Plasma Magnetosphere of Oscillating and Rotating Neutron Stars in General Relativity

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17 November 2015, FIAS/Institut für Theoretische Physik, Frankfurt

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Main Co-authors on Plasma MS of NSs in GR

- **Viktoriya Morozova, postdoctoral scholar, CalTech**
- **Olindo Zanotti, University of Trento**

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Vacuum EMFs of NSs

- Vacuum EMFs of Newtonian Spherical Star – Armin Deutsch (1955). Vacuum EMFs of Newtonian Oscillating Magnetized Star – McDermott et al (1984; 1988); Muslimov & Tsygan (1986).
- The exact analytical solution for the static magnetic dipole in Schwarzschild spacetime – Ginzburg & Ozernoy (1964); Petterson (1974); extended to multipoles – Anderson & Cohen (1970), Wasserman & Shapiro (1983).
- The magnetized rotator in GR – Konno & Kojima (2001), Kojima, Matsunaga & Okito (2003). Rezzolla, Ahmedov & Miller (2001) and Rezzolla & Ahmedov (2004) – EMFs in the exterior of a slowly rotating neutron star as well as inside the star and investigated the impact of stellar oscillations.
- MF evolution in GR context – Geppert, Page & Zannias (2000), Page, Geppert & Zannias (2000), Zanotti & Rezzolla (2002).

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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

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

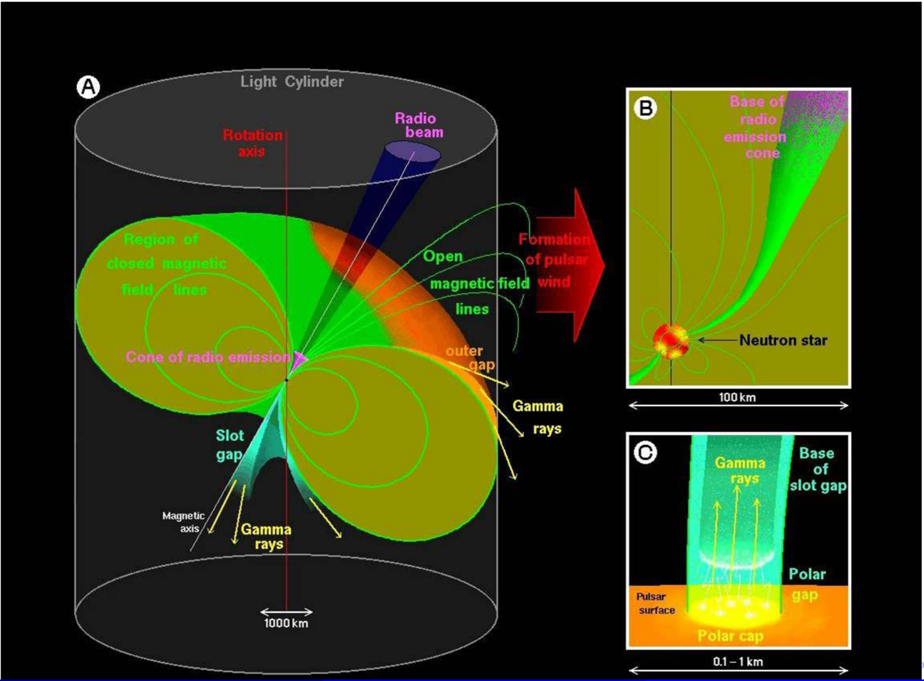
and exterior magnetic field should decay with t^{-1} (Ginzburg & Ozernoy 1964, Anderson & Cohen 1970, Zeldovich & Novikov 1971).
The correct decay rate at late times of an initially static dipole electromagnetic radiation field outside a black hole is $t^{-(2l+2)}$ (Price 1972, Thorne 1971).

NS Magnetosphere

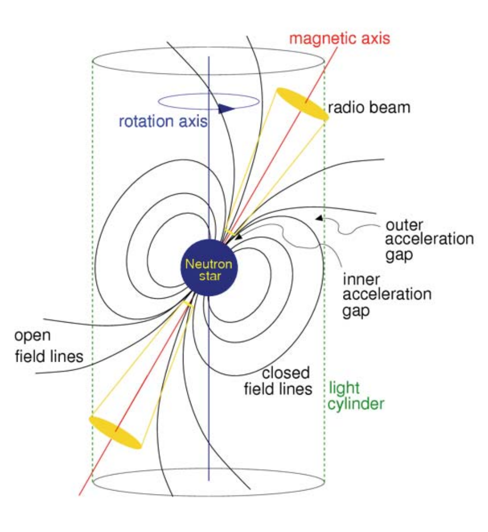
EF on the Star Surface:

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

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.


A
Light Cylinder
Radio beam
Rotation axis
Region of closed magnetic field lines
Open magnetic field lines
Formation of pulsar wind
Cone of radio emission
outer gap
Gamma rays
Slot gap
Magnetic axis
Gamma rays
1000 km
B
Base of radio emission cone
Neutron star
100 km
C
Gamma rays
Base of slot gap
Polar gap
Pulsar surface
Polar cap
0.1 – 1 km

Goldreich & Julian (1969)



- *Magnetic field of the neutron star is assumed to be dipolar ~ 10^{12} G*
- *The interior of the neutron star is assumed to be a perfect conductor*

$$\vec{E}_{in} + \frac{(\vec{\Omega} \times \vec{r})}{c} \times \vec{B} = 0$$

- *Assuming vacuum outside the neutron star, one gets the surface electric field ~ 10^{12} G*

BHs in MF

- Wald (1971) – exact solution for BH immersed in MF.
- Blandford & Znajek (1977) – extraction of energy of Kerr BH immersed in MF.
- Expulsion of magnetic flux/Meissner-like effects for extreme BH – King, Lasota & Kundt (1975), Bicak & Janis (1985)
- Membrane paradigm – MacDonald & Thorne (1982), Thorne et al. (1986)
- Lyutikov (2011) – boosted Schwarzschild black holes as unipolar inductors

The strength of MF in the vicinity of stellar mass and supermassive black holes is

$$B \approx 10^8 \mathrm{Gauss}, \quad \text{for} \quad M \approx 10 M_\odot$$

$$B \approx 10^4 \mathrm{Gauss}, \quad \text{for} \quad M \approx 10^9 M_\odot$$

V.S. Morozova, Rezzolla L., Ahmedov B.J., Nonsingular electrodynamics of a rotating black hole boosted in an asymptotically uniform magnetic test field, **PRD**, 2014, V.89, 104030.

Oscillating NSs

- NSs are endowed with intense EM fields, but they are also subject to oscillations of various type.
- Evidence for stellar oscillations coming from the observation of QPOs following giant flares of SGRs (Israel et al., 2005; Strohmayer & Watts, 2005; Watts & Strohmayer, 2006, 2007).
- The study of internal structure of NSs is of great importance for fundamental physics because matter inside NS is under extreme conditions. The study of proper oscillations of isolated NSs may provide an opportunity to obtain important information about the internal structure of these objects.

Model Assumptions

Difficulty of simultaneously solving the Maxwell eqs

$$3!F_{[\alpha\beta,\gamma]} = 2\left(F_{\alpha\beta,\gamma} + F_{\gamma\alpha,\beta} + F_{\beta\gamma,\alpha}\right) = 0 \ , \qquad F^{\alpha\beta}{}_{;\beta} = 4\pi J^{\alpha} \ ,$$

and the highly nonlinear Einstein eqs

$$R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R = \kappa T_{\alpha\beta} \ , \quad T_{\alpha\beta} = T_{(G)\alpha\beta} + T_{(em)\alpha\beta} \ .$$

E/M Fields are considered in a given background Geometry: Very Good Approximation

$$T_{(G)\alpha\beta} \gg T_{(em)\alpha\beta} \ , T_{\alpha\beta} \approx T_{(G)\alpha\beta} \ .$$

Model Assumptions

MF does not contribute to the total energy momentum

$$\frac{B^2}{8\pi \langle \rho_0 \rangle c^2} \simeq 1.6 \times 10^{-6} \left(\frac{B}{10^{15}\ \mathrm{G}} \right)^2 \left(\frac{1.4\ M_\odot}{M} \right) \left(\frac{R}{15\ \mathrm{Km}} \right)^3 .$$

Space-time metric

$$ds^2 = -e^{2\Phi(r)} dt^2 + e^{2\Lambda(r)} dr^2 - 2\omega(r) r^2 \sin^2\theta dt d\phi + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 .$$

$\omega(r)$ is the Lense-Thirring angular velocity and outside the star is given by

$$\omega(r) \equiv \frac{d\phi}{dt} = -\frac{g_{0\phi}}{g_{\phi\phi}} = \frac{2J}{r^3} .$$

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Model Assumptions

Velocity perturbation

$$\delta u^{\alpha} = \Gamma\left(1, \delta v^{i}\right) = \Gamma\left(1, e^{-\Lambda}\delta v^{\hat{r}}, \frac{\delta v^{\hat{\theta}}}{r}, \frac{\delta v^{\hat{\phi}}}{r\sin\theta}\right) .$$

For small velocity perturbations $\delta v^{i}/c \ll 1$:

$$\Gamma = \left[-g_{00}\left(1 + g_{ik}\frac{\delta v^{i}\delta v^{k}}{g_{00}}\right)\right]^{-1/2} \simeq e^{-\Phi} .$$

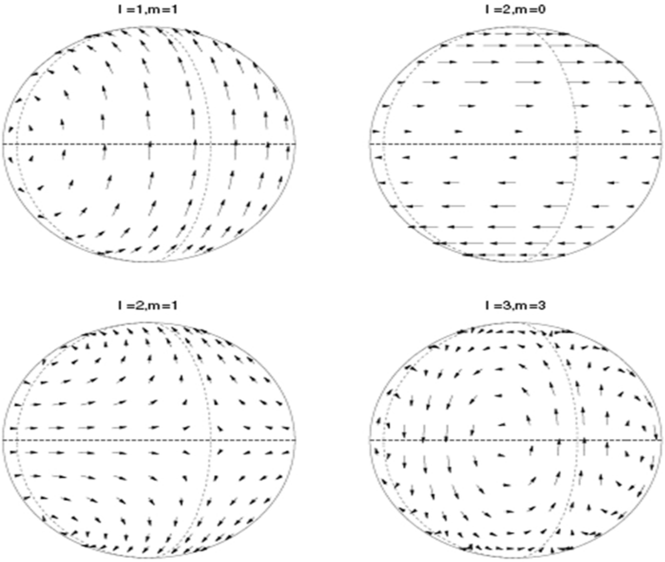
Toroidal Oscillations

$$\delta v^{\hat{i}} = \left\{0, \frac{1}{\sin\theta}\partial_{\phi}Y_{\ell' m'}(\theta,\phi) , -\partial_{\theta}Y_{\ell' m'}(\theta,\phi)\right\}\eta(r)\mathrm{e}^{-\mathrm{i}\omega t} .$$

Frequency range for small velocity perturbations

$$\omega\bar{\xi} \ll c , \quad \bar{\xi} \approx 10^{-3}R = 10^{3}\mathrm{cm} , \quad \omega \ll 3\times 10^{7}\mathrm{Hz} .$$

Toroidal Oscillations



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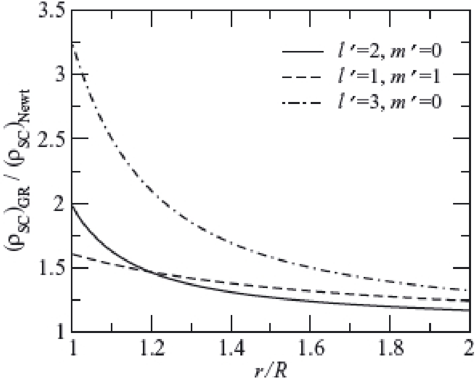
Electric Charge Density in MS



Abdikamalov E.B., Ahmedov B.J. & Miller J.C., The Magnetosphere of Oscillating Neutron Stars in General Relativity, **MNRAS**, 2009, V. 395, 443

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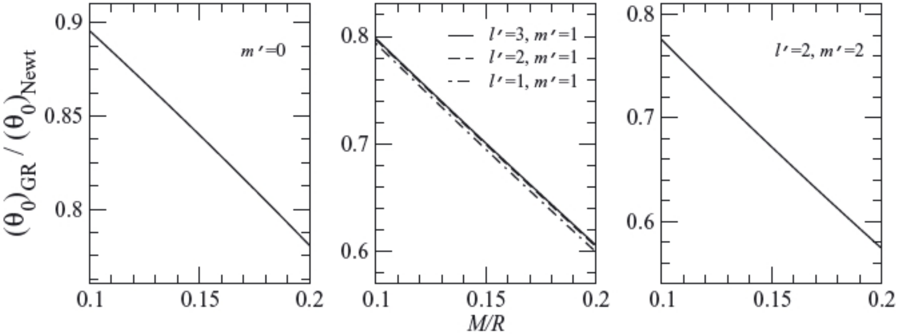
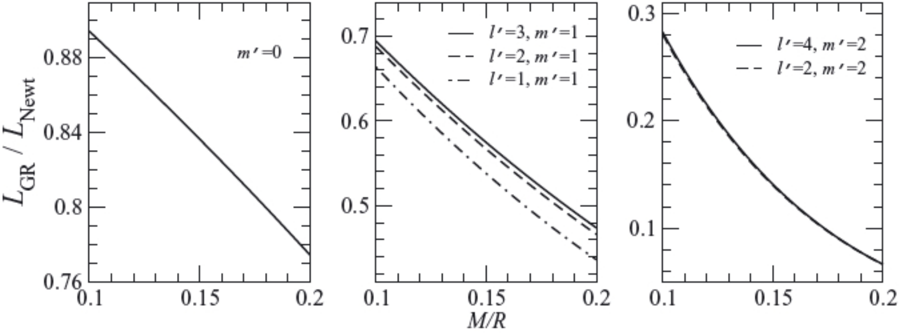
Shrink of Polar Cap in GR



Energy Losses



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Space-time metric

$$ds^2 = -N^2 dt^2 + N^{-2} dr^2 + r^2 \left(d\theta^2 + \sin^2\theta d\phi^2\right) - 2\omega_{\rm LT} r^2 \sin^2\theta d\phi dt \ .$$

$N \equiv (1 - 2M/r)^{1/2}$ is lapse function, $\omega_{\rm LT} = 2aM/r^3$ is the Lense-Thirring angular velocity, R is the star radius, $\bar{r} = r/R$ 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 $\kappa = \varepsilon\beta$.

V. S. Morozova, B. J. Ahmedov and O. Zanotti, General relativistic magnetospheres of slowly rotating and oscillating magnetized neutron stars, **MNRAS**, 2010, V 408, 490.
V. S. Morozova, B. J. Ahmedov and O. Zanotti, Explaining radio emission of magnetars via rotating and oscillating magnetospheres of neutron stars, **MNRAS**, 2012, V 419, 2147.
O. Zanotti, V. S. Morozova and B. J. Ahmedov, Particle acceleration in the polar cap region of an oscillating neutron star, **A & A**, 2012, V 540, A 126.

GR Effects in Pulsar MS

Goldreich-Julian charge density

$$\rho_{GJ} = -\frac{\Omega B_0}{2\pi c}\frac{1}{N\eta^3}\frac{f(\eta)}{f(1)}\left\{1-\frac{\kappa}{\eta^3}-L\left(1-\frac{\varepsilon}{\eta}\right)\frac{1}{\eta^2}\frac{4\sin^2\frac{\theta}{2}}{\sin^2\theta}\right\} .$$

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

$$\rho = \frac{\Omega B_0}{2\pi c}\frac{1}{N\eta^3}\frac{f(\eta)}{f(1)}A(\xi) ,$$

where $\xi = \theta/\Theta$, and polar angle Θ of the last open magnetic line

$$\Theta \cong \sin^{-1}\left\{\left[\eta\frac{f(1)}{f(\eta)}\right]^{1/2}\sin\Theta_0\right\} , \quad \Theta_0 = \sin^{-1}\left(\frac{R}{R_{LC}f(1)}\right)^{1/2} ,$$

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Muslimov & Tsygan (1990, 1992), Beskin (1990), Muslimov & Harding (1997)

GR Effects in Pulsar MS

EF $E_{\|}$ is

$$E_{\|} = -E_{vac}\Theta_0^2 \frac{3(\kappa - L\varepsilon)}{2\eta^4}(1-\xi^2) \ ,$$

where $E_{vac} \equiv (\Omega R/c)B_0$.

The ratio of polar-cap energy losses

$$\frac{(L_p)_{max}}{(L_p)_{max\ (l=0)}} = 1 - \frac{L(\kappa + \varepsilon - 2\kappa\varepsilon)}{\kappa(1-\kappa)} + \frac{L^2\varepsilon(1-\varepsilon)}{\kappa(1-\kappa)} \ .$$

V. S. Morozova, B. J. Ahmedov and V. G. Kagramanova, General Relativistic Effect of Gravitomagnetic Charge on Pulsar Magnetosphere and Particle Acceleration in a Polar Cap, **ApJ**, 2008, V 684, 1359.

GJ charge density for slowly rotating and oscillating NS

$$\rho_{\rm GJ} = -\frac{\Omega B_0}{2\pi c}\frac{1}{\alpha \bar{r}^3}\frac{f(\bar{r})}{f(1)}\left(1-\frac{\kappa}{\bar{r}^3}\right) - \frac{1}{4\pi c}\frac{1}{R\bar{r}^4}\frac{B_0 e^{-i\omega t}}{\Theta^2(\bar{r})}\frac{1}{N}\frac{f(\bar{r})}{f(1)}\tilde{\eta}(\bar{r})l'(l'+1)Y_{l'm'} \ .$$

Using small angles θ approximation

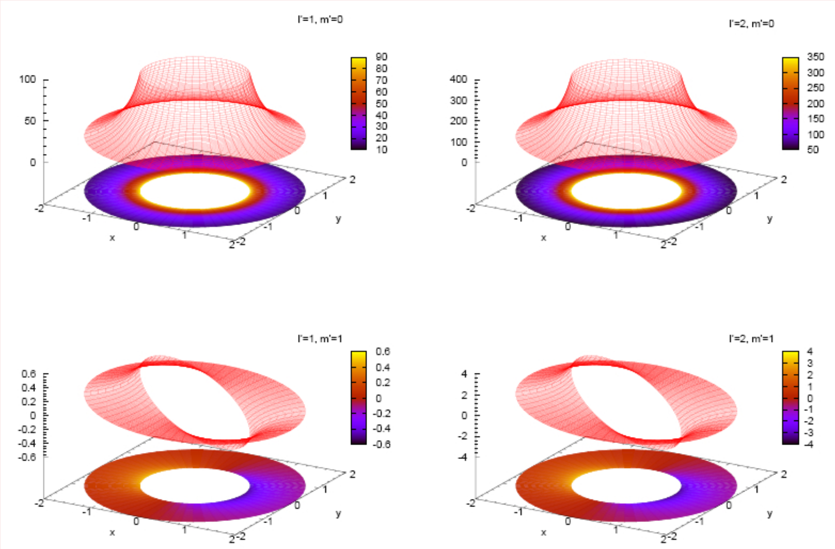
$$Y_{l'm'}(\theta,\phi) \approx A_{l'm'}(\phi)\theta^m \ ,$$

one could get the ratio $\delta\rho_{\rm GJ\ l'm'}/\rho_{\rm GJ,0}$ in the form

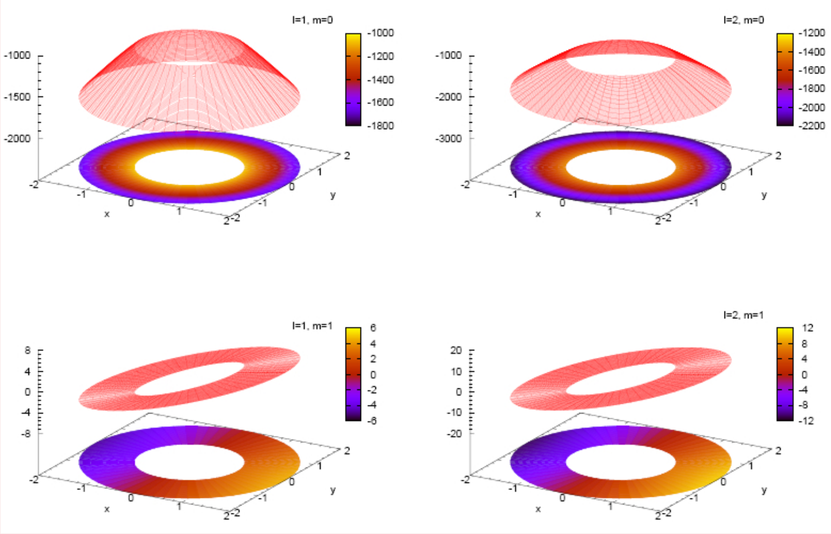
$$\delta\rho_{\rm GJ\ l'm'}/\rho_{\rm GJ,0} = \frac{K}{2\bar{r}^{2-m/2}}\Theta_0^{m-2}\left(\frac{f(\bar{r})}{f(1)}\right)^{\frac{2-m}{2}}\frac{l'(l'+1)A_{l'm'}(\phi)}{\left(1-\frac{\kappa}{\bar{r}^3}\right)} \ ,$$

where $K = \tilde{\eta}(1)/\Omega R$.

Ratio $\delta\rho_{\mathrm{GJ}\ \mathrm{l'm'}}/\rho_{\mathrm{GJ},0}$ for the mode $(1,0)$ (left-hand top panel), $(1,1)$ (left-hand bottom panel), $(2,0)$ (right-hand top panel) and $(2,1)$ (right-hand bottom panel). NS parameters $\kappa = 0.15$, $\varepsilon = 1/3$, $K = 0.01$, $\Theta_0 = 0.008$, $\Omega = 1\mathrm{rad\ s}^{-1}$.



Ratio of longitudinal component of EF to E_0 for the mode $(1,0)$ (left-hand top panel), $(1,1)$ (left-hand top panel), $(2,0)$ (right-hand top panel) and $(2,1)$ (right-hand bottom panel).



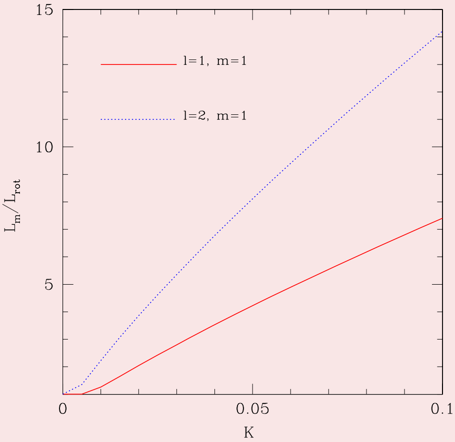
Energy losses of slowly rotating and oscillating NS

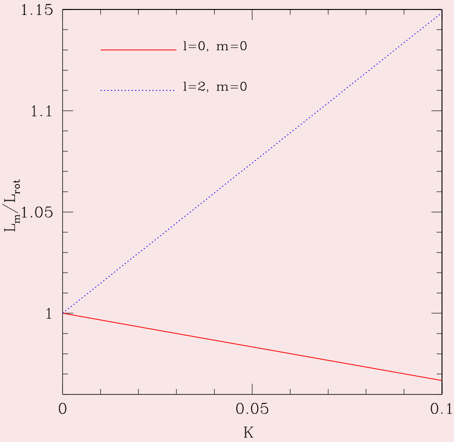
$$
\begin{aligned}
L_{|m\neq 0} &= R^3 N_R B_0^2 \Bigg| \Bigg\{ \frac{\Omega^2 R}{2cN_R}(1-\kappa)^2 \frac{\Theta_0^4}{4} \\
&+ \frac{\Omega}{4c}\frac{1}{N_R}(1-\kappa)\tilde{\eta}(1) l(l+1) A_{lm} \frac{\Theta_0^{m+4}}{m+4} \\
&- \frac{\Omega}{2c}\frac{1}{N_R}(1-\kappa) A_{lm}\tilde{\eta}(1) \frac{\Theta_0^{m+2}}{m+2} \\
&- \frac{1}{2c}\frac{1}{RN_R} A_{lm}^2 \tilde{\eta}^2(1) l(l+1) \frac{\Theta_0^{2m+2}}{2m+2} \Bigg\} \Bigg|
\end{aligned}
$$

and

$$
\begin{aligned}
L_{|m=0} &= R^3 N_R B_0^2 \frac{\Theta_0^4}{8} \Bigg| \left[\Omega R(1-\kappa) - A_{l0}\tilde{\eta}(1)\right] \Bigg\{ \frac{\Omega}{cN_R}(1-\kappa) \\
&+ \frac{1}{2c}\frac{1}{N_R}\tilde{\eta}(1) l(l+1) A_{l0} \Bigg\} \Bigg| .
\end{aligned}
$$

Left-hand panel: the ratio L_m/L_{rot} as a function of parameter $K = \tilde{\eta}(1)/\Omega R$ for modes $(1,1)$ (continuous red line) and $(2,1)$ (dotted blue line). Right-hand panel: the ratio L_m/L_{rot} as a function of parameter $K = \tilde{\eta}(1)/\Omega R$ for modes $(0,0)$ (continuous red line) and $(2,0)$ (dotted blue line).





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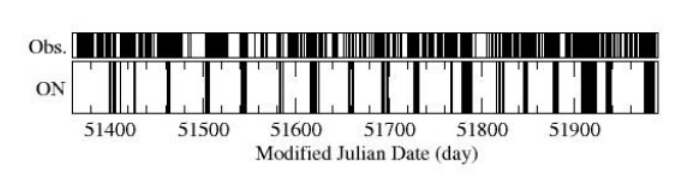
PSR B1931+24

The first part time pulsar (Kramer et al., 2006)



Only visible for 20% of time

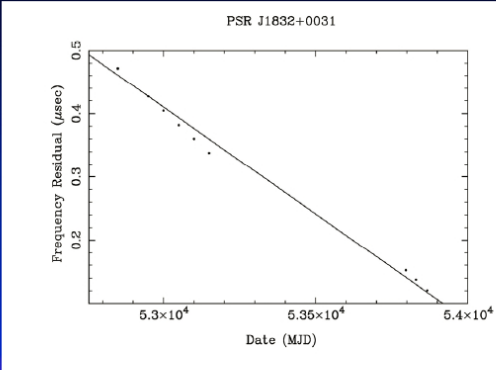
ON period 5-10 days
OFF period 25-35 days
Spin period 813 ms

$\dot{\nu}_{ON} = -16.3(4) \times 10^{-15} \mathrm{Hz s}^{-1}$
$\dot{\nu}_{OFF} = -10.8(2) \times 10^{-15} \mathrm{Hz s}^{-1}$
Distance $\sim 4.6 \mathrm{kpc}$

The whole process is quasi-periodic!

More intermittent pulsars

Properties: J1832+0031



- 'on' state >300 days
- 'off' state ~700 days
- Quasi-periodicity ?
- Increase in slow-down rate during 'on' state similar to B1931+24

Possible explanations

- **Nulling?** (Backer (1970))

  Nulling phenomenon lasts only for a few pulse periods and not on a time-scales of tens of days

- **Precession?**

  Cannot produce a transition from the ON to the OFF state in less than 10 s

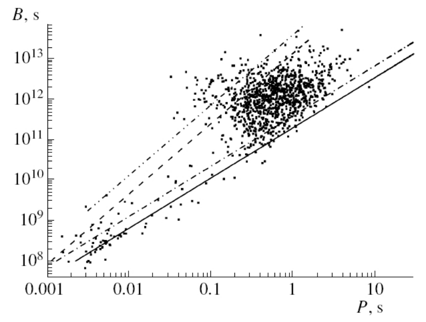
- **Global failure of charge particles currents in the magnetosphere?** (Lyne (2009), Gurevich&Istomin (2007))

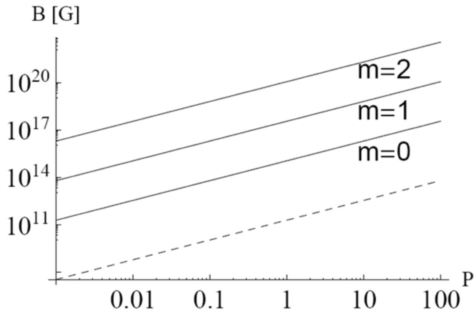
  Lack of a physical mechanism for changing the plasma flow in the magnetosphere in such a drastic way

There is no self-consistent explanation of the phenomena yet

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

Damping times of toroidal modes for a neutron star

Mode	ν (kHz) (1)	$E_{\rm T}$(erg) (2)	$L_{\rm em}^{\rm Newt}$(erg s^{-1}) (3)	$L_{\rm em}^{\rm GR}$(erg s^{-1}) (4)	$\tau_{\rm gw}(s)$ (5)	$\tau_{\rm em}^{\rm Newt}(s)$ (6)	$\tau_{\rm em}^{\rm GR}(s)$ (7)	$\tau_{\rm gw}/\tau_{\rm em}^{\rm GR}$ (8)	$\tau_{\rm em}^{\rm Newt}/\tau_{\rm em}^{\rm GR}$ (9)
$_1t_1$	17.9	1.09×10^{49}	1.77×10^{43}	1.57×10^{44}	...	1.23×10^{6}	1.39×10^{5}	...	8.85
$_1t_2$	30	6.40×10^{48}	1.44×10^{44}	1.28×10^{45}	...	8.88×10^{4}	1.00×10^{4}	...	8.88
$_1t_3$	43	1.59×10^{48}	5.98×10^{44}	5.30×10^{45}	...	5.32×10^{3}	6.00×10^{2}	...	8.87
$_1t_4$	52.7	2.72×10^{47}	1.33×10^{45}	1.18×10^{46}	...	4.08×10^{2}	4.60×10^{1}	...	8.87
$_2t_0$	0.36	3.31×10^{47}	6.86×10^{32}	3.45×10^{33}	6.62×10^{11}	9.65×10^{14}	1.92×10^{14}	3.45×10^{-3}	5.03
$_2t_1$	17.9	3.26×10^{49}	9.32×10^{42}	4.96×10^{43}	7.60×10^{5}	7.00×10^{6}	1.31×10^{6}	0.58	5.34
$_2t_2$	30	1.92×10^{49}	2.17×10^{44}	1.15×10^{45}	2.33×10^{5}	1.77×10^{5}	3.33×10^{4}	70	5.32
$_2t_3$	43	4.76×10^{48}	1.83×10^{45}	9.72×10^{45}	1.51×10^{4}	5.21×10^{3}	9.79×10^{2}	15.43	5.32
$_2t_4$	52	8.15×10^{47}	6.10×10^{45}	3.24×10^{46}	4.68×10^{3}	2.67×10^{2}	5.03×10^{1}	93.04	5.31

Damping times of spheroidal modes for a neutron star

Mode	ν (kHz) (1)	$E_{\rm T}$(erg) (2)	$L_{\rm em}^{\rm Newt}$(erg s^{-1}) (3)	$L_{\rm em}^{\rm GR}$(erg s^{-1}) (4)	$\tau_{\rm gw}(s)$ (5)	$\tau_{\rm em}^{\rm Newt}(s)$ (6)	$\tau_{\rm em}^{\rm GR}(s)$ (7)	$\tau_{\rm gw}(s)/\tau_{\rm em}^{\rm GR}(s)$ (8)	$\tau_{\rm em}^{\rm Newt}/$ (9)
$_2p_2$	104.72	1.55×10^{50}	9.04×10^{44}	4.56×10^{45}	0.23×10^{-3}	3.43×10^{5}	6.79×10^{4}	0.34×10^{-6}	4.4
$_2f$	28.56	1.59×10^{52}	2.38×10^{43}	7.41×10^{44}	7.50×10^{-3}	1.34×10^{9}	4.29×10^{7}	1.75×10^{-10}	31.24
$_2s_2$	14.61	2.53×10^{53}	4.46×10^{43}	1.03×10^{45}	1×10^{4}	1.13×10^{10}	4.90×10^{8}	0.2×10^{-4}	23.06
$_2s_1$	8.6	1.32×10^{54}	5.13×10^{43}	1.12×10^{45}	4.32×10^{4}	5.15×10^{10}	2.36×10^{9}	1.83×10^{-5}	21.82
$_2i_2$	0.63	4.08×10^{47}	5.49×10^{43}	1.16×10^{45}	5.04×10^{9}	1.48×10^{4}	7.01×10^{2}	0.72×10^{7}	21.11
$_2i_1$	0.35	1.63×10^{53}	5.49×10^{43}	1.16×10^{45}	8.64×10^{5}	5.93×10^{9}	2.80×10^{8}	3.1×10^{-3}	21.18
$_2g_2^s$	0.12	5.49×10^{43}	5.49×10^{43}	1.16×10^{45}	7.57×10^{16}	5.24×10^{-3}	2.47×10^{-4}	3.1×10^{20}	21.21
$_2g_3^s$	0.1	1.96×10^{40}	5.49×10^{43}	1.16×10^{45}	1.17×10^{17}	0.71×10^{-3}	0.34×10^{-4}	3.4×10^{21}	20.88

New alternative idea for the explanation of part time pulsars phenomena

- During the ON state pulsar is oscillating: stellar oscillations create relativistic wind of charged particles by virtue of additional accelerating electric field
- In a period of about 10 days the stellar oscillations are damped and the OFF period starts
- Quasi-periodic stellar glitches excite oscillations again, thus, being responsible for the emergence of new ON states with a certain periodicity

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NSs

- RADIO PULSARS: 2000 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

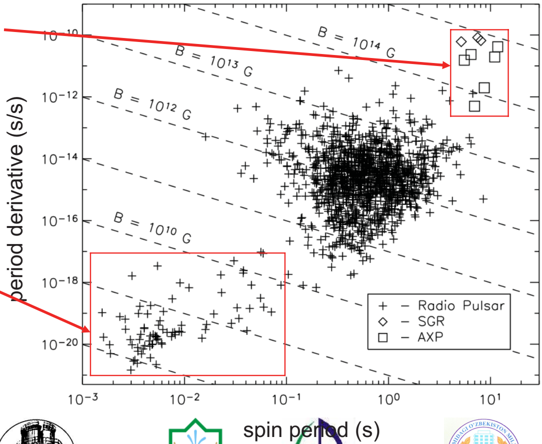
Magnetars (28 (incl candidates) discovered to date: http://www.physics.mcgill.ca/ pulsar/magnetar/main.html)

- 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

Spinning-down Neutron Stars (non-accreting)

magnetars

`recycled' pulsars



Woods & Thompson 2004 (astro-ph/0406133)

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Relativistic death line for magnetars

- **The activity of magnetars is observed in the form of bursts in X-ray and γ-ray bands, while there is no periodic radio emission from the majority of magnetars in the same range of frequencies of ordinary pulsars.**
- **Istomin & Sobyanin 2007 (IS07) – the absence of radio emission from magnetars is related to their slow rotation, i.e. the low energy of the primary particles, accelerated near the surface of the star.**
- **IS07 – the death-line for magnetars, i.e. the line in the $P - \dot{P}$ diagram that separates the regions where the neutron star may be radio-loud or radio-quiet.**
- **We consider the influence of magnetar oscillations on the conditions for the radio emission generation in the MS of magnetars and revisit the problem of magnetars death-line, by taking into account the role both of rotation and of toroidal oscillations in a relativistic framework.**

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The critical magnetic field is defined as $B_c = m^2c^3/e\hbar \approx 4.414 \times 10^{13}\mathrm{G}$, where m is the electron mass and e is the electron charge.

When distance between two neighboring Landau levels becomes equal to the rest energy of the electron $\hbar\omega_c = mc^2$, $\omega_c = eB_c/mc$.

Characteristic energy of the curvature gamma quanta is $\epsilon_\gamma \approx \hbar c\gamma^3/R_c$.

EM scalar potential

GR EM scalar potential provided by Muslimov & Tsygan 1992, which is valid at angular distances $\Theta_0 << \eta - 1 << R_c/R_s$:

$$\Phi = \frac{1}{2}\Phi_0\kappa\Theta_0^2\left(1-\frac{1}{\eta^3}\right)(1-\xi^2)\cos\chi + \frac{3}{8}\Phi_0\Theta_0^3 H(1)\left(\frac{\Theta(\eta)H(\eta)}{\Theta_0 H(1)}-1\right)\xi(1-\xi^2)\sin\chi\cos\phi \, ,$$

with

$$H(\eta) = \frac{1}{\eta}\left(\varepsilon-\frac{\kappa}{\eta^2}\right)+\left(1-\frac{3}{2}\frac{\varepsilon}{\eta}+\frac{1}{2}\frac{\kappa}{\eta^3}\right)\left[f(\eta)\left(1-\frac{\varepsilon}{\eta}\right)\right]^{-1} ,$$

$$f(\eta) = -3\left(\frac{\eta}{\varepsilon}\right)^3\left[\ln\left(1-\frac{\varepsilon}{\eta}\right)+\frac{\varepsilon}{\eta}\left(1+\frac{\varepsilon}{2\eta}\right)\right] .$$

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EM scalar potential

where $\eta = r/R_s$ is the dimensionless radial coordinate, $\Theta(\eta)$ is the polar angle of the last open magnetic field line

$$\Theta \cong \sin^{-1}\left\{\left[\eta\frac{f(1)}{f(\eta)}\right]^{1/2}\sin\Theta_0\right\}, \quad \Theta_0 = \sin^{-1}\left(\frac{R}{R_{LC}f(1)}\right)^{1/2},$$

$R_c = 1/\Omega$, $\Phi_0 = \Omega B_0 R_s^2$, χ is the inclination angle between the angular momentum of the neutron star and its magnetic moment, $\varepsilon = 2GM/R_s$ is the compactness parameter, $\beta = I/I_0$ is the moment of inertia of the star in units of $I_0 = MR_s^2$, $\kappa = \varepsilon\beta$, and $\xi = \theta/\Theta$.

Dependence of death-lines from parameter κ

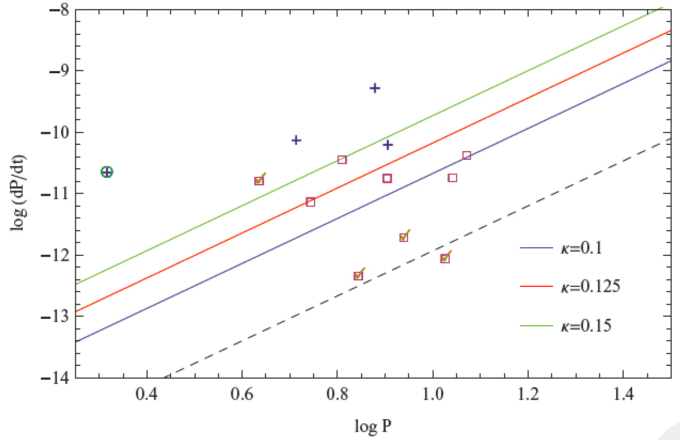
When $\chi = 0$ the value of the magnetic field for which the generation of secondary plasma still possible is

$$B_0 \gtrsim \left(\frac{\kappa}{f(1)}\right)\left(\frac{P}{1\mathrm{s}}\right)^{7/3}\left(\frac{R_s}{10\mathrm{km}}\right)^{-3} 10^{12}\mathrm{G}\ ,$$

which gives the expression for the death-line of the magnetars in the form

$$\log \dot{P} = \frac{11}{3}\log P - 15.6 - 2\log\left(\frac{\kappa}{f(1)}\right) - 6\log\left(\frac{R_s}{10\mathrm{km}}\right)\ .$$

Death-lines for the aligned magnetar for different values of the parameter κ. The dashed line indicates the position of the death-line from IS07. Crosses and squares indicate the position of SGRs and AXPs, respectively. AXPs from which the radio emission has been registered are marked with ticks, radio-loud soft gamma-ray repeater is enclosed in circle.

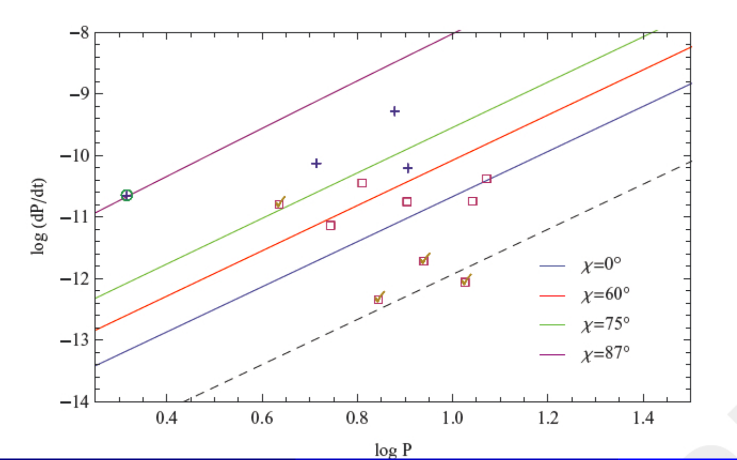


Dependence of death-lines from inclination angle χ

The expression for the death-line of the inclined magnetar is

$$B > 2^{-\frac{8}{3}} 3\xi_{min}^{-\frac{2}{3}} \left\{ \left| \frac{\kappa}{f(1)} \cos\chi (1-\xi_{min}^2) + \frac{3}{4}\frac{1}{(f(1))^{3/2}}\sqrt{\frac{R_s}{R_c}} \left(\frac{\Theta(\eta)}{\Theta_0} - H(1) \right) \sin\chi \right| \right\}^{-1} \left(\frac{P}{1s}\right)^{\frac{7}{3}} \left(\frac{R_s}{10km}\right)^{-3} 10^{12}\mathrm{G} \,.$$

Death-lines for the misaligned magnetar for different values of the inclination angle χ. The value of κ is taken to be 0.1. The dashed line indicates the position of the death-line from IS07. Crosses and squares indicate the position of SGRs and AXPs, respectively. Anomalous X-ray pulsars from which the radio emission has been registered are marked with ticks, radio-loud soft gamma-ray repeater is enclosed in circle.



Content

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EM scalar potential

GR EM scalar potential in the polar cap region of rotating and oscillating aligned magnetar magnetosphere is given by

$$\Psi(\theta,\phi) = \frac{B_0}{2}\frac{R_s^3}{R_c^2}\frac{\kappa}{f(1)}\left(1-\xi^2\right) - e^{-i\omega t}\tilde{\eta}(R_s)B_0R_s\sum_{l=0}^{\infty}\sum_{m=-l}^{l}Y_{lm}(\theta,\phi)\ .$$

The condition for radio emission on the intensity of MF is given by

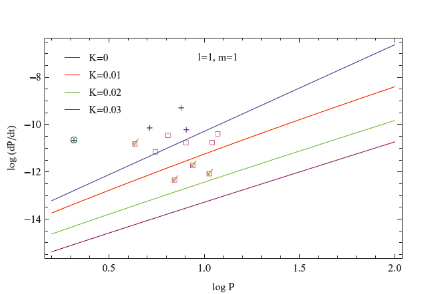
$$\begin{aligned} B \quad > \quad & 2^{-\frac{8}{3}}6\pi\left\{\int_0^{2\pi}\xi_{min}^{2/3}\left|\frac{\kappa}{f(1)}(1-\xi_{min}^2)\right.\right. \\ - \quad & \left.\left. 2\frac{\tilde{\eta}(R_s)}{f^m(1)}\left(\frac{R_s}{R_c}\right)^{\frac{m}{2}-2}\xi_{min}^m A_{lm}(\phi)\right|d\phi\right\}^{-1} \times \left(\frac{P}{1s}\right)^{\frac{7}{3}}\left(\frac{R_s}{10km}\right)^{-3}10^{12}\mathrm{G}\ , \end{aligned}$$

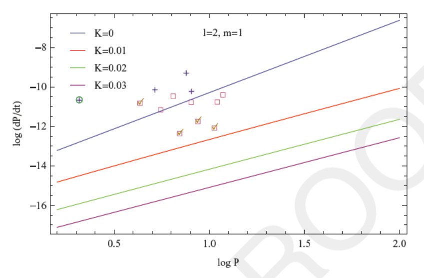
in the approximation $Y_{lm}(\theta,\phi) \approx A_{lm}(\phi)\theta^m$ being valid in the limit of small polar angles θ.

Dependence of death-lines from parameter K

The amplitude of the oscillation is now parametrized in terms of the small number $K = \tilde{\eta}(1)/\Omega R$, giving the ratio between the velocity of oscillations and the linear rotational velocity of magnetar. The death-lines for rotating as well as oscillating magnetars for two modes of oscillations and different values of the parameter K are provided.

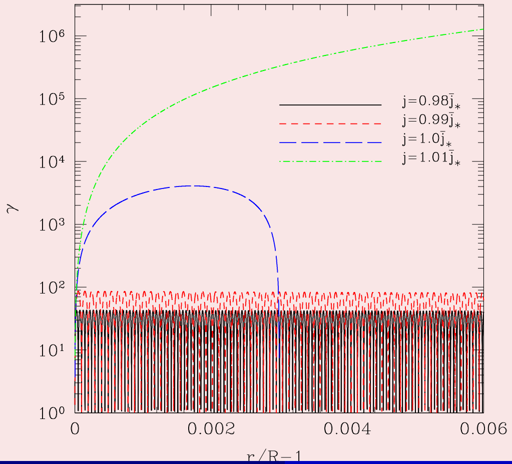
Death-lines for rotating and oscillating magnetars in the $P - \dot{P}$ diagram. The left panel corresponds to the mode $(1,1)$ and values of $K = 0\ , 0.01\ , 0.02\ , 0.03$. The right panel corresponds to the mode $(2,1)$ and values of $K = 0\ , 0.01\ , 0.02\ , 0.03$. Other parameters are taken to be $R_s = 10\text{km}$, $M = 2M_\odot$ and $\kappa = 0.15$. Crosses and squares indicate the position of SGRs and AXPs, respectively. AXPs from which the radio emission has been registered are marked with ticks, radio-loud soft gamma-ray repeater is enclosed in circle.



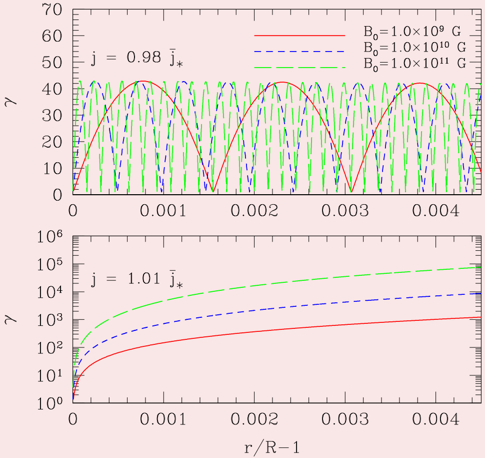


Content

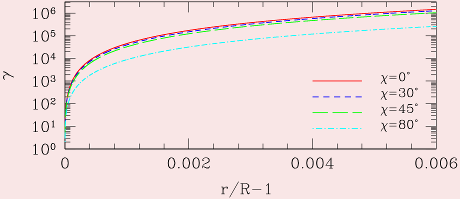
Dependence of the Lorentz factor on the ratio $j/\bar{j}_*$ for a neutron star with $M = 1.4M_\odot$, $R = 10$ km, $P = 0.1s$, $\chi = 30°$, $B_0 = 1.0 \times 10^{12}$G, $\theta_* = 0°$, $\Theta_0 = 2°$, $\gamma_* = 1.01$.



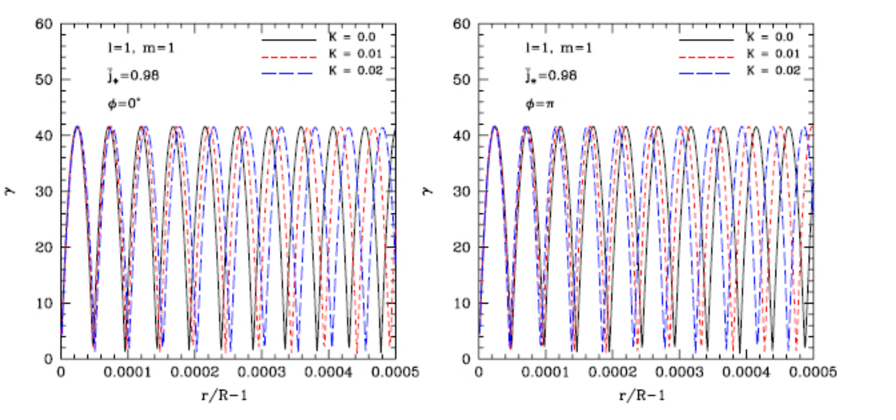
Lorentz factor dependence on the intensity of the magnetic field for a neutron star with $M = 1.4M_{\odot}$, $R = 10$ km, $P = 0.1s$, $\chi = 30°$, $\theta_* = 0°$, $\Theta_0 = 2°$, $\gamma_* = 1.01$. Top panel: $j = 0.98\bar{j}_*$. Bottom panel: $j = 1.01\bar{j}_*$.



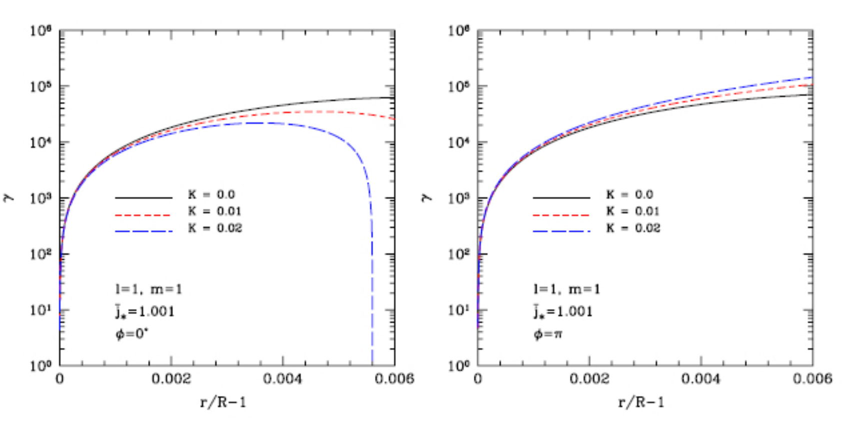
Lorentz factor dependence on the inclination angle χ for a neutron star with $M = 1.4M_\odot$, $R = 10$ km, and $P = 0.1s$, $j = 1.01\bar{j}_*$, $\theta_* = 0°$, $\Theta_0 = 2°$, $\gamma_* = 1.01$, $B_0 = 1.0 \times 10^{12}$G. The Lorentz factor decreases for larger inclination angles.



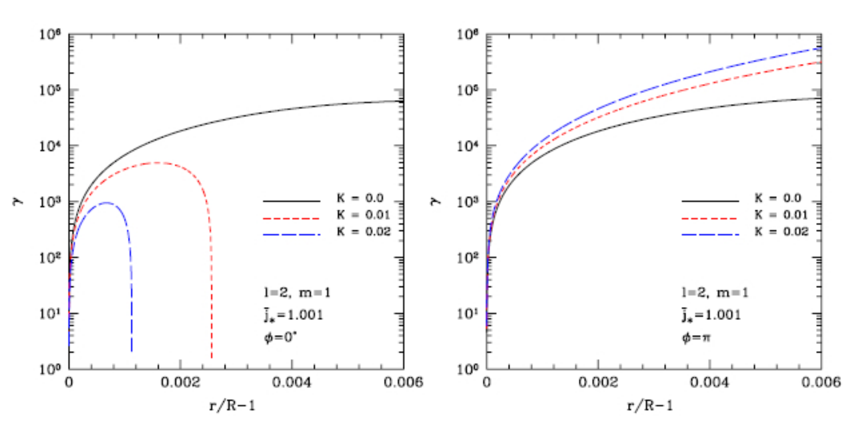
Lorentz factor dependence on the normalized amplitude of the stellar oscillations K for the mode of oscillations $(l, m) = (1, 1)$ with $\theta_* = 2°$, $\Theta_0 = 3°$, $\gamma_* = 1.015$, $B_0 = 1.0 \times 10^{12}$G for the case $j = 0.98\bar{j}_*$. The left panels show the solution for $\phi = 0$, the right panels for $\phi = \pi$.



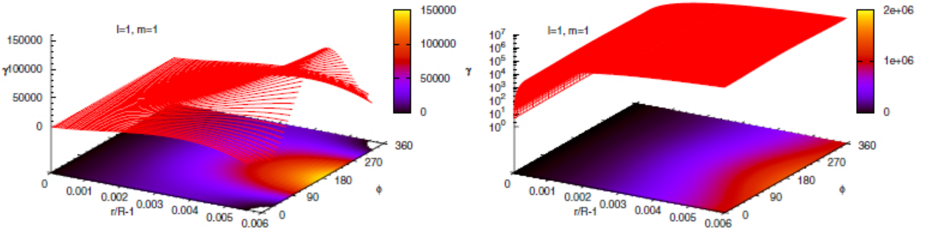
Lorentz factor dependence on the normalized amplitude of the stellar oscillations K for the mode of oscillations $(l,m) = (1,1)$ with $\theta_* = 2°$, $\Theta_0 = 3°$, $\gamma_* = 1.015$, $B_0 = 1.0 \times 10^{12}$G for the case $j = 1.001\bar{j}_*$. The left panels show the solution for $\phi = 0$, the right panels for $\phi = \pi$.



Lorentz factor dependence on the normalized amplitude of the stellar oscillations K for the mode of oscillations $(l, m) = (2, 1)$ with $\theta_* = 2°$, $\Theta_0 = 3°$,$\gamma_* = 1.015$, $B_0 = 1.0 \times 10^{12}$G. The two panels correspond to the case $j = 1.001\bar{j}_*$. The left panel shows the solution for $\phi = 0$, the right panel for $\phi = \pi$



Lorentz factor as a function of radial distance and azimuthal angle ϕ for a model with stellar oscillations $K = 0.02$, $(l, m) = (1, 1)$, $\theta_* = 2°$, $\Theta_0 = 3°$,$\gamma_* = 1.015$, $B_0 = 1.0 \times 10^{12}$G. Left panel: $j = 1.001\bar{j}_*$. Right panel: $j = 1.01\bar{j}_*$.



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Content

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Drifting Subpulses as a Tool for Studies of Pulsar Magnetosphere

- Phenomena of drifting subpulses
- Existing models for the drifting subpulses
- Our results in frame of the space charge limited flow model

V.S. Morozova, Ahmedov B.J., O. Zanotti, Explaining the subpulse drift velocity of pulsar magnetosphere within the space-charge limited flow model, **MNRAS**, 2014, V. 444, 1144

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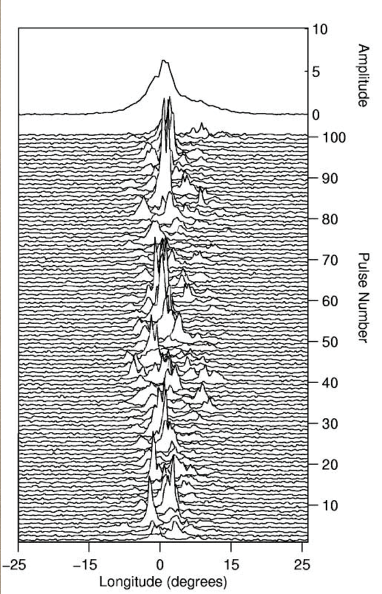
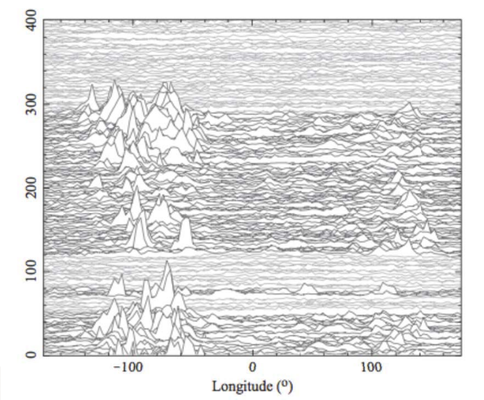
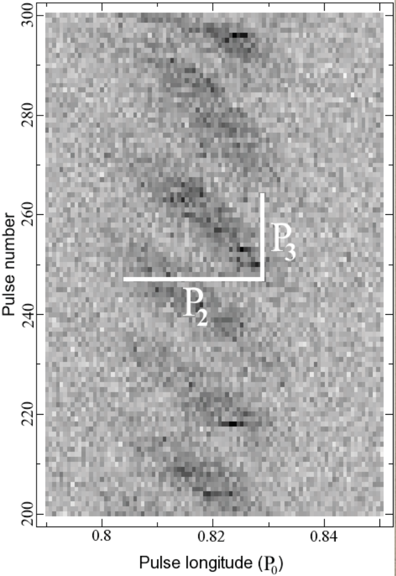
Drifting subpulses



- *Average pulse profile is very stable and represents a unique "fingerprint" of a given pulsar*
- *Subsequent pulses plotted on top of each other show rich microstructure*



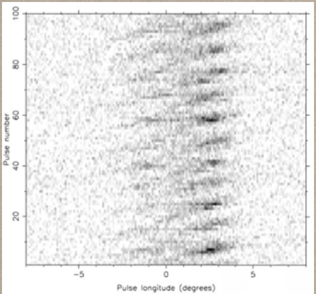
Drifting subpulses



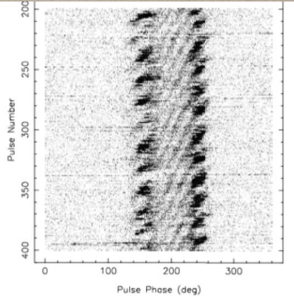
Subpulse drift velocity

$$\omega_D = \frac{P_2}{P_3}$$

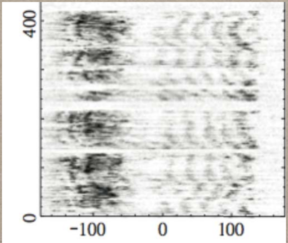
Various subpulse behavior



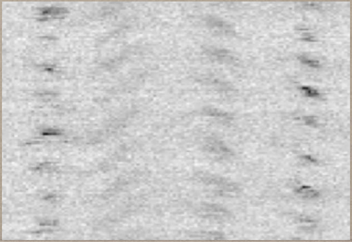
PSR B0320+39 from R. T. Edwards et al. (2003)



PSR B0818–41 from B. Bhattacharyya et al. (2007)



PSR B0826-34 from van Leeuwen & Timokhin (2012)



PSR J0815-09 from Qiao et al. (2004)

Content

How many charged particles will actually leave the surface of the star?

A. All required for the screening of the induced electric field

Arons & Scharlemann (1979)
Space-charge limited flow (SCLF) model

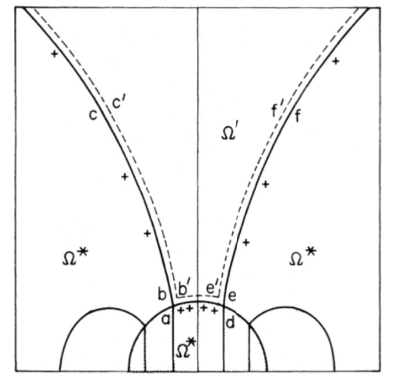
B. None

Ruderman & Sutherland (1975)
Vacuum gap model

C. Some part of the amount required for the screening

Gil & Sendyk (2000)
Partially screened gap model

Vacuum gap model



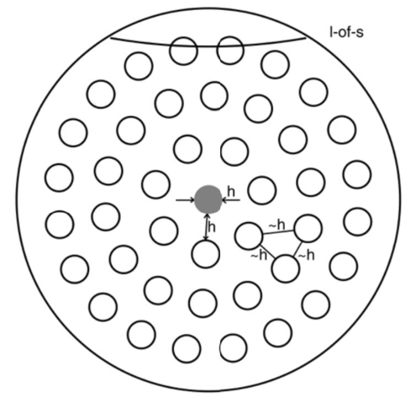
- *A vacuum gap will be formed close to the surface of the star*
- *The gap will periodically discharge in the form of sparks*
- *Sparks are assumed to be responsible for the appearance of the drifting subpulses*

$$\omega_D = \frac{\Delta V}{B_s r_p} c$$

potential drop of the gap (ΔV); *surface magnetic field* (B_s); *radius of the polar cap* (r_p)

Predicted velocities are too large in comparison with the observed

Partially screened gap model



- *Even when the vacuum gap is screened on ~95%, the remaining potential drop is enough for the spark discharges to appear*
- *Sparks are assumed to densely populate the polar cap region*

Predicted velocities can be brought to correspondence with the observed ones, but the degree of screening (shielding factor) is fine tuned and different for different pulsars

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SCLF model

- *Scalar potential is induced due to the difference between the actual charge density in the magnetosphere and the charge density needed to screen the accelerating electric field*

$$\Delta V = -4\pi(\rho - \rho_{GJ})$$

- *Provides analytical solutions for the charge density and electromagnetic field regions close to the surface and far from the surface of the neutron star*

Was never used for the explanation of the drifting sub pulses:

- Potential drop is too small (10^9 V vs 10^{12} V)

- No place for the discharges

van Leeuwen & Timokhin (2012)

$$v_D = \frac{\Delta V}{B_s r_p} c \quad ?$$

$$v = \frac{\vec{E} \times \vec{B}}{B^2} c \qquad \vec{E} = -\nabla V$$

$$\boxed{v_D = \frac{180^\circ}{\xi} \frac{dV}{d\xi}} \qquad \xi \equiv \frac{\theta}{\theta_{pc}}$$

The drift velocity is defined by the shape of the potential, not by its absolute value

What if we try to check the SCLF model?

Expression for the plasma velocity

$$\omega_{D\ \mathrm{low}} = \frac{180^\circ}{\xi}\frac{12\sqrt{1-\varepsilon}\Theta_0}{\bar{r}}\Bigg\{-2\kappa\cos\chi\sum_{i=1}^{\infty}\left[\exp\left(\frac{k_i(1-\bar{r})}{\Theta_0\sqrt{1-\varepsilon}}\right)-1+\frac{k_i(\bar{r}-1)}{\Theta_0\sqrt{1-\varepsilon}}\right]\frac{J_1(k_i\xi)}{k_i^3 J_1(k_i)}$$
$$+\Theta_0 H(1)\delta(1)\sin\chi\cos\phi\sum_{i=1}^{\infty}\left[\exp\left(\frac{\tilde{k}_i(1-\bar{r})}{\Theta_0\sqrt{1-\varepsilon}}\right)-1+\frac{\tilde{k}_i(\bar{r}-1)}{\Theta_0\sqrt{1-\varepsilon}}\right]\frac{J_0(\tilde{k}_i\xi)-J_2(\tilde{k}_i\xi)}{2\tilde{k}_i^3 J_2(\tilde{k}_i)}\Bigg\}$$

$\bar{r} \equiv \frac{r}{R}$ $\quad \xi \equiv \frac{\theta}{\theta_{pc}}$ $\quad \phi$ *- spherical coordinates*

- *Are the values of drift velocity predicted by this expression compatible with the observed subpulse velocities?*
- *May the angular dependence of the drift velocity help in explaining the longitudinal subpulse behavior?*

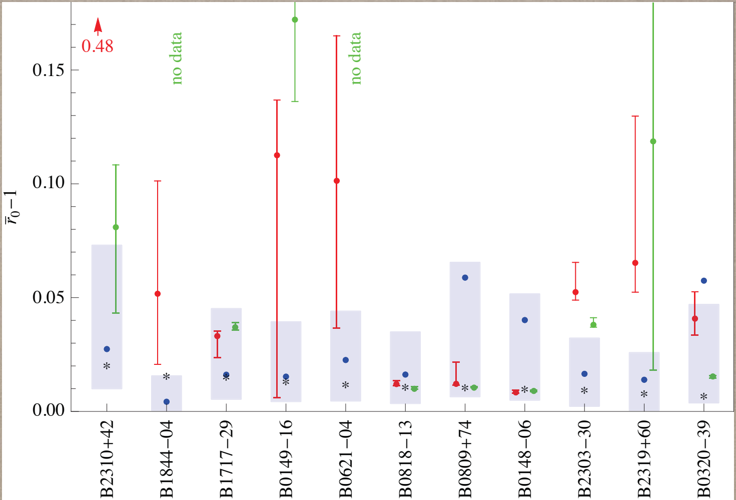
Comparison with the pulsar data

- *Weltevrede et al. (2006), (2007) did the first systematic study of the subpulse behavior of large amount of pulsars (at 21 cm and 92 cm observational wavelength)*
- *From 187 pulsars more than 55 % show the subpulse phenomena (revealed by the spectral methods)*
- *We chose 13 pulsars with known observing geometry (the inclination angle χ)*

$$\omega_D = \omega_D(\bar{r}, \xi, \phi) \qquad \xi = 0.9\,, \;\; \phi = \pi$$

Find $\bar{r}$ **so that** $\omega_D(\bar{r}) = \omega_{observed}$

- *One pulsar does not have a solution, one has the opposite drift sense at two observing frequencies*



Red data points correspond to the observing wavelength at 21 cm

Green data points correspond to the observing wavelength at 92 cm

Blue shadowed rectangles and blue points indicate the pair formation front (PFF)

Pair formation front

- *Primary particles, emitted from the surface, accelerate in the inner magnetosphere and emit high energy gamma photons via:*

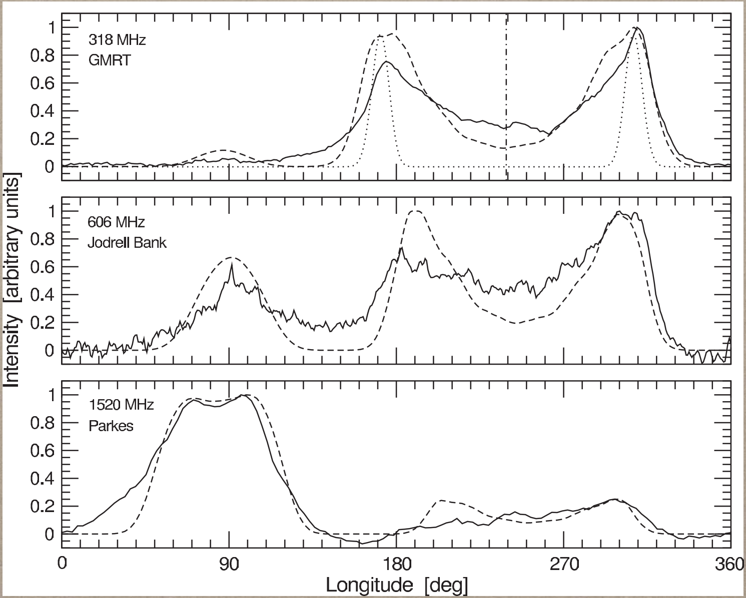
  - Curvature radiation

  - Inverse Compton scattering

- *Emitted gamma photons produce electron-positron pairs in the background magnetic field*

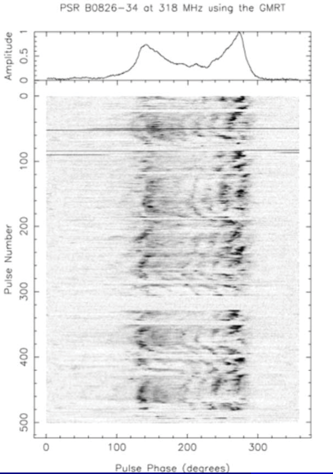
- *Pair production leads to the screening of the accelerating electric field and prevents further acceleration above the pair formation front*

PSR B0826-34


318 MHz
GMRT
606 MHz
Jodrell Bank
1520 MHz
Parkes
Intensity [arbitrary units]
Longitude [deg]
0
90
180
270
360
0
0.2
0.4
0.6
0.8
1

PSR B0826-34

Observing frequency (MHz)	Measured drift velocity ($^\circ/P$)	Reference	Average drift velocity ($^\circ/P$)
318	$-0.8 \div 1.9$	Gupta et al. (2004)	0.55
645	$-1.5 \div 2.1$	Biggs et al. (1985)	0.3
1374	$-3.2 \div 3.6$	Esamdin et al. (2005)	0.2
1374	$-1 \div 1.5$	van Leeuwen & Timokhin (2012)	0.25



Measured subpulse separation

$$P_2 = 24.9^\circ \pm 0.8^\circ$$

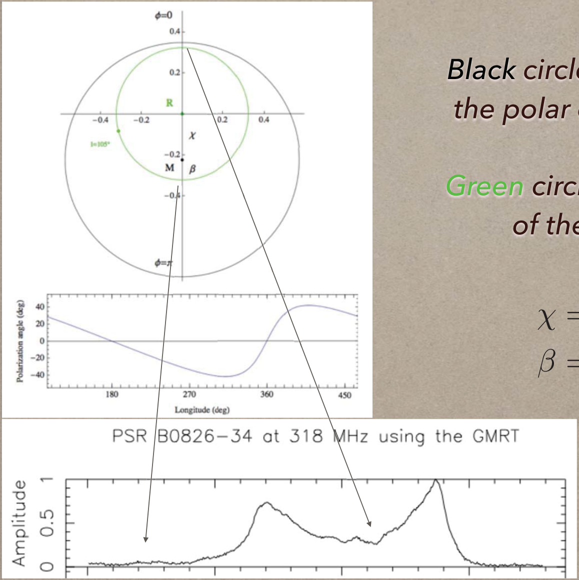
The pulsar is almost aligned, our model predicts negative drift velocity

What if the positive average drift is only apparent?

$$\omega_D = (0.55^\circ - 24.9^\circ)/P = -24.35^\circ?$$

$$P_3 \approx P \quad ?$$

Our model for the observing geometry



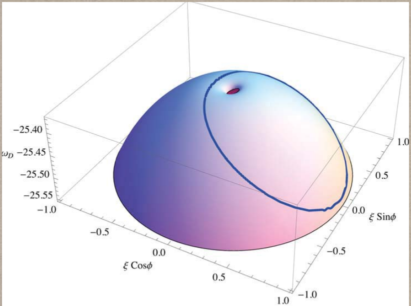
Black circle - boundary of the polar cap (0.57 deg)

Green circle - line of sight of the observer

$$\chi = 0.225^\circ$$
$$\beta = 0.098^\circ$$

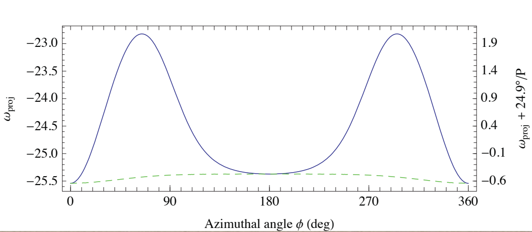
Consistent with the polarization data and with the width of the profile

Explaining the range of measured velocities

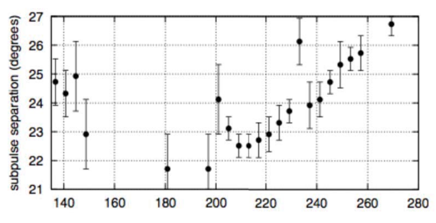


- *Plasma drift velocity across the pulsar polar cap in the SCLF model*

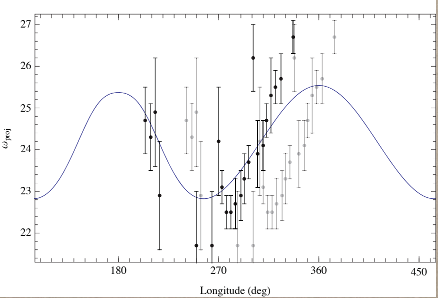
$$\vec{\omega}_{proj} = \frac{\vec{\omega}}{\sqrt{1+\left(\frac{d\xi}{d\phi}\right)^2}}$$



Explaining the longitudinal dependence of subpulse separation

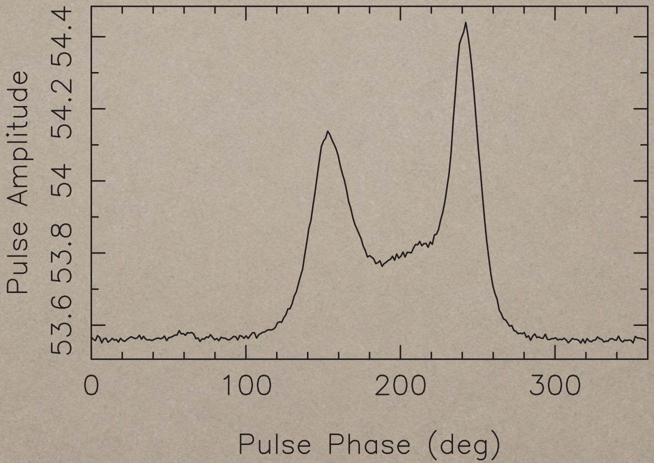


Measured subpulse separation of B0826-34 from Gupta et al. (2004)



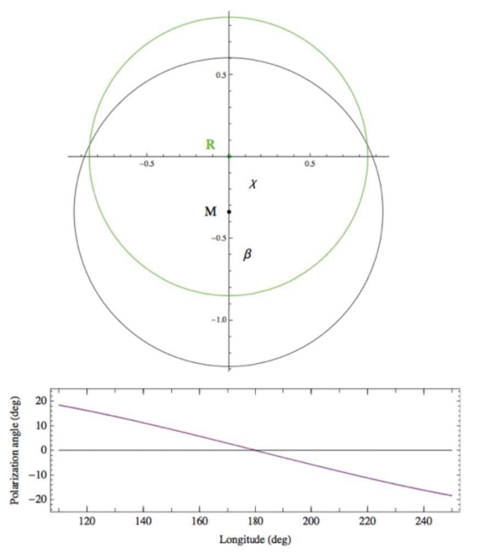
Black points represent the observed data (given in gray), shifted in order to get the visual correspondence

PSR B0818-41

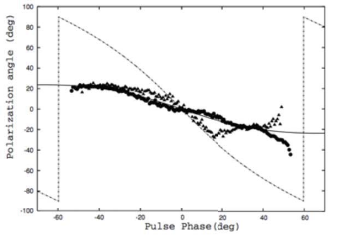


$P = 0.545$ sec $\qquad B_s = 1.03 \times 10^{11}$ G

Our model for the observing geometry

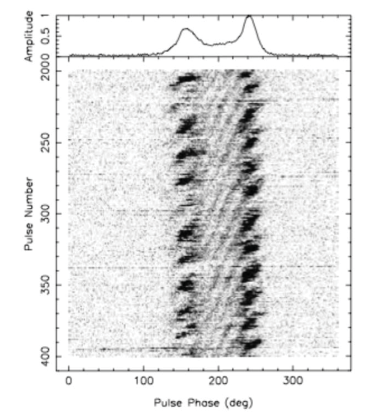


Consistent with the polarization data and with the width of the profile

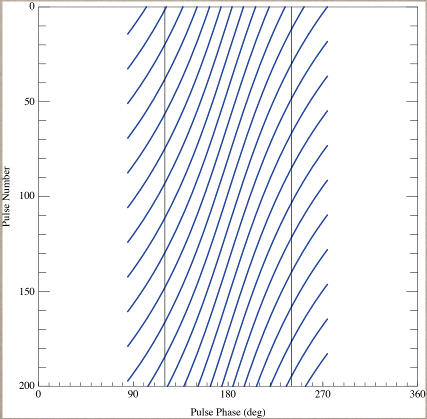


from Bhattacharyya et al. (2009)

Angular dependence of the drift velocity can account for the curved subpulse drift bands of B0818-41



from Bhattacharyya et al. (2009)



obtained with our model

Content

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Conclusion

- The new dependence for the energy losses on the oscillating behavior reflects in a new relation between the product $P\dot{P}$ and the amplitude of the stellar oscillation.
- A connection between the phenomenology of intermittent pulsars, characterized by the periodic transition from active to dead periods of radio emission in few observed sources, with the presence of an oscillating magnetosphere. During the active state, star oscillations may create relativistic wind of charged particles by virtue of the additional accelerating electric field. After a timescale of the order of tens of days stellar oscillations are damped, and the pulsar shifts below the death line in the $P-B$ diagram, thus entering the OFF invisible state of intermittent pulsars.

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- A detailed analysis of the position of the death-line in the $P - \dot{P}$ diagram for a magnetar is performed. When the compactness of the neutron star is increased, the death line shifts upwards in the $P - \dot{P}$ diagram, pushing the magnetar in the radio-quiet region.
- When the inclination angle χ between the angular momentum vector and magnetic moment is increased, the death-line shifts upwards in the $P - \dot{P}$ diagram, pushing the magnetar in the radioquiet region.
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- **The angular dependence of the plasma drift velocity in the SCLF model provides a natural explanation for the variation of the subpulse separation along the pulse**
- **In particular it may explain the curved subpulse driftbands of PSR B0818-41 and the range of the observed drift velocities of PSR B0826-34**

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Thank You

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