Plasma magnetosphere of slowly rotating magnetized neutron star in branewold

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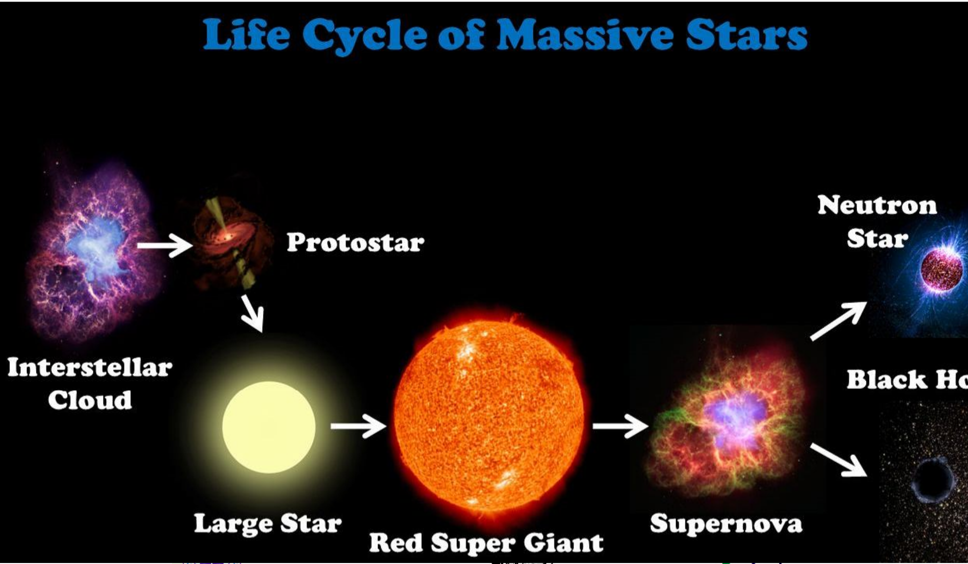
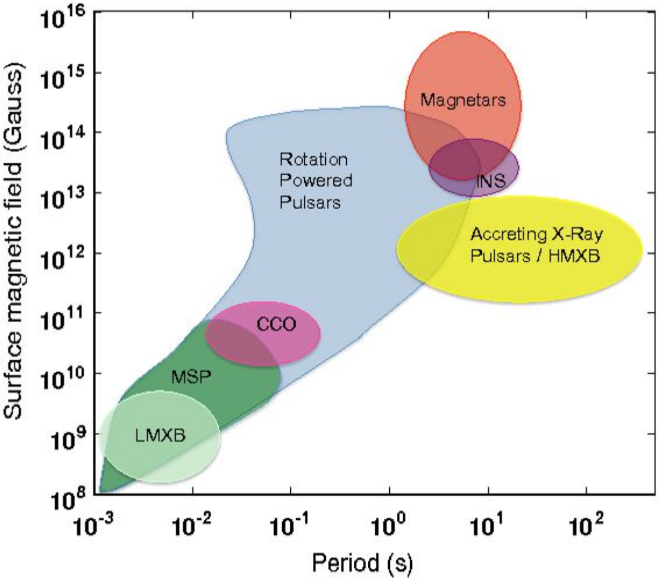
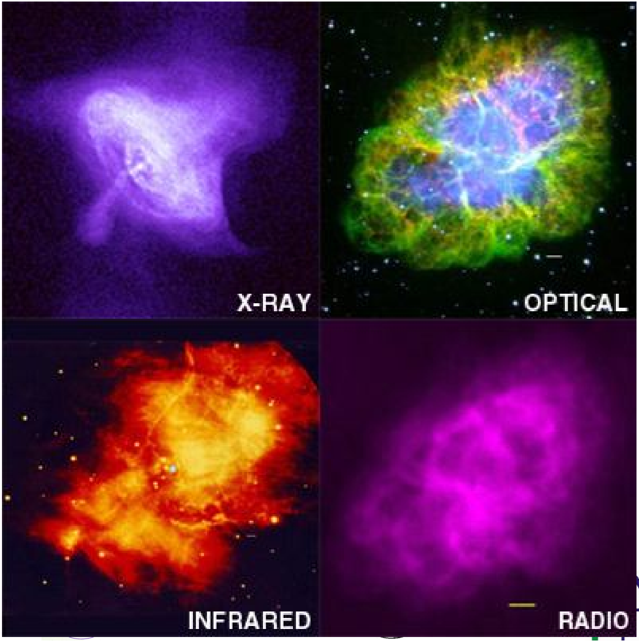
Object	B-field (Gauss)
Galactic nuclei	10^{-2}-10^{-3}
Our Galaxy	$2x10^{-6}$
Planets:	
Jupiter	4
Earth	0.6
Sun (general field)	1
(sunspots)	4,000
Common iron magnet	100
Common MRI field	10,000
Strongest SUSTAINED Lab fields	$4.5x10^{5}$
Strongest man-made B	10^{7}
Radio Pulsars	10^{12}-10^{13}
Magnetars	10^{14}-10^{15}


Life Cycle of Massive Stars
Interstellar Cloud
Protostar
Large Star
Red Super Giant
Supernova
Neutron Star
Black Ho


Magnetars
Rotation
Powered
Pulsars
INS
Accreting X-Ray
Pulsars / HMXB
CCO
MSP
LMXB
Surface magnetic field (Gauss)
Period (s)
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}


X-RAY
OPTICAL
INFRARED
RADIO

Gravitational collapse of the magnetized star

Due to conservation of magnetic flux during collapse

$$BR^2 = const \Rightarrow B = B_0 \left(R_0/R\right)^2$$

in the nonrelativistic limit magnetic moment $\mu \sim BR^3$ decays as

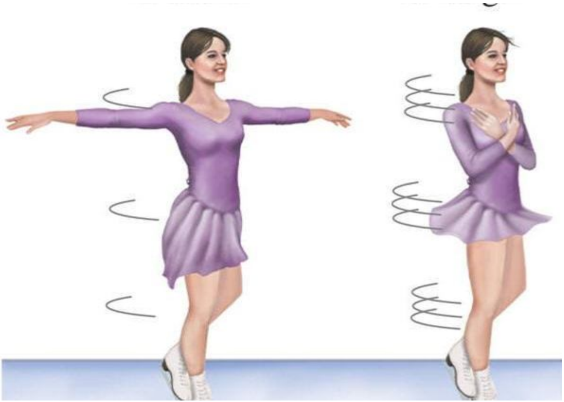
$$\mu = \mu_0 \left(R/R_0\right) \Rightarrow \lim_{R \to 0} \mu = 0 \ .$$

In GR during collapse magnetic moment decays as

$$\mu(t) = \mu_0 \left(4M^2/3R_0 ct\right) \ ,$$

and exterior magnetic field should decay with t^{-1} (Ginzburg & Ozernoy 1964, Anderson & Cohen 1970, Zeldovich & Novikov 1971). The correct decay rate at late times of an initially static dipole electromagnetic radiation field outside a black hole is $t^{-(2l+2)}$ (Price 1972, Thorne 1971).

Why so fast?



Fast rotation of NS is due to conservation law of moment inertia $I\Omega^2 = const \Rightarrow \Omega = \Omega_0(R^2/R_0^2)$

$R_0 = 10^6\text{km},\ P_0 = 30\text{day},\ R = 10\text{km},\ P = \frac{R^2}{R_0^2}P_0 = \frac{10^2}{10^{10}}30\text{day} \simeq 0.3\text{ms}$

Pulsar-Energetics

The kinetic energy of a spinning neutron star: $E = \frac{I\Omega^2}{2} = \frac{2\pi^2 I}{P^2}$, where $I = \kappa M R^2$ and κ is relativistic correction to inertia of NS, in Newtonian case $\kappa = 2/5$.
Energy loss would lead to period change, implying

$$\frac{dE}{dt} = -\frac{4\pi^2 I \dot{P}}{P^3}$$

It is for Crab pulsar $P = 33ms$, and $P^{-1}\dot{P} \sim 10^{-11}\mathrm{s}^{-1}$
Suppose that $M = 1.4M_{\odot}$ and $R = 10\mathrm{km}$
This gives $I = 1.1 \times 10^{45}\mathrm{g} \cdot \mathrm{sm}^2$, $dE/dt \sim -4 \times 10^{38}\mathrm{erg/s}$

In fact that the X-ray luminosity of the Crab nebula is observed to be $L_x \sim 1.5 \times 10^{37}\mathrm{erg/s}$
Thus, the energy extraction from the rotation of the central star is sufficient to power the Crab nebula
The characteristic age of a pulsar (assuming that the energy loss is due to magnetic dipole radiation) is given by $2\tau = P\dot{P}^{-1}$, and it is for the Crab pulsar($\dot{P} = 4 \times 10^{-14}$) $\tau \simeq 1300\mathrm{yr}$

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Landau's prediction

Landau improvised the concept of neutron stars in a discussion with Bohr and Rosenfeld just after the news of the discovery of the neutron reached Copenhagen in February 1932. The discussion must have taken place in March 1931, before the discovery of the neutron, and that they, in fact, discussed the paper written by Landau in Zurich in February 1931 but not published until February 1932 (Phys. Z. Sowjetunion 1, 285). In this paper, Landau mentioned the possible existence of dense stars that look like one giant nucleus; this could be regarded as an early theoretical prediction or anticipation of neutron stars, albeit prior to the discovery of the neutron.

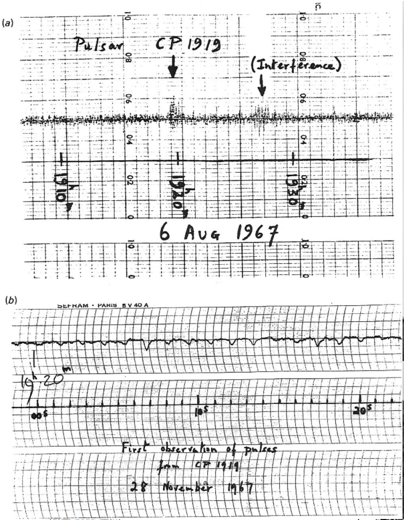
Baade and Zwicky – Prediction

W. Baade (Mt. Wilson Observatory)
F. Zwicky (Caltech)

The meeting of American Physical Society
(Stanford, December 15-16, 1933)
Published in Physical Review
(January 15, 1934)

38. Supernovae and Cosmic Rays. W. Baade, *Mt. Wilson Observatory*, and F. Zwicky, *California Institute of Technology.*—Supernovae flare up in every stellar system (nebula) once in several centuries The [illegible] er-nova is about twenty days and its absolute brightness a maximum may be as high as $M_{vis} = -14^M$. The visibl radiation L_ν of a supernova is about 10^8 times the radiatio of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculation indicate that the total radiation, visible and invisible, i of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The super-nova therefore emits during its life a total energy $E_\tau \geq 10^5 L_\tau = 3.78 \times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, E_τ / c^2 is of the same order as M itself. In the *supernova* process *mass in bulk is annihilated.* In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae.* Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order $\sigma = 2 \times 10^{-3}$ erg/cm² sec. The observational values are about $\sigma = 3 \times 10^{-3}$ erg/cm² sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

Discovery of NS in survey



A. Hewish, S. J. Bell, J. D. Pilkington, P. F. Scott, and R. A. Collins, Nature 217, 709 (1968)

NSs

- RADIO PULSARS: more than 2200 discovered to date
- Radiate covering most of the electromagnetic spectrum
- Rotate with periods that span five decades (ms to a few hours)
- Are powered by their own rotational energy, residual surface heat or accretion
- Live tens of millions of years

Magnetars (about 30 (including candidates) discovered to date: http://www.physics.mcgill.ca/ pulsar/magnetar/main.html)

- Magnetars are magnetically powered, rotating neutron stars
- Radiate almost entirely in X-rays, with luminosities 10^{33} to 10^{36} erg/s
- Emit typically brief (1-100 ms) bursts and very rarely, Giant Flares
- Rotate in a very narrow period interval (2-11 s) and slow down faster than any other object (10^{-10}-10^{-11} s/s^{-1})
- Powered by MF energy, which heats the NS and the surface glows persistently in X-rays, and fractures the crust inducing short, repeated bursts
- Die rather young; typical ages are 10 000 yrs

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The Vacuum model

EMF of rotating dipolar magnetized non-relativistic star studied by Deutsch in 1955

Ginzburg & Ozernoy (1964) and Anderson & Cohen(1970) had studied the EMF of relativistic magnetized star in Schwarzschild spacetime.

Kojima and Konno (2000) has studied GR modifications of a rotating NS's EMF and it is shown that the general relativistic effects make magnetic field of neutron star stronger than its Newtonian values

L.Rezzolla, B.Ahmedov and J.Miller (2001,2004) had studied EMF configurations and occillations of slowly rotating magnetized NS in detail, finding exact solution of Maxwell equation in the slowly rotating spacetime.

The Plasma Magnetospheric model

The plasma magnetosphericmodel of the NS was first presented in the pioneering paper by Goldreich & Julian (1969) and hitherto, mechanisms of generating plasma magnetosphere and radiation processes had been developed by several authors.

Influence of non-zero inclination angle of the NS to G-J charge density and accelerating electrical fields was checked for the small-polar angle approximation cases by Muslimov & Tsygan in 1992.

Influence of nonvanishing NUT parameter of the plasma magnetosphere of the NS was studied by Morozova et.al in 2008

The influence of spacetime deformation to the G-J charge density, accelerating field and radiation of NS has been considered in our previous work

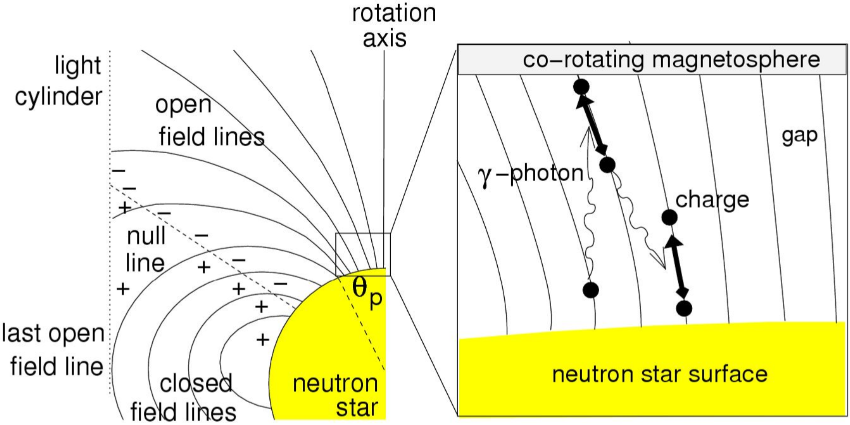
J.R. Rayimbaev, B.J. Ahmedov, N.B. Juraeva, A.S. Rakhmatov, **Astrophys Space Sci** (DOI 10.1007/s10509-014-2208-0), Volume 356, Issue 2, pp.301-308 (2015)

NS plasma magnetosphere

EF on the Star Surface:

$$E \propto \frac{\Omega R}{c} B \propto \frac{\Omega \xi}{c} B \propto 10^{10} \mathrm{V} \cdot \mathrm{cm}^{-1}$$

Goldreich & Julian, 1969, Astrophys.J, 157, 869
Cascade generation of electron-positron plasma leads to formation of MS with plasma screening longitudinal EF.
Plasma is corotating with the neutron star.
Charges along open field lines create plasma modes.


rotation
axis
light
cylinder
open
field lines
null
line
last open
field line
closed
field lines
neutron
star
θ_p
co–rotating magnetosphere
gap
γ–photon
charge
neutron star surface

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Slowly rotating spacetime metric in braneworlds

$$ds^2 = -N^2 dt^2 + N^{-2} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 - 2\omega r^2 \sin^2\theta d\phi dt \ . \qquad (1)$$

$N^2 = 1 - 2M/r + Q/r^2$ is lapse function (at $r >= R$) R and M-radius and mass of the NS,$\omega = \omega_{\rm LT}(1 - Q/2Mr)$ - angular velocity of the dragging of inertial frame in the braneworld , $\omega_{\rm LT} = 2aM/r^3$ is the Lense-Thirring angular velocity, $\eta = r/R$ is the dimensionless radial coordinate, $\varepsilon = 2M/R$ is the compactness parameter,
$\beta = I/I_0$ is the moment of inertia of the star in units of $I_0 = MR^2$ and $\kappa = \varepsilon\beta$ and we have introduced the new dimensionless brane parameter $b = |Q^*|/M^2$

Goldreich-Julian charge density

$$\rho^*_{\rm GJ} \simeq \frac{\Omega B_0}{2\pi c \eta^3 N_*}\frac{f_*(\eta)}{f_*(1)}\left[\left(1-\frac{\kappa}{\eta^3}W_*\right)\cos\chi+\frac{3}{2}H_*(\eta)\theta\sin\chi\cos\phi\right] , \quad (2)$$

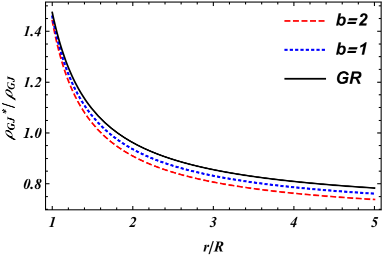
where χ is the angle between magnetic dipole moment and rotational axis

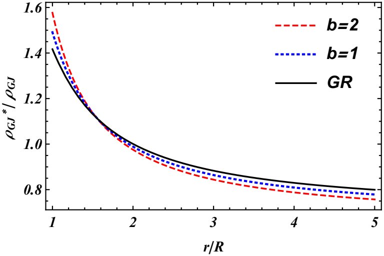
Charge density ρ which is proportional to MF with the proportionality coefficient being constant along the given MF line

$$\rho^* = \frac{\Omega B_0}{2\pi c}\frac{1}{\eta^3 N_*}\frac{f_*(\eta)}{f_*(1)} \times \left(C_*(\xi)\cos\chi + D_*(\xi)\sin\chi\cos\phi\right) , \quad (3)$$

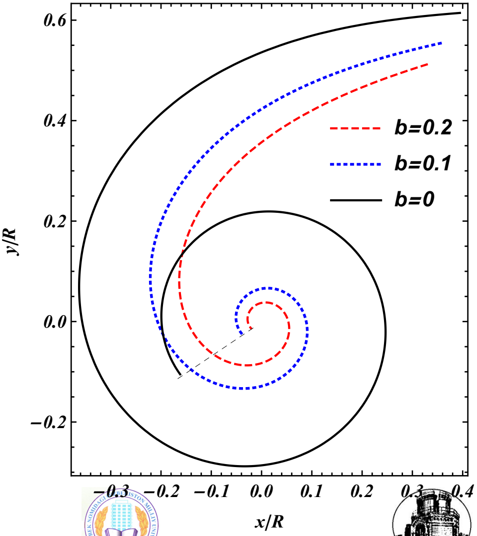
where $C_*(\xi)$ and $D_*(\xi)$ are the functions of the normalized angle ξ which can be found from the boundary conditions.

Electric Charge Density in MS





Particle motion in polar cap region in $x-y$ plane



EM scalar potential

Poisson equation in braneworld

$$\nabla \cdot \left(\frac{1}{N_*} \nabla \Phi_* \right) = -4\pi(\rho^* - \rho^*_{\rm GJ}) \ , \qquad (4)$$

GR EM scalar potential, which is valid at angular distances $\Theta_0 << \eta - 1 << R_c/R_s$:

$$\begin{aligned} \Phi_* &= \frac{1}{2}\Phi_0 \kappa \Theta_0^2 \left[1 - \frac{1}{\eta^3} + \frac{\epsilon b}{4}\left(1 - \frac{1}{\eta^4}\right)\right](1-\xi^2)\cos\chi \\ &+ \frac{3}{8}\Phi_0\Theta_0^3 H_*(1)\left(\frac{H_*(\eta)\Theta_*(\eta)}{H_*(1)\Theta_0} - 1\right)\xi(1-\xi^2)\sin\chi\cos\phi \ , \end{aligned} \qquad (5)$$

with

$\Phi_0 = B_0 \Omega R^2$, $\Theta_0 = \sin^{-1}(R/R_{\rm LC})^{1/2}$ where $R_{\rm LC} = c/\Omega$ is the radius of the light-cylinder

Accelerating electrical field

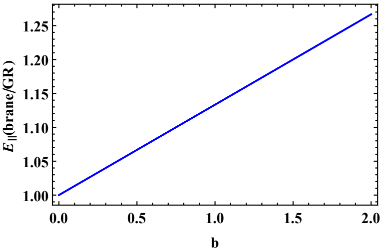
EF $E_{\|}$ is

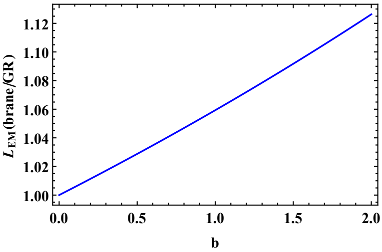
$$E^{*}_{\|} = -\frac{3}{2}\Phi_0\kappa\Theta_0^2\frac{1}{\eta^4}\left(1+\frac{\epsilon b}{3\eta}\right)(1-\xi^2)\cos\chi$$
$$-\frac{3}{8}\Phi_0\Theta_0^2 H_*(\eta)\Theta_*(\eta)\delta_*(\eta)\xi(1-\xi^2)\sin\chi\cos\phi \quad (6)$$

Energy losses

$$\frac{L^{*}_{\rm EM}(\chi=0)}{L^{*}_{\rm EM}(\chi=\pi/2)} \simeq \frac{8\times10^4}{\pi}\frac{\sqrt{f_*(1)}}{H_*(1)}\kappa(1-\kappa)P \quad (7)$$

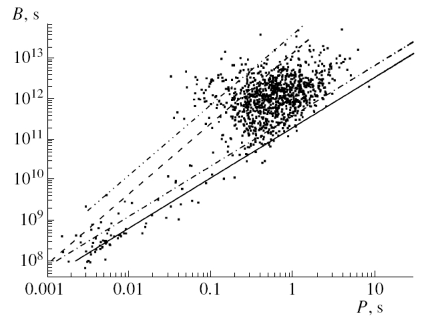
Energy Losses

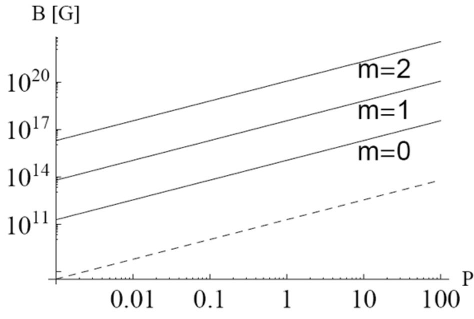




Transition from the OFF to the ON state of intermittent pulsar could correspond to the reactivation of a 'dead' pulsar above 'death line' (Zhang, Gil & Dyks, 2007)

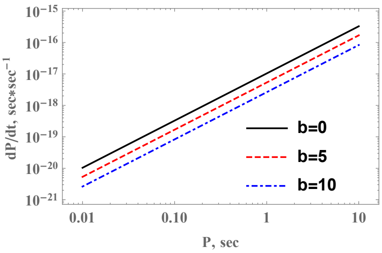
Death line is the $P - \dot{P}$ or $P - B$ diagram which indicates the region where pulsar can support radio emission from magnetosphere (Kantor, Tsygan, 2004).

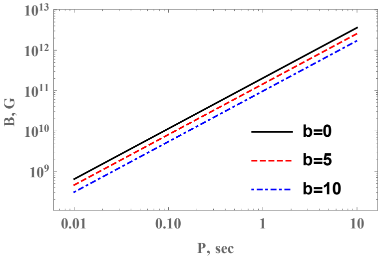




Ahmedov B.J., Morozova V.S. Plasma Magnetosphere Formation Around Oscillating Magnetized Neutron Stars, **ApSS**, 2009, V. 319, 115

effect of braneworlds on deathline of Pulsars





Thank You