known observed parameters i.e. observed strength of the magnetic field on the surface (known parameter) and the assumed strength and the functional form of the magnetic field inside the neutron star. They adopted the density dependent magnetic field strength expressed as [41,42].

$$B(\rho) = Bs + Bo\,[\,1 - \exp\{-\alpha\,(\rho/\rho o)\gamma\}] \qquad (1)$$

where Bs = strength of magnetic field on the surface of neutron star. In general, the value of Bs = 1012 G.
Bo = the strength of magnetic field inside the denser region than that of the saturation density ρo (i.e. 0.153 fm- 3); Bo = 2.5 x 1018 G at ρo = 0.153 fm-3.

Here the free parameters are Bo, α, γ but the value of Bo varies for fixed values of α, γ. Here, α, γ are the two free parameters which are the indicator of fast or slow magnetic field changes from centre to the surface of the neutron star (i.e. magnetar). Note that, considering the core magnetic field of neutron star (i.e. magnetar) Bcore = 1.75 x 1018 G and 4.38 x 1018 G and using the density dependent magnetic field parameterization Equation (1) Mallick et al. [46]. found that (i) an increase in magnetic field shows the increase in mass of the neutron star (i.e. magnetar) but at Bcore = 2.6 x 1018G no maximum mass is observed. This implies that the neutron star (i.e. magnetar) has no maximum mass for a strong enough magnetic field at the core. (For this reason, the mass of neutron star (i.e. magnetar) increases only 3 – 4 % for higher magnetic field).

The energy density (ε) and the pressure of hadronic matter in the presence of magnetic field are

$$\varepsilon = \varepsilon m + B2 / 2 \qquad (2)$$

$$p = pm + B2 / 2 \qquad (3)$$

where εm and pm are the energy density and the pressure of hadrons such that the contribution of B2 / 2 from the magnetic field are negligible.

The realistic frequency range parameters of observed millisecond pulsars show a variation in the neutron star mass from 1.89M⊙ to 2M⊙. Here two noted observational findings are:

- Constraint on surface magnetic field of a magnetar type neutron star:
- Observation of 30 magnetars shows the maximally ~ 1015G on the surface magnetic field. In the case of 31stmagnetar (i.e. cosmic baby) surface magnetic field is ~ 2.7 x 1014 G [43].

Constraint on the EoS arises from neutron star radius:

Observational data of the gravitational wave event GW170817 shows the upper limit for radius is 13.76 km [44] at neutron star mass M = 1.4M⊙. NICER observation of PSRJ0030+0451 provides the upper limit of neutron star radius is 13.02+1.24-1.06km at M = 1.44+1.5-0.14 M⊙ [45]. A summary of the results, as obtained by Watanabe et al [39], is shown in Table 4.

α	$B(\rho_o)$	γ = 1		γ = 2		γ = 3		γ = 4	
	G	$M_{max}M_\odot$	$R_{1.4M\odot}$ km	$M_{max}M_\odot$	$R_{1.4M\odot}$ km	$M_{max}M_\odot$	$R_{1.4M\odot}$ km	$M_{max}M_\odot$	$R_{1.4M\odot}$ km
0	2.59 x 10^{16}	2.177	13.63	2.188	13.63	2.268	13.63	2.485	13.64
0	5.05 x 1016	2.182	13.66	2.22	13.65	2.394	13.67	2.664	13.7
0	7.79 x 1016	2.19	13.71	2.262	13.69	2.5	13.72	2.782	13.78
0	9.90 x 1016	2.2	13.78	2.31	13.74	2.589	13.79	2.869	13.86
0.1	1.23 x 1017	2.212	13.87	2.359	13.89	2.665	13.86	2.939	13.95
0.1	1.47 x 1017	2.227	13.98	2.409	13.88	2.731	13.94	2.997	14.05

Table 4: Strength of Magnetic field B (ρo) at saturation density (ρo) = 0.153 fm-3 for different values of Maximum mass (Mmax) and corresponding radius for various values of "α" for a considered Equation of State (EoS) with the surface magnetic field Bs = 1012G (Parameters taken from ref [39]).

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Considering the basic idea of massive neutron star which arises from the pressure offered by its strong internal magnetic field Watanabe, et al. [39] estimated the internal magnetic field for various EoS with the known observed surface magnetic field Bs = 1012 G and core magnetic field Bo = 2.5 x 1018 G and found the maximum mass of the neutron star for $\alpha = 0.06$, $\gamma = 1, 2, 3, 4$ are{ 2.227 $M\odot$, radius $R1.4M\odot$ = 13.98 km }, {2.409 $M\odot$, radius $R1.4M\odot$ = 13.88km}, {2.731 $M\odot$, radius $R1.4M\odot$ = 13.94km} and {2.997 $M\odot$, radius $R1.4M\odot$ = 14.04km}, respectively. For considered EoS the credibility is 68% w.r.t. maximum mass and radius at 1.4 $M\odot$ in the cases

$\gamma = 2$, $\alpha = 0.03, 0.04, 0.05$ and 0.06
$\gamma = 3$, $\alpha = 0.01, 0.02, 0.03$ and 0.04
$\gamma = 4$, $\alpha = 0.01$

Regarding variation of internal magnetic field for surface magnetic field Bs = 1012 G and core magntic field Bo = 2.5 x 1018G the internal magnetic field varies from 2.59 x 1016G to 1.47 x 1017G. In the case of normal neutron star (i.e. magnetar) the magnitude of internal magnetic field is one or two order magnitude more than the surface magnetic field. So, in the case of normal rotating neutron star (i.e. magnetar) i.e. PSRJ1119-66127: as the surface magnetic field Bs = 4.1 x 1013 G so one can expect its internal magnetic field may vary ~ 2.59 x 1017G to 1.47 x 1017G (for one order magnitude more) or ~ 2.59 x 1018G to ~ 1.47 x 1019G (if two order magnitude more) with possible core magnetic field ~ 1019G to ~ 1020G.

On argumental basis, if one assumes that there will be no such drastic change in internal magnetic fields due to the change in surface magnetic field from Bs = 1012G to 1013G then it can be considered that the minimum value of the internal magnetic field would be as that of Bs = 1012G i.e. the magnetic field configuration of PSRJ1119 – 6127 would be:

Surface magnetic field Bs = 4.1 x 1013 G, Internal magnetic fields strength (at least or minimum) $\gtrsim$2.59 x 1016G to $\gtrsim$1.47 x 1017G, Core magnetic field strength $\gtrsim$ 2.5 x 1018G.

This means that althoughPSRJ1119 – 6127 is a radio pulsar but realistic sense it is a magnetar- like due to its internal magnetic field configuration resulting which this pulsar is capable to exhibit the characteristics as magnetar does.

Triaxiality and Deformation of PSRJ1119-6127 due internal strong magnetic field

Introducing the strong magnetic field in the equation of state (EoS) Watanabe et al. [39] show the possibility to have a strong internal magnetic field ~ 1016G to 1017G and core magnetic field strength ~ 1018G in a rotating normal neutron star. This means that (i) internal magnetic field and core magnetic field are 4 to 5 order and 6 order magnitude, respectively more than the surface magnetic field which is feasible in realistic case as such high order magnetic fields are observed in magnetars. (ii) A normal rotating neutron star or pulsar with surface magnetic field Bs ~ 1012 G can be treated as magnetar-like star and can exhibit those characteristics as observed from a magnetar.

Estimation of Core Magnetic Field Strength of Pulsar (i.e. Neutron Star)

The general picture on the structure of a neutron star interior is divided into four regions: the surface or outer crust, the inner crust, the outer core and the inner core or central core. The precise region of the quantum chromodynamics (QCD) phase diagram inside the neutron star matter is not yet known. As a result, there are three popular models of neutron star structure:

- One possible model —is the neutron star baryon density is low enough such that it is composed of hadrons;
- The second one (quark star) model — the neutron star may exist in the region beyond the deconfined boundary i.e. neutron stars are primarily composed of "quarks" (so called "quark stars");
- The third one (hybrid) model — is near their surfaces the density of neutron star is low enough to hold hadrons but may be high enough in the deep interior to support deconfined quarks i.e. "hybrid stars".

In the core of hybrid model, at mass density greater than the drip density $\rho = 4 \times 1011 g/cm3$, neutrons begin to leak out of the nuclei so that the matter at highest densities of the inner crust is composed of primarily a neutron superfluid accompanied by some protons, electrons and a few muons [46]. With the increase of density, the outer core appears where matter is expected to be fluid containing various hyperons in stable form amongst the neutron fluid. Finally, the inner core at densities several times of the saturation density $\rho s = 2.8 \times 1014$ g/cm-3 which is leading to quark deconfinement i.e. the equilibrium composition and the equation of state (EoS) formed by an absolutely stable phase consisting of roughly equal numbers of up ('u'), down ('d') and strange ('s') quarks plus a small number of electrons to guarantee charge neutrality [47-49]. The main problem is in determining the phase of the quark matter inside the neutron star. Because the QCD is very difficult to solve at that temperature and high densities expected to arise in the neutron star core. As the neutron stars are expected to exist at moderate energies and finite densities there remain many questions (such as stiff EoS to attain larger maximum mass) to be answered.

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One of such important features of neutron star is the presence of strong magnetic fields. Studies of EoS in a uniform magnetic field [50,51] show an anisotropic i.e. with different pressure arising in the different directions along and transverse to the magnetic field, respectively. This implies that the transverse and longitudinal pressures were found when the quantum-statistical average of the energy momentum tensor is considered.

But in the case of realistic situation, the contribution of charged particles to be considered in calculating the EoS for many particle systems in a magnetic field. These charged particles will be affected (i) by the Landau quantization of their transverse momenta and (ii) by the interaction between the magnetic field with the particles' anomalous magnetic moment (AMM), while for (iii) neutral composite particles i.e. neutrons the contribution of AMM is present implying that neutrons in a magnetic field do not contribute towards the softening in the pressure whereas stiffen the system's EoS , if the pressure anisotropy and the Maxwell pressure are not considered.

Considering the facts:

- longitudinal pressure vanishes at sufficiently high magnetic fields;
- star's gravitational pressure is in magneto-hydrostatic equilibrium; and
- neutron matter pressure is anisotropic in the presence of a magnetic field,

recent investigations [52-55] show the maximum magnetic field strength inside the core of neutron star is ~ 1017 G. This value is an order of magnitude smaller than one obtained by considering the equipartition of the gravitational and magnetic energies in the framework of the scalar virial theorem which gives the maximum amount of the average magnetic field inside a star is ~ G M2 /R ~ B2 R3 /6 or B ~ 2 x 1018 G for a neutron star with mass M = 1.4 M⊙ and R = 10 km [56].

It is to be noted that neutron stars are considered as one of the possible remnants of supernova explosions and due to conservation of angular momentum and magnetic flux, the rotation frequencies and magnetic fields of these stars are amplified exceptionally reaching values of period (P) ~ 1 s and surface magnetic field (Bs) ~ 1012G, respectively. Even, the surface magnetic fields of some radio pulsars reaching of the order of 1013 – 1014 G [57] and for some special compact objects like magnetars this values are of the order of 1014 – 1015 G (inferred from spectroscopic and spin down studies of soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) [58].

Regarding inner magnetic field strength, the estimated value varies ranging from 1018G for nuclear matter stars to 1019 – 1020G for quark stars [59]. The effect of such strong magnetic fields on the equation of state (EoS) of neutron star matter has been studied by various authors under different formalisms. Significant findings are:

1. Sotani & TAtsumi 2015 [59]— For a rapidly rotating neutron star (i.e. pulsar) its spin down or spin up produces strong stresses and strains in the stellar crust. If the inner magnetic field strength is > 1018G or more, say 1019 – 1020G, then the resulting magnetic dipole is nearly orthogonal to the stellar spin which contrasts the situation of a spatially much more extended equatorial orthogonal moment (as expected in a spinning down millisecond pulsars) resulting which the stresses associated with the internal magnetic field (i.e. B2 / 8) exceeds the yield strength of the solid crust which finally leads to much more frequent glitches and outbursts.
2. Pais et al. 2021 [60] — They studied the structure of the bottom layers in the presence of a strong magnetic field and found the extension of the neutron star's crust is directly related when a liquid-gas type transition is present in the nuclear matter [61]. Their result confirms the extension of the inner crust and this extension may be larger than expected in the presence of magnetic field intensities of the order of 5 x 1016 G to 5 x 1017G.
3. Scurto et al. 2023 [62]— the purpose of their study is to determine the geometry and characteristics of the neutron star's crust inhomogeneity arises due to presence of strong Internal magnetic fields and observe through numerical simulation that the inner crust is almost unaffected for the field below 1016 G but only marginally affected for higher order fields.
4. Gomes et al. 2019 [63] — Their study was concentrated on the structure of neutron star because of poloidal magnetic field and to determine the limiting value of the largest magnetic field strength that induces a deformation between the polar and equatorial radii. They found a limiting magnetic moment ~ 2 x 1031Am2 (i.e. the corresponding magnetic field of the order of ~ 2 x 1016 G at the surface and ~ 8 x 1016G at the centre of the star) above which the deformation of neutron star is more than 2%. They have also found same effect for a dipole magnetic moment of ~ 5 x 1031 Am2 (i.e. corresponding to a surface magnetic field of the order of ~ 5 x 1016G and a central magnetic field of ~ (2 – 4) x 1017 G.

Finally, it can be said that the dipole magnetic moment of ~ 5 x 1031 Am2 is very crucial and the allowable core magnetic field strength is ~ (2 – 4) x 1017G that can produce a measurable deformation more than 2% of the star.

Estimation of Ellipticity

Ellipticity arises from strong magnetic field inside a rotating neutron (i.e. magnetar) can be estimated in different

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ways. For example:

The best fitting expression relating the ellipticity (ϵ) to the surface dipole magnetic field (Bs or Bdipole) of a neutron star (i.e. magnetar) (Xie et al [64]) is:

Log ϵ = – 22.50+2.15-2.22 + (1.29+0.15-0.14) log Bdipole (4)

While neutron star deformation (ϵ) induced by strong internal magnetic field (Binternal) in the stellar core (Majid et al [66], Rizaldy and Suloksono [66], Parui [21,31,67]) via the expression

ϵ 10 – 8 (Binternal / 1012) (5)

In this study I use the expression in calculating the ellipticity of a Magnetar like pulsar PSRJ1119-6127 (following de Araujo et al [67], for details see the text of this ref [67]) as

$$\varepsilon = \frac{3Ic^3}{4\pi^2 GM^2R^2} P\dot{P}K \qquad (6)$$

$$\varepsilon = \frac{3Ic^3 B_{cs}2}{4\pi^2 GM^2R^2\{3.2\times10^{19}\}^2} K \qquad (7)$$

where fiducial standard neutron star properties of I = 1045 g cm2, M = 1.4 M⊙, R =10 km are taken; P, Ṗ are known parameters, the distortion parameter k = 10 for realistic case. Bcs = the corresponding surface magnetic field for that dipole magnetic moment which produces core magnetic field strength ~ 1017G o of the star and measurable deformation more than 2%. Applying the above fiducial values and Bcs = 5 x 1016 G in the relation (7) the values of the ellipticity for PSRJ1119-6127 and PSRJ1824 –1744 are ϵ = 5.0019 x 10 – 8 and ϵ = 1.30331682 x 10 – 7, respectively.

Estimation of the Time Scale of Triaxiality

If we consider the model of uniform density ellipsoid with axis a1, a2 and a3 (parallel to the rotational axis Ω) then the limit can be expressed as one on the ellipticity(ϵ) as

ϵ = (a1 – a2) /a1 which is ≲ 10 – 7 – 10 – 8 [68] (8)

In this case, the sequence of equilibrium configuration of the object can be characterized by the single parameter i.e. the angular momentum (J) such that for small values of 'J', the configuration is axisymmetric (a1 = a2) which is known as Maclaurin spheroid (having eccentricity e 2 = (1 – a22/a12); With the increasing J, the sequence will be changed, and the new will be [68]

eb= 0.81267, and

the term (i.e. ratio of kinetic energy to gravitational energy) Ω2 / Gρ = 0.37423,

for Jb = 0.30375 (GM3<a> ½ (9)

where G = Gravitational constant, M = the mass, ρ = density and <a> = (a12 a3)1/3;

(c) If the sequence is bifurcated into two [according to Chandrasekhar [1] i.e. the previous or original axisymmetric (i.e. Maclaurin sequence) and the new one i.e. triaxial one (known as Jacobian ellipsoid). This means that when an object can be able to spin up to beyond the bifurcation value Jb (i.e. Ωb, eb) before breaking up (for example via equatorial mass shedding) at the critical value Jc (effective for a triaxial shaped object).

It is to be noted that these Jacobian ellipsoids have a special property (which makes remarkably different from Maclaurin spheroid) i.e. they spin up with the loss of angular momentum.

Now, in the case of newborn pulsar with a period 'P' the bifurcation ratio term is

Ω2 / Gρ =4 2 / p2Gρ ~ 0.3768 Pms- 2 ρ* - 1 (10)

where P= the bifurcation point, Pms = in millisecond and ρ* = 5 x 1014 g. c c – 1.

As the millisecond pulsars are very nearly axisymmetric with a very small value of ellipticity ϵ then at the exact bifurcation point

(Ω2 / G ρb = 0.37423, (11)

which gives the value of p = 1.003ρ* - ½ MS implying that millisecond pulsars are located just in the neighbourhood of the bifurcation point.

As our requirement is duration of triaxial shape (i.e. J >Jb) and under such situation gravitational radiation would remove angular momentum that leads to decrease in ellipticity but consequently an increase in angular momentum. Thus, the triaxial phase of this object will cover a time scale (t) (assuming ϵ will remain constant)

Ω4 (t) = Ωo4 / (1 + kt) (12)

where k ~ Ω4 (256/25) GM/c5. ϵ 2<a>2 = 2.763 x 10 – 7 (ϵ-82 / ρo*4) yr– 1(13)

Using the fiducial values of pulsars i.e.

M = 2 x 1033gm,

<a> = 10 km,

Ωo ~ 6.8 x 103 rad s – 1 at critical point, and

Ω (t) ~ 4.2 x 103 rad s – 1 at bifurcation point for ρ ~ 4 x 1014 g. cc – 1 (i.e. for stiff equation of state) one can obtain

t ~ 5.53 x 106 (1 / ϵ-82) yr- 1 (14)

In fact, in realistic case the ellipticity ϵ will change with Ω (i.e. Jacobi ellipsoid) but the value of "t" will give a plausible estimate for the time that the object would spend on the

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Jacobi sequence.

Estimated Triaxial Time Scale for Pulsar PSR J1119 - 6127

Putting the ellipticity value $\epsilon = 5.0019 \times 10 - 8$ in the equation (14) it gives t = 0.221031983 x 106yr = 2.21032 x 105 yr. This means that by allowing ϵ to be changed with Ω (Jacobian ellipsoid) the plausible estimated time scale is t = 2.21032 x 105 years implying that the object i.e. PSR J1119 – 6127 would spend on the Jacobian sequence with exhibiting its triaxial phase for a period of 2.21032 x 105 years. Since the characteristic age of this pulsar is $\tau = 1.6$ kyr meaning is there is a possibility that the PSR J1119 – 6127 would possess its triaxial phase for the next period of 212432 years (i.e. 221032 – 1600) or ~ 212.432kyr. Another point to be noted that the average value of the radius i.e. <a> will be = 0.68 km (the observed data) instead of considered value 10km. Thus, the value of time scale will be changed by a very small amounting that can be neglected.

Estimated Triaxial time scale for Pulsar PSR J1814 - 1744

Using the value of ellipticity $\epsilon = 1.30331682 \times 10 - 7$ in equation (14) one will obtain the value of t = 32515.55 yr. i.e. the possible period for exhibiting triaxiality is 32.51555 kyr. As the characteristic age of the pulsar PSR J1814 – 1744 is 85 Kyr implying that this PSR has already crossed the estimated time. In realistic case, a pulsar can exhibit its triaxial phase for a period of ~106yr [68]. So, if one considers such situation then there is a possibility that the pulsar PSR J1814 – 1744 have a time of 15,000 year (i.e. 1000,000 – 85,000) to continue further its triaxiality.

Transitional Time Period

In the realistic case a magnetar will show its triaxiality for a period of ~103 years while a high magnetic radio pulsar exhibits for a period of ~106 years [68]. This means that in the case of PSRJ1119-6127 it will exhibit its triaxiality for the next ~ 212 Kyr and the PSRJ1814-1744 will continue its triaxial phase for next 15000 years in realistic case Table 5.

Analysis of the observed data indicates that for a millisecond pulsar the spin down rate via gravitational wave radiation imposes the limit of ellipticity should be $\epsilon < 10 - 7 - 10 - 8$. According to Chau et al . [68] if a young pulsar, assumes a triaxial shape, and gravitational radiation reduces its ellipticity which drives the ϵ to change from Jacobian sequence to Maclaurin sequence then time period of its stay in Jacobian sequence ~ 106 years i.e. duration in triaxial phase of a pulsar is ~ 106 years. This means that a millisecond pulsar will exhibit its triaxiality with its ellipticity $\epsilon \sim 10 - 7 - 10 - 8$ for a period of ~ 106 years Table 6.

As the ellipticity (ϵ) of the millisecond pulsar PSRJ1119-6127 (with age ~ 1.6 year) and PSRJ1814-1744 (with age 85kyear) are within the range of triaxial phase i.e. $10 - 7 - 10 - 8$ then their triaxial phases will continue for the next ~212kyear and 15kyear, respectively. In other words, one can say that PSRJ1119 – 6127 and PSRJ1814-1744 are triaxial star. Note that, in the case of cosmic baby its aegis ~ 240 years. As the magnetar will exhibit its triaxial phase with ellipticity $\epsilon \sim 10\text{-}3 - 10\text{-}4$ for a period of few thousand years, Parui [32,42] suggested that cosmic baby will pass through its triaxial phase for at least next 760 years. Below a comparison is given for present studied high magnetic radio pulsars and magnetars.

Name of the Object (Type)	Spin Period (P)	Surface dipolar magnetic field (G)	Age	Internal core magnetic field (Binternal)	Ellipticity (ϵ)	Condition fulfilled for exhibiting Triaxial phase
PSRJ1119-6127 (High magnetic Radio Pulsar)	0.407 s	4.1 x 1013	1600 years	> ~ 2.5 x 1018 G (at least for one order)	7.216057 x 10 – 8	Satisfied
PSRJ1814-1744 (High magnetic Radio Pulsar)	3.975	5.5 x 1013	85,000 years	~ 2.5 x 1018 G	1.303316 x 10 – 7	Satisfied
Magnetar of GRB 130310A (magnetar)	80 Ms	1014 - 1015	2 weeks	3.95 x 1017	4.0 x 10-3	Satisfied
Cosmic Baby Swift J1818.0 – 1607 (Magnetar)	1.36 s	2.7 x 1014	240 years	8.5 x 1017	4.48 x 10-3	Satisfied
SGR1806-20 (Magnetar)	7.547s	20 x 1014	240 years	54.39 x 1017	5.439 x 10-2	Satisfied
1E1547.0-5408 (Magnetar)	2.0721 s	3.2 x 1014	690 years	11.4 x 1017	1.14 x 10-2	----------
PSRJ1846-0258 (Magnetar)	0.3265 s	0.49 x 1014	730 years	1.77 x 1017	1.77 x 10-3	----------

Table 5: Various parameters of High magnetic Radio Pulsars and Magnetars.

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Operative Mode	Initial mangetic field (Bo)	Initial core temperature (t)	At the considered time	Effective on core temperature
(a) Ambipolar diffusion decomposed intosolenoidal component i.e. solenoidal mode	1016 G	109 K	at t = 103 year at t = 106 year at t = 105 year	40 % higher than that if there is no decay. 10% higher. Neutron dominated cooling era leaves and photon emission dominated cooling begins. Core is heated but core decay is slow slightly.
(b) Irrotational mode i.e. decay is more slowly	10^{16} G	10^{9} K	at t = 10^{6} year	Cooling is more active and temperature reduces more. Neutron star is more pronounced.
(c) Hall drift is active , Ambipolar diffusion is unimportant	10^{15} G	10^{9} K	at t = 10^{5} year	Heating by magnetic field decay and cooling by neutrinos attainequilibrium as long as B > 10^{15} G. Photon cooling is active.
	Significant finding: Decay of magnetic field through ambipolar diffusion turns a new source of surface heating. In the case of ultra-magnetized neutron star i.e. magnetar thermal conduction is affected by magnetic field decay.			

Table 6: Important Results of Magnetar's Magnetic Field Decay as Obtained Heyl nd Kulkarni [77].

Preservation of Strong Magnetic Field by Millisecond Pulsar for Magnetar-like Activity

The important birth parameters fo studying the neutron star properties are rotation period (P), strength of magnetic field (B) and the velocity of neutron star. Based on the observation of Crab pulsar it was first thought that if neutron stars were born with their initial period of tens of millisecond, then their magnetic field strength would be confined within a narrow limit range of 1011 – 1012 G [69]. The next improved idea arose in 1996 when Usov and Melrose [70] proposed that pulsar wind dominated bound pair, rather than freely streaming electrons and positrons, would be capable to produce magnetic field more than 0.1 Bcr (where Bcr is the critical magnetic field ≈4.4 x 1013 G). In 1995 Thompson and Duncan [71] suggested the existence of a new form of neutron star (beyond millisecond pulsars), so called magnetar, with magnetic strength more than Bcr. Observational evidence of soft gamma repeaters (i.e. avariety of magnetar) and long-period pulsars in young supernova remnants [72,73] offered the following consequences:

- Soft X-ray emission is possible through magnetic field decay [74] and by neutron star cooling [75];
- In the case of magnetar the primary source of energy stored in magnetic field i.e. magnetic field decay leads to potentially detectable soft X-ray emission [74].

Studies [76,77] of magnetic field decay in isolated neutron stars showed three possible modes:

- Ohmic decay — dominates in weakly magnetized decay in neutron star (B ≲ 1011 G);
- Hall Drift —effective for intermediate field decay (B ~ 1012 – 1013 G);
- Ambipolar diffusion — active for mostly strong magnetic field (B≲ 1014 G).

In this context, Thompson and Duncan [74] suggested that an equilibrium between neutrino cooling and heating arises due to magnetic field decay is possible for magnetic field B ~ 1015 G and temperature T ~ 108 K.

Considering individual decay mode of magnetar's (i.e. neutron stars) core magnetic field Heyl and Kulkarni [77] obtained significant findings shown in Table 7.

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Operative Mode	Initial magnetic field (B_o)	Initial core temperature (t)	At the considered time	Effective on core temperature
(a) Ambipolar diffusion decomposed intosolenoidal component i.e. solenoidal mode	10^{16} G	10^9 K	at t = 10^3 year	40% higher than that if there is no decay.
			at t = 10^4 year	10% higher.
			at t = 10^6 year	Neutron dominated cooling era leaves and photon emission dominated cooling begins. Core is heated but core decay is slow slightly.
(b) Irrotational mode i.e. decay is more slowly	10^9 K	10^9 K	at t = 10^6 year	Cooling is more active and temperature reduces more. Neutron stars are more pronounced.
(c) Hall drift is active, Ambipolar diffusion is unimportant	10^{15} G	10^9 K	at t = 10^5 year	Heating by magnetic field decay and cooling by neutrinos attain equilibrium as long as B > 10^{15} G. Photon cooling is active.
Significant finding: Decay of magnetic field through ambipolar diffusion turns a new source of surface heating. In the case of ultra-magnetized neutron star i.e. magnetar thermal conduction is affected by magnetic field decay.				

Table 7: Important Results of Magnetar's Magnetic Field Decay as Obtained Heyl And Kulkarni [77].

In another investigation of magnetar's magnetic field decay Soni et al. [78] considered high temperature phase transition that occurs in the inner core of magnetar. This causes the following important results: This phase transition dynamically aligns the magnetic moments of all the neutrons resultiis unimportantnated cooling begins. Core is heated but core decay is slow slightingng which a large magnetic field is produced in the core. A large change of flux gives rise a situation such that it acts as a shielding or screening currents in the surrounding high conductivity plasma (i.e. envelope attached with the magnetar's surface) that do not allow the flux or field to exit to the surface.

On the other hand, ambipolar diffusion assists the field to transport or to reach to the crust that is capable to dissipate energy through neutrinos and X-rays. As a result, due to ohmic dissipation in the crust, the upwelling field cleaves in the form of flares and X-rays radiation until the screening currents are damped and the surface dipole field reaches to its final value (i.e. new one which is more than the earlier one).

Significant Findings of this Model

This model, considering ambipolar diffusion in the core, is capable to create large magnetic field strength than that of at the initial. The strength of the surface dipole magnetic field increases w.r.t. the dynamo and other models in which the strength of surface polar magnetic field decreases with time. This model is feasible at least in the aspect that in a millisecond pulsar (i.e. neutron star) its surface dipole magnetic field strength and core magnetic field could reach at the level of that of the magnetar to explain magnetar-like activities.

Significance of (Triaxial) PSR J1119 – 1627

The millisecond pulsar PSRJ1119-6127 draws attention to the astronomers for the following reasons:

1. Astronomers detected peculiar behaviour of magnetar-like activities from this millisecond pulsar as rotational radio-transient (RRAT).
2. These peculiar behaviours make the pulsar PSR J1119-6127 as an important source which may provide the possible clues for the missing link between the pulsars and magnetars.
3. As a radio transient this pulsar PSR J1119-6127 may provide valuable information regarding transient phase i.e. possible phase journey from pulsar to magnetar.
4. Astronomers believed that rotation powered pulsars have high surface magnetic field strength (B) > 4.4 x 1013 G. Recent detection of glitch and other pulse profiles originated from this pulsar PSR J1119-6127 confirm it.
5. A gamma ray source: In a study Johnston and Romani [80] found that few young energetic pulsars exhibiting a relatively strong individual pulses (not related to glitch), in particular to the trailing edge which can be dubbed as "giant micro pulses", a similar one as observed as the trailing edge of PSR B1706-44. The common characteristic of these micro-pulses observed in PSR J1119-6127 and PSR B1706-44 is that they are both detected at γ-ray energies [80]. Not only that the Ė of PSR J1119-6127 suggests that it might be a γ-ray source.
6. PSR J1119-6127 and PSR B0656+14 both share a link by exhibiting rotating radio transient (RRAT)-like emission i.e. both pulsars provide a link between the "Normal "pulsar and the RRAT-like pulsars. The characteristics exhibited by the pulsar PSR J1119-6127 are like that of the other pulsars: A chart is given below in Figure 2.

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PSR J1119-6127 and its Triaxiality	↗	Spin parameters ($\tau c = 0.8$ kyr, $B \approx 4 - 5 \times 10^{13}$ G) are very similar for PSR J1119-6127 and PSR J1846-0258 (Yuan et al. [81])
	↗	Young pulsars normally exhibit smaller glitches which is applicable for Crab pulsar and PSR J1119-6127 (Wang et al. [82])
	→	Shows anomalous glitch recoveries for very large glitches as in the case of PSR B0355+54, PSR B2334+61, PSR B1800-21
	↘	Anomalous recovery the glitches having a single connected event for PSR J1846-0258, PSR J1819-1458
	↘	Glitch model involving the Physics of the interior i.e. glitches produced by a sudden transfer of angular momentum from the inner neutron superfluid to the solid crust: for PSR B1737-30 (Johnston, Ẅisberg [83])
	↘	Glitch Model: Pulse profile in double peak mode has striking similarities with a group of young pulsars, energetic wide beam pulsars i.e. relatively wide double peaked profile with steep inner edge and a high degree of linear polarization. For example: PSR J1015-5719, PSR J1105-6107, PSR J1420-6048

Figure 2: Shows Various Parameters / Properties are Similar between PSR J1119-6127 and other Pulsars Indicating a Possible Link that Need Further Investigation Possibly based on Triaxiality.

Conclusion

The evolution of magnetic field in millisecond pulsars is not clearly understood. But these stars have relatively small surface magnetic field (Bs) ~ 10 8 G compared to the young population of radio pulsars i.e. 1011<Bs< 1013 G. Study of tantalizing population [84] shows as evidence that millisecond pulsars have a minimum ellipticity of $\epsilon \approx 10 - 9$ around their spin axis, and spin down arises due to mostly through gravitational wave emission. Regarding triaxial nature of this PSRJ1119 – 6127 Chau et al. [68] suggested that ellipticity would be ~ 10 – 7 – 10 – 8 (which is above the value of minimum ellipticity) and duration of exhibiting of the triaxiality's ~ 212kyr. Discovery of cosmic baby shows evidence of youngest magnetar with age ~ 240 years in comparison to the detected other magnetars whose ages around ~ million years. This magnetar is suggested as "first evidence of Triaxial Star" [21] and its triaxial phase will continue for next ~ 760 years. In this context, the estimated values hint that PSRJ1119 – 6127 will exhibit its triaxial nature for the next ~ 212kyears and in realistic casePSRJ1814 – 1744 for 15k years following the behaviour of cosmic baby.

Acknowledgement

The author is greatly indebted to the anonymous reviewers for their value comments and suggestions. He expresses his sincere gratitude to Dr T Shetty for her kind inspiration. He is grateful to Prof. Chris Linttot, Dept. of Physics, Oxford University, UK for his valuable suggestions. He wishes to thank Prof. H N K Sarma, Dept. of Physics, Manipur University, B K Ganguly, Mrs. Tapati Parui and specially to Rajarshi Parui for his help in computer works.

Data Availability

Data sharing is not applicable as no data sets were analysed.

References

1. Chandrasekhar S (1969) Ellipsoidal Figures of Equilibrium. Yale University Press, New Haven, USA, pp: 252.

2. Vajiram (2026) The Standard Model of Particle Physics.

3. Saraswat PK (2023) The Standard Model of Particle Physics: Limitations and Beyond. Tuijin Jishu J Propul Technol 44(4): 716-727.

4. Haber HE, Kane GL (1985) The Search for Supersymmetry: Probing Physics Beyond the Standard Model. Phys Rep 117(2–4): 75-263.

5. Paudel ER (2021) Problems of Standard Model, Review. BMC J Sci Res 4(1): 65-73.

6. Gagnon P (2014) The Standard Model: A Beautiful but Flawed Theory. Quantum Diaries.

7. Parui RK (2023) A Remark on "Do Triaxial Supermassive Compact Star Exist?" Int Astron Astrophys Res J 5(1): 33-37.

8. Parui RK (2024) Commentary on "Cosmic Baby and the Detection of a New Compact Star—the 'Triaxial Star': A Possibility". J Nanotechnol Nanomaterials 5(2): 56-60.

9. Parui RK (2024) New Astronomy with the Swift

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Observatory: Discovery of Cosmic Baby, Supernova explosion and other Extremes. Open J Astron 2(2): 000118.

10. Parui RK (2026) Cosmic Baby and the Detection of a Neo-Natal Triaxial Star: A Possibility. Int J Sci Res 15: 1697.

11. Parui RK (2026) Cosmic Baby, Neutron Star and the Extreme Precision. Iris Online J Sci 2: 000532.

12. Saikumar D (2024) Exploring the Frontiers: Challenges and Theories Beyond the Standard Model. arXiv 2404: 03666.

13. Bonazzola S, Frieben J, Gourgoulhon E (1996) Triaxial Neutron Star — A possible source of Gravitational adation. In Proc. XXXIRenContres de Moriond — Dark matter in Cosmology, Quantum Mechanics and Experimental Gravity. Les Arces, France, pp: 389: 373.

14. Bonazzola S, Gourgoulhon E, Grandelement P, Novak J (2003) Constraints scheme for Einstein equation based in Dirac gauge and spherical candidates. Phys Rev D 70: 10400.

15. Chandrasekhar S, Miller JC (1974) On slowly rotating homogeneous masses in General Relativity. MNRAS 167: 63-80.

16. Bonazzola S, Frieben J, Gourgoulhon E (1998) Spontaneous symmetry breaking of rapidly rotating stars in general relativity: influence of the 3D-shift vector. Astron Astrophys 331: 280-290.

17. Friedman JL Stergiouslas J (2013) Rotating relativistic stars. Cambridge University Press, UK, pp: 409.

18. Straumann N (2013) General Relativity. Springer, Netherland, pp: 736.

19. Esposito P, Rea N, Borghese A, Coti Zelati FC, Viganò D, et al. (2020) A Very Young Radio-loud Magnetar. Astrophys J Lett 896(2): L30.

20. Camilo F, Kaspi VM, Lyne AG, Manchester RN, Bell JF, et al. (2000) Discovery of Two High-Magnetic-Field Radio Pulsars. Astrophys J 541(1): 367-373.

21. Parui RK (2023) A New Compact Star—the "Triaxial Star"—and the Detection of a Cosmic Baby: A Possibility. Int Astron Astrophys Res J 5(1): 38-47.

22. Göğüş E, Lin L, Kaneko Y, Kouveliotou C, Watts AL (2016) Magnetar-like X-ray bursts from a rotation-powered pulsar, PSR J1119–6127. Astrophys J Lett 829(2): L25.

23. Dai S, Johnston S, Weltevrede P, Kerr M, Burgay M, et al. (2018) Peculiar spin frequency and radio profile evolution of PSR J1119–6127 following magnetar-like X-ray bursts. MNRAS 480(3): 3584-3594.

24. Mignani RP, Perna R, Rea N, Israel GL, Mereghetti S, et al. (2007) VLT/NACO observations of the high-magnetic field radio pulsar PSR J1119–6127. Astron Astrophys 471(1): 265-270.

25. Gonzalez ME, Safi-Harb S (2003) Chandra Detection of the High Magnetic Field Radio Pulsar J1119–6127 in the Supernova Remnant G292.2–0.5. Astrophys J Lett 591(2): L143-L146.

26. Blumer H, Safi-Harb S, McLaughlin MA (2017) PSR J1119–6127 and Its Pulsar Wind Nebula Following the Magnetar-like Bursts. Astrophys J Lett 850(1): L18.

27. Wang HH, Lin LCC, Dai S, Takata J, Li KL, et al. (2020) A Multiwavelength Study of PSR J1119–6127 after 2016 Outburst. Astrophys J 902(2): 96.

28. Gonzalez ME, Kaspi VM, Camilo F, Gaensler BM, Pivovaroff J, et al. (2007) PSRJ1119-6127 and the X-ray emission from high magnetic field radio pulsars. Astophys Sp Sci 308: 89-94.

29. Gehrels N, Chincarini G, Giommi P, Mason KO, Nousek JA, et al. (2004) The Swift Gamma-Ray Burst Mission. Astrophys J 611(2): 1005-1020.

30. Esposito P, Rea N, Borghese A, Coti Zelati FC, Vigano D, et al. (2020) A Very Young Radio-loud Magnetar. Astrophys J Lett 896(2): L30.

31. Parui RK (2023) Cosmic Baby and the Detection of a New Compact Star – the "Triaxial Star": A Possibility. Astrophys Space Sci 368(6): 46.

32. Kaspi VM, Beloborodov AM (2017) Magnetars. Annu Rev Astron Astrophys 55(1): 261-301.

33. Thompson C, Duncan RC (1996) The Soft Gamma Repeaters as Very Strongly Magnetized Neutron Stars. II. Quiescent Neutrino, X-Ray, and Alfvén Wave Emission. Astrophys J 473(1): 322-342.

34. Pearlman AB, Majid WA, Prince TA (2019) Observations of Radio Magnetars with the Deep Space Network. Adv Astron: 6325183.

35. Olausen SA, Kaspi VM (2014) The McGill Magnetar Catalog. Astrophys J Suppl Ser 212(1): 6.

36. Woods PM, Thompson C (2006) Soft Gamma Repeaters and Anomalous X-Ray Pulsars: Magnetar Candidates. In: Lewin WHG, van der Klis M (Eds.), Compact Stellar X-Ray

Copyright© Parui RK.

Sources. Cambridge University Press, Cambridge, UK, pp: 547-586.

37. Archibald RF, Kaspi VM, Tendulkar SP, Scholz P (2016) A magnetar like bursts from a high B radio pulsar. Astrophys J 829: L20.

38. Livingstone MA, Kaspi VM, et al. (2006) A Braking Index for the Young, High Magnetic Field, Rotation-Powered Pulsar in Kesteven 75. Astrophys J 647: 1286.

39. Watanabe C, Yoshinaga N, Ebata S (2022) Equation of state for hadronic matter and mass radius relations of neutron stars with strong magnetic fields. Universe 8: 48.

40. Fartin M, Avancini SS, Providencia C, Vidana I (2017) Hypernuclei and massive neutron stars. Phys Rev C 95: 065803.

41. Casali RH, Castro LB, Menezes DP (2014) Hadronic and Hybrid stars subjected to density dependent magnetic field. Phys Rev C 89: 015805.

42. Bandyopadhyay D, Chakraborty S, Pal S (1997) Quantizing magnetic field and quark hadron phase transition in a neutron star. Phys Rev Letter 79: 2176.

43. Miller MC, Lamb FK, Dittmann AJ, Guillot S, Lattimer JM, et al. (2019) PSRJ0039+0451 Mass and radius from NICER data and implication for the properties of neutron star matter. Astrophys J Lett 887: L24.

44. Annala E, Gorda T, Kurkela A, Vuorinen A (2018) A Gravitational wave constraints on the neutron star matter Equation of State. Phys Rev Lett 120: 172703.

45. Miller MC, Lamb FK (2016) Determining Neutron star properties by fitting oblate-star waveform models to x-ray burst oscillations. European Physical Journal A52: 63.

46. Baym G (1971) Groung state of Matter at high Densities. Astrophys J 170: 299.

47. Farhi E, Jaffe RL (1984) Strange matter. Phys Rev D 30(11): 2379-2390.

48. Haensel P, Zdunik JL, Schaeffer R (1986) Strange Quark Star. Astron Astrophys 160: 121.

49. Alcock C, Farhi E, Olinto A (1986) Strange Stars. Astrophys J 310: 261-272.

50. Ferrer EJ, Incera DLV, Keith JP, Portillo I, Springsteen PL, et al. (2010) Equation of state of a dense and magnetized fermion system. Phys Rev C 82: 065802.

51. Canuto V, Chiu HY (1968) Quantum theory of an electron gas in intense magnetic fields. Phys Rev 173: 1210.

52. Ferrer EJ, Incera DLV, Paret DM, Martínez AP, Sanchez A, et al. (2015) Insignificance of the anomalous magnetic moment of charged fermions for the equation of state of a magnetized and dense medium. Phys Rev D 91: 085041.

53. Broderick A, Prakash M, Lattimer JM (2000) The Equation of State of Neutron Star Matter in Strong Magnetic Fields. Astrophys J 537(1): 351.

54. Chakraborty S (1996) Quark Matter in Strong Magnetic Field. Phys Rev D 54: 1306-1316.

55. Manreza Paret D, Perez Martinez A, Ferrer EJ, de la Incera V (2014) Effects of AMM on the EoS of magnetized dense systems. Astron Nachr 335(6-7): 685-690.

56. Dong L, Shapiro SL (2013) Cold Equation of State in a Strong Magnetic Field: Effects of Inverse beta -Decay. Astrophys J 383: 745.

57. Livingstone AM, Kaspi VM (2011) Long-Term X-ray monitoring of the young pulsar PSR B1509−58. Astrophys J 742(1): 31.

58. Tiengo A, Esposito P, Mereghetti S, Turolla R, Nobili L, et al. (2013) A variable absorption feature in the X-ray spectrum of a magnetar. Nature 500: 312-314.

59. Sotani H, Tatsumi T (2015) Massive hybrid quark stars with strong magnetic field. MNRAS. 447(4): 3155-3161.

60. Pais H, Bertolino B, Fang J, Wang X, Providencia C, et al. (2021) Strong magnetic fields, Neutron star with an extended inner crust. Euro Phys J A 57: 193.

61. Muller H, Serot BD (1995) Phase transitions in warm, asymmetric nuclear matter. Phys Rev C52: 2072.

62. Scurto L, Pais H, Gulminelli F (2023) Strong magnetic fields and Pasta phases reexamined. Phys Rev C 107: 045806.

63. Gomes RO, Pais H, Dexheimer V, Providencia, Schramm S, et al. (2019) Limiting magnetic field for minimal deformation of a magnetized neutron star. Astron Astrophys 627: A61.

64. Xie L, Wei DM, Wang Y, Jin ZP (2022) Constraining the ellipticity of newborn magnetar with the observational data of long GRBs. Astrophys J 934(2): 125.

65. Majid WA, Pearlman AA, Prince TA, Naudet CJ Bansal K, et al. (2022) Flattening of Swift J1818.0-1607's spectral

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index via dual radio frequency observation with the Deep Space Network.

66. Rizaldy R, Sulaksono A (2018) Magnetized deformation of neutron star, in Proc. 3rdPadjadjaran Int. Phys Conf Symp J of Phys Conf Ser 1080(1): 012031.

67. Araujo deJCN, Coelho JG, Costa CA (2017) Gravitational Waves from pulsars in the context of magnetic ellipticity. Euro Phys J C77: 350.

68. Chau WY, Cheng KS, Zhang JL (1992) Remarks on Triaxiality spin up and magnetic field obliquity of some millisecond pulsars. Astrophys J 390: 486-488.

69. Narayan R (1987) The Birthrate and Initial Spin Period of Single Radio Pulsars. Astrophys J 319: 162.

70. Usov VV, Melrose DB (1996) Bound Pair Creation in Polar Gaps and Gamma-Ray Emission from Radio Pulsars. Astrophys J 464: 306.

71. Thompson C, Duncan RC (1995) Soft gamma repeaters as very strongly magnetized neutron stars. MNRAS 275: 255.

72. Vasisht G, Gotthelf EV (1997) The Discovery of an Anomalous X-Ray Pulsar in the Supernova Remnant Kes 73. Astrophys J 486: L129.

73. Kulkarni SR, Frall DA (1993) Identification of a supernova remnant coincident with the soft γ-ray repeater SGR1806 – 20. Nature 365: 33.

74. Thompson C, Duncan RC (1996) The Soft Gamma Repeaters as Very Strongly Magnetized Neutron Stars. II. Quiescent Neutrino, X-Ray, and Alfvén Wave Emission. Astrophys J 473: 322.

75. Heyl JS, Hernquist L (1997) The Thermal Evolution of Ultramagnetized Neutron Stars Astrophys. J 491: L95.

76. Goldreich P, Reisenegger A (1992) Magnetic Field Decay in Isolated Neutron Stars. Astrophys J 395: 250.

77. Heyl JS, Kulkkarni SR (1998) How common are magnetars ? The consequences of magnetic field decay. Astrophys J 506: L61.

78. Soni V, Bhattacharya D, Patel S, Gupta S, Bera P, et al. (2019) Magnetar signature – the U curve. MNRAS 482: 5336.

79. Johnston S, Romani R (2002) Simultaneous single-pulse observations of radio pulsars. MNRAS 332: 109.

80. Abdo A, Ackermann AM, Ajello M, Atwood WB (2010) The First Fermi Large Area Telescope Catalog of Gamma-Ray Pulsars. Astrophys J Suppl 187: 460.

81. Yuan JP, Manchester N, Wang P (2010) Astrophys J 719: 111.

82. Wang N, Manchester RN (2000) Glitches in southern pulsars. MNRAS 317: 843.

83. Johnston S, Weisberg JM (2002) A search for giant pulses in Vela-like pulsars MNRAS 332: 109.

84. Woan G, Pitkin MD, Haskell B, Jones DI, Laksy P, et al. (2018) Evidence for a Minimum Ellipticity in millisecond pulsars. Astrophys J Lett 863: L40.

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