Superatomic Physics: Millisecond pulsars

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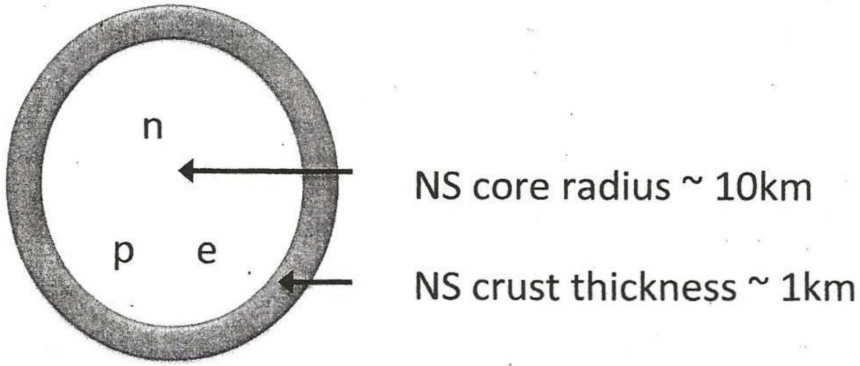
1% of the stellar mass in our Galaxy is in superfluid neutrons and superconducting protons of neutron stars (pulsars)

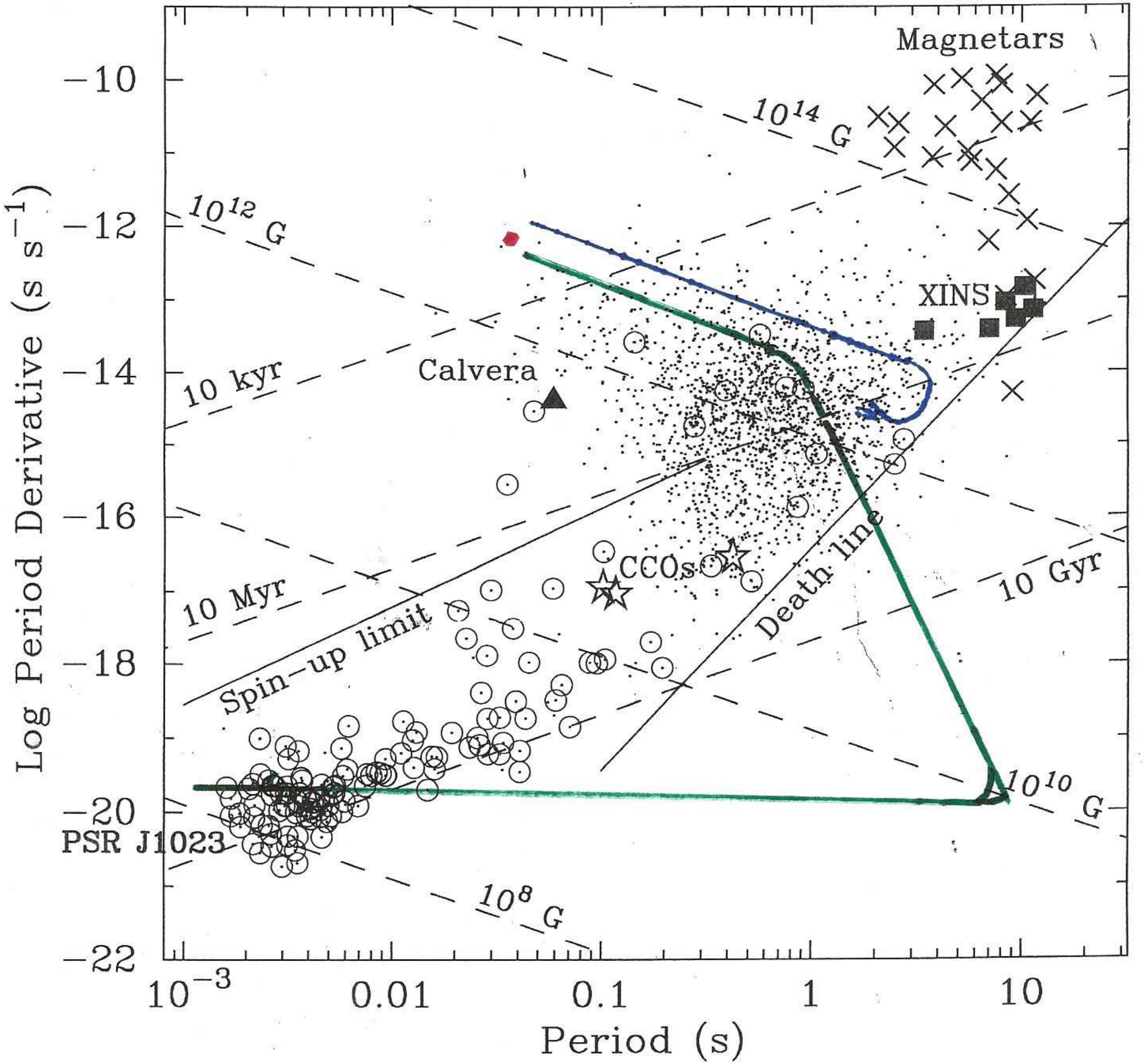


NS is a giant (solar mass) atomic nucleus with $N_n \sim 10$ N

Initial spin period $P_0 \sim 10^{-2}$ sec

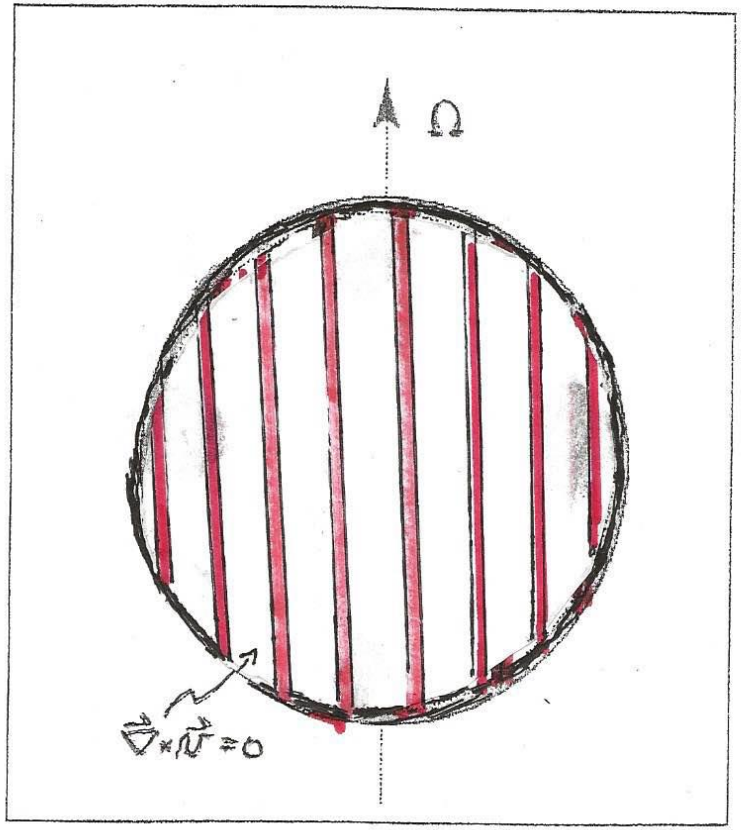
Initial magnetic dipole $B_d \sim 3 \times 10^{12}$ G

(angular momentum and flux conservation from ancestor)



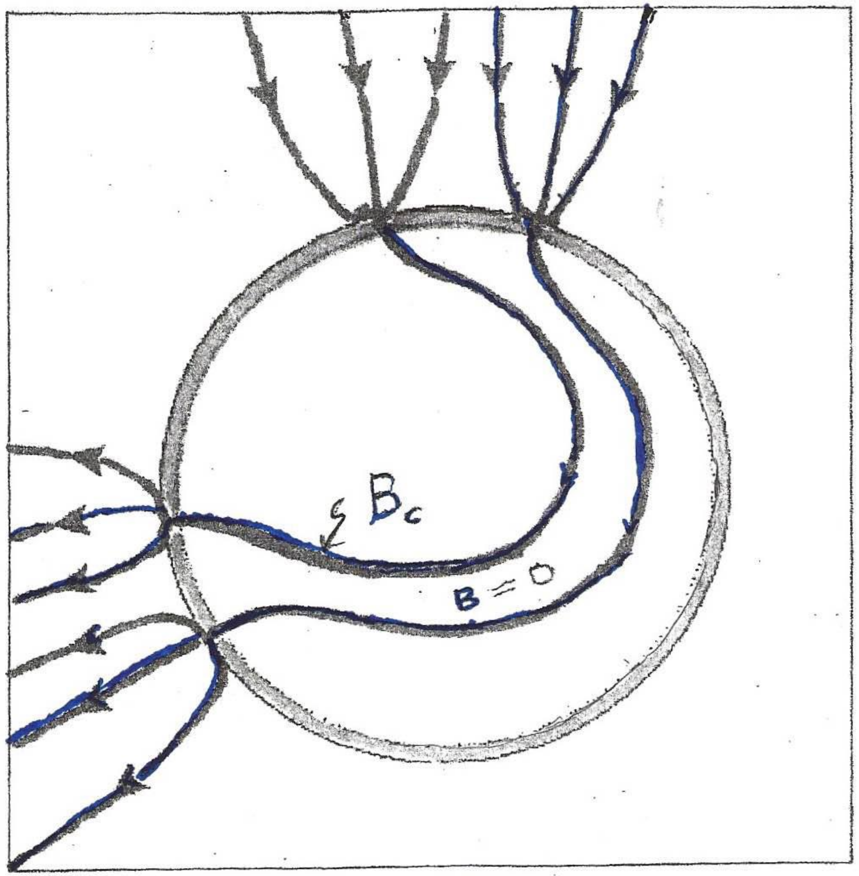
Magnetars
10^{14} G
10^{12} G
XINS
Calvera
10 kyr
10 Myr
Spin-up limit
CCOs
Death line
10 Gyr
10^{10} G
10^{8} G
PSR J1023
Log Period Derivative (s s^{-1})
Period (s)
−10
−12
−14
−16
−18
−20
−22
10^{-3}
0.01
0.1
1
10

“Uniformly” rotating neutron superfluid core



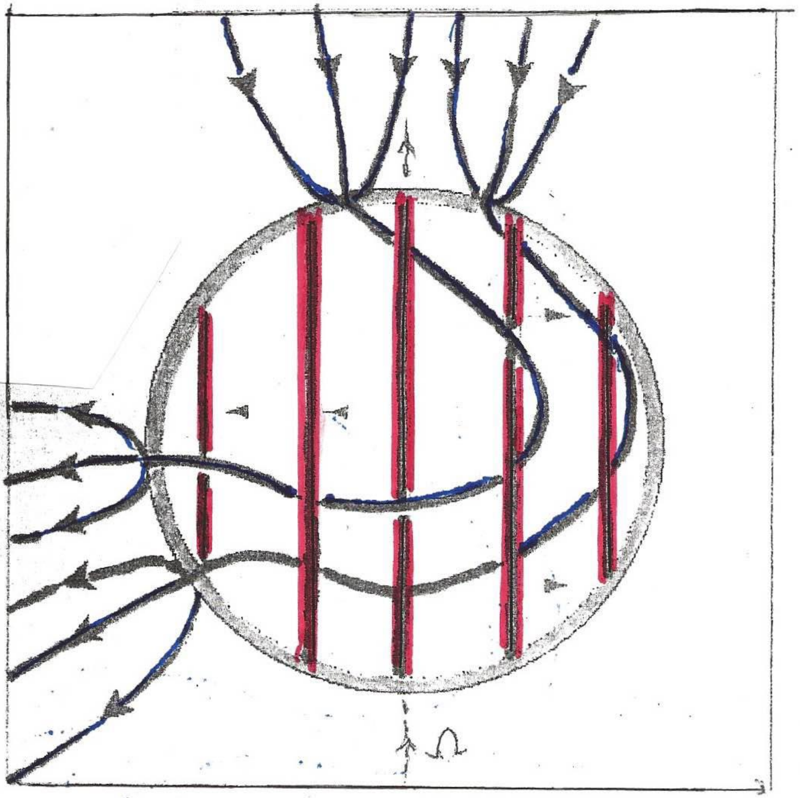
$$n_v = \frac{2 m_n \Omega}{\pi \hbar} = \left(\frac{10^4}{P(\text{sec})} \text{cm}^{-2} \right)$$

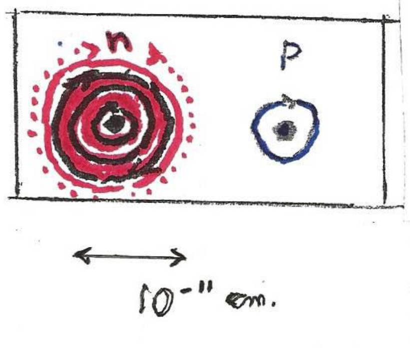
Magnetic field in (type II) proton superconductor core

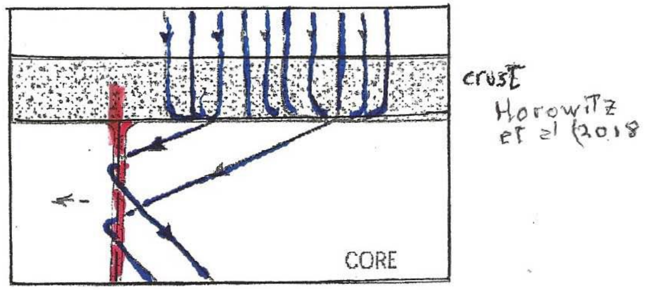


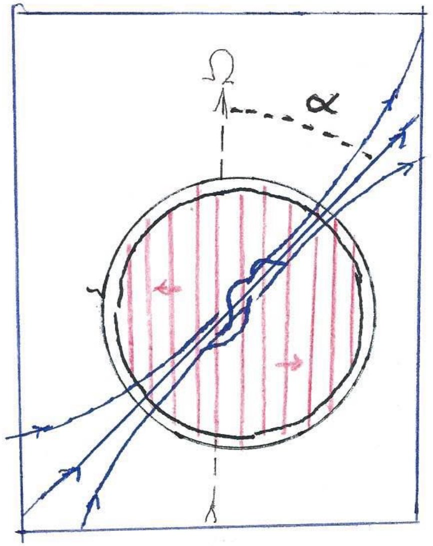
$B_c \sim 10^{15}$ Gauss $\left(n_{\Phi} \sim \bar{B}_{13} \cdot 10^{20}\ cm^{-2} \right)$

$\Phi_0 = \hbar \pi c / e$


Ω


n
p
10⁻¹¹ cm.


crust
Horowitz
et al (2018
CORE



$$\sin^2\alpha \sim \frac{\hat{\Omega}}{\Omega}$$

$$I\dot{\Omega} = -\frac{\mu^2}{c^3}\left(1+\sin^2\alpha\right)\Omega^3$$

$$\mu \equiv B_d R^3$$

Gruzinov (2005)

Spitkovsky (2008)

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adolescent pulsar: $t \sim 10^3 - 10^4$ yrs : $\sin^2\alpha \to 1$

$$2.5 < \frac{\ddot{\Omega}\,\Omega}{\dot{\Omega}^2} \equiv n < 3 \qquad \begin{pmatrix} 2.9 & 2.8 & 2.5 \\ 2.2 & 2.1 & \cdot \end{pmatrix}$$

$(2 < \quad \Omega < \hat{\Omega})$

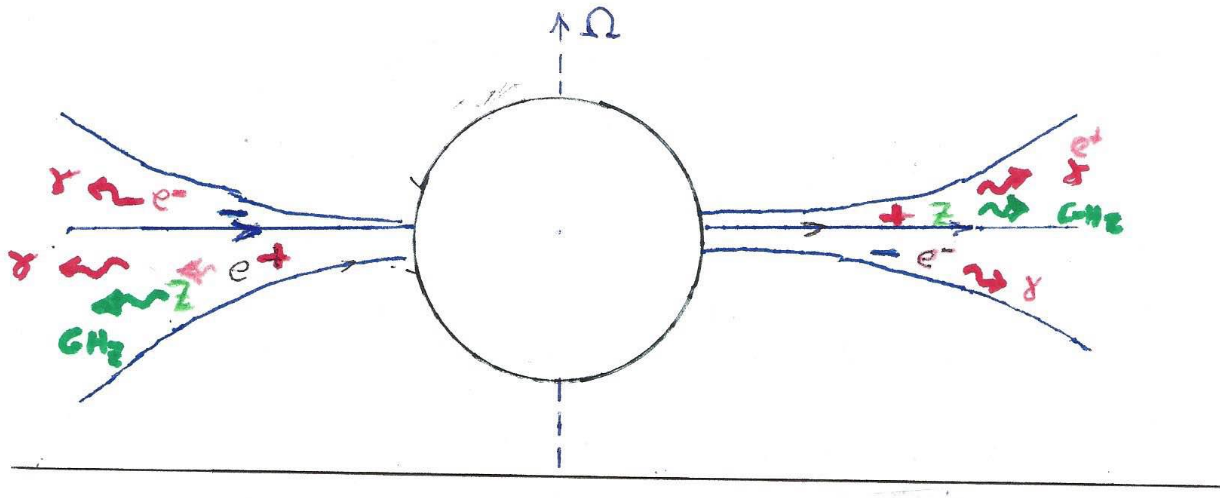
Senior citizen: $t \gtrsim$ crust Eddy current decay time (10^6 yrs ?)

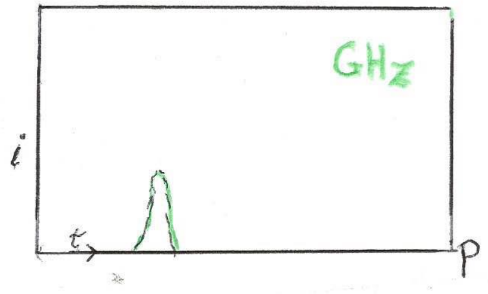
$$B_d \sim \left(\frac{\Omega}{\Omega_0}\right) B_0 \Rightarrow n = 5$$

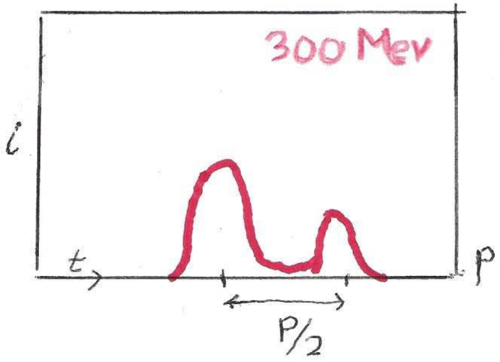
Cordes + Chernoff (1998)

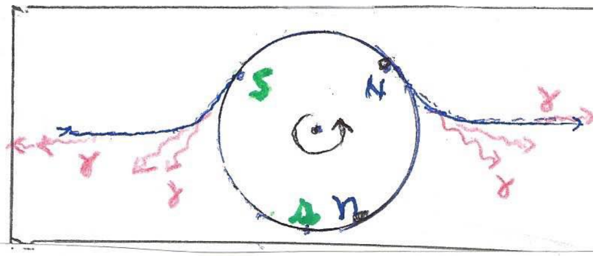
$n = 4.5 \pm 0.8$

Mature pulsar : $10^4 - 10^6$ years ($\sin^2\alpha \sim 1$)









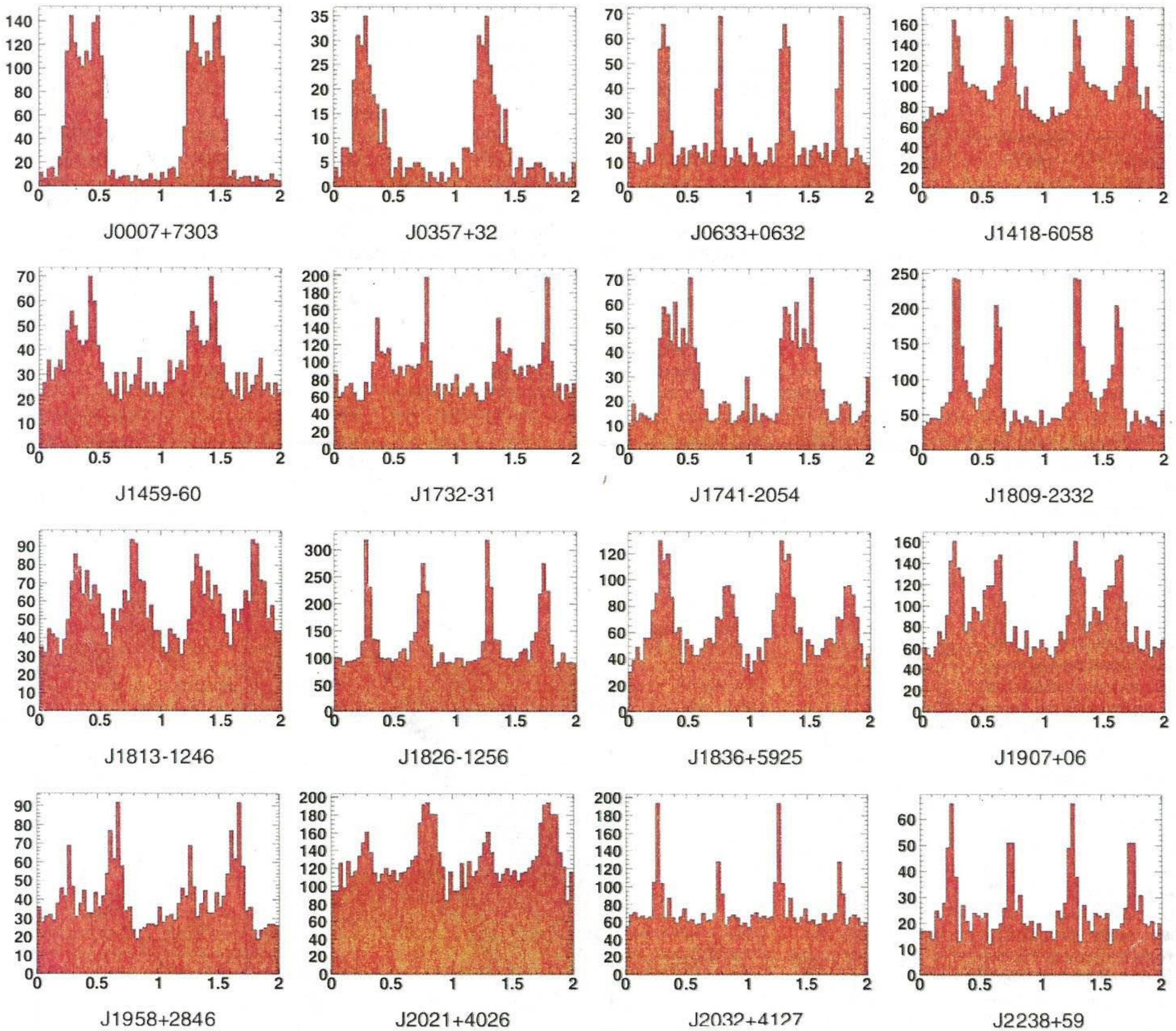
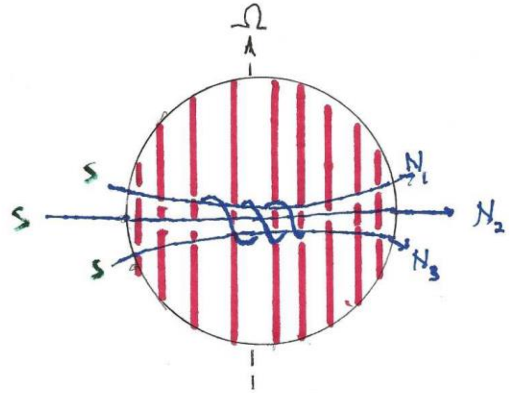
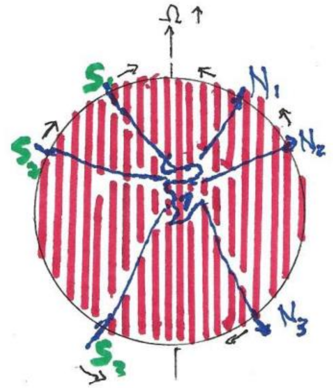


Fig. 2. Folded light curves, with a resolution of 32 phase bins per period, of the 16 pulsars discovered with the Fermi LAT, using 5 months of data with $E >$ 300 MeV,

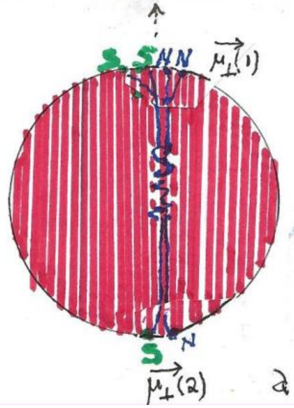
Neutron Star Spin-up



$\dot{\Omega} = 0$
(Ω spin-up)

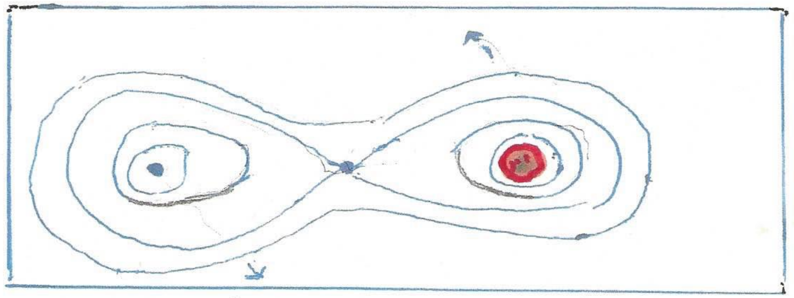


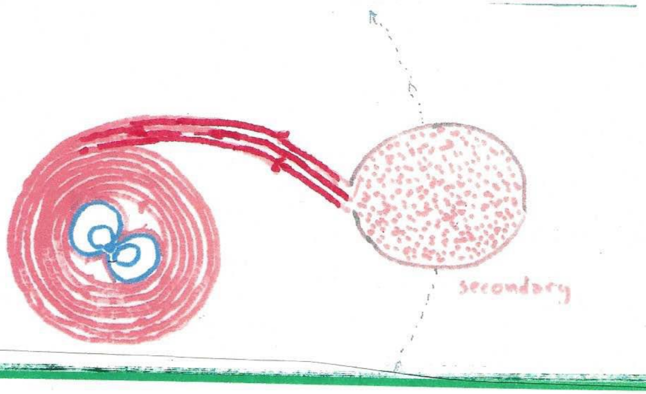
$\dot{\Omega} > 0$

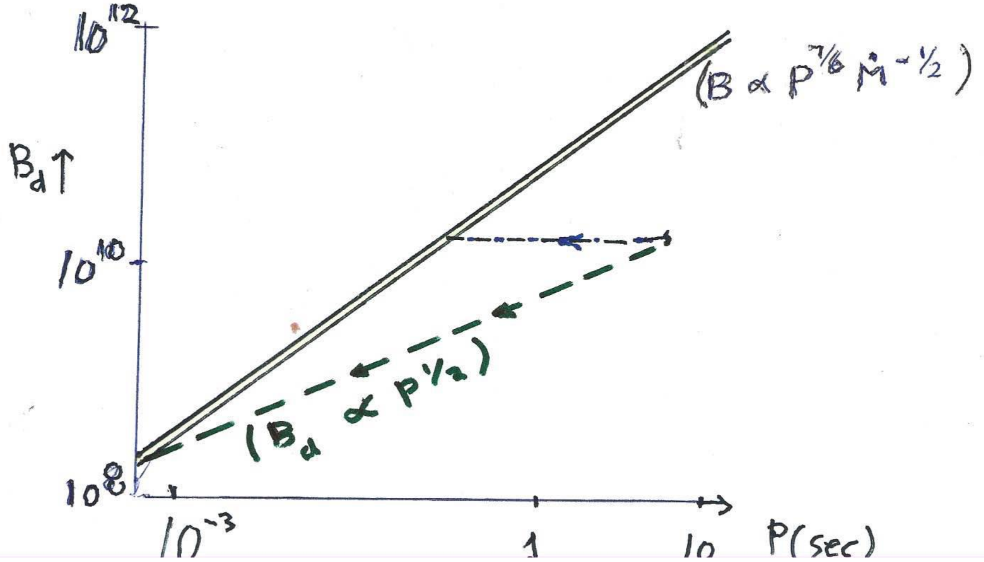


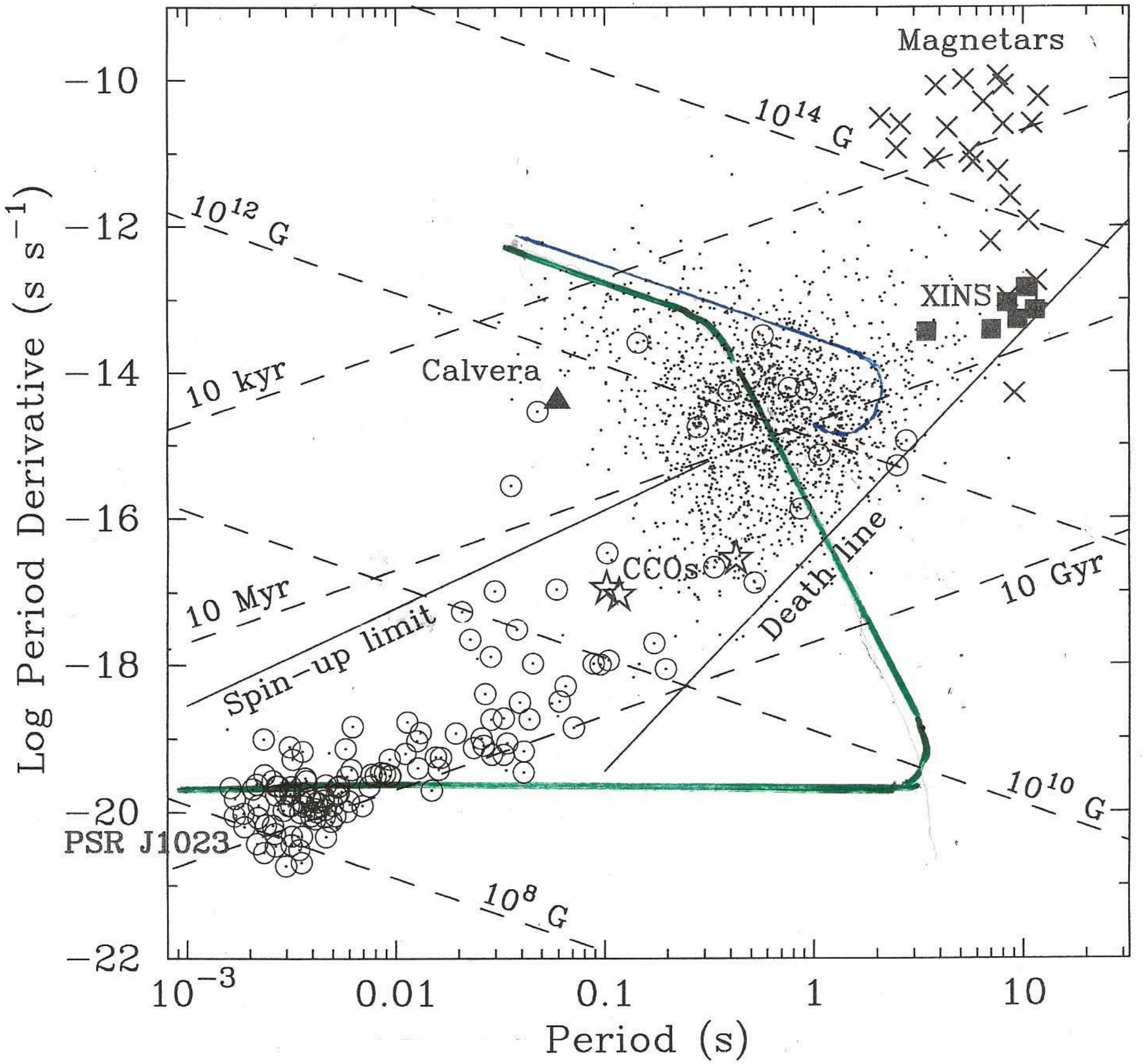
$\Omega = \Omega_{MSP}$

$d \sim R\left(\frac{\Omega_{SU}}{\Omega_{MSP}}\right)^{1/2} \sim 10^{-2} R$




secondary


10^{12}
$(B \propto P^{7/6} \dot{M}^{-1/2})$
$B_d \uparrow$
10^{10}
$(B_d \propto P^{1/2})$
10^{8}
10^{-3}
1
10
P(sec)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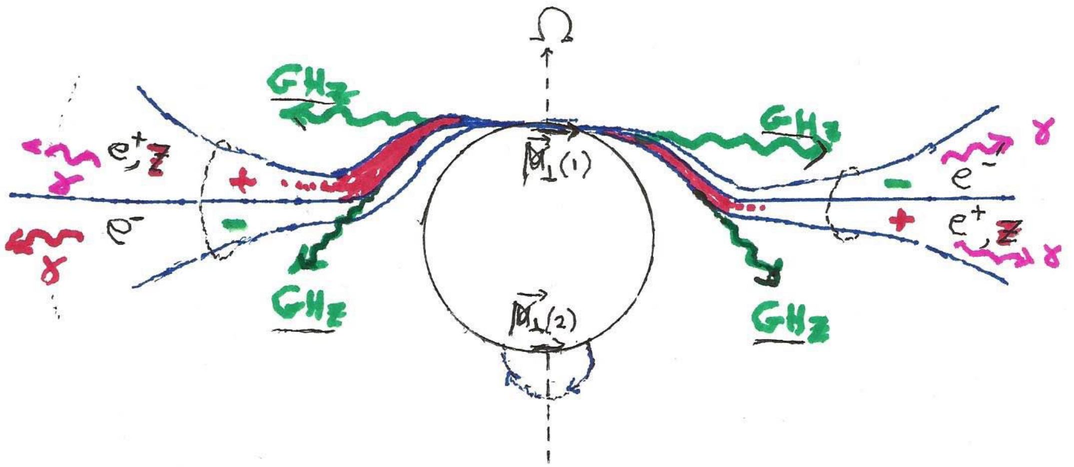
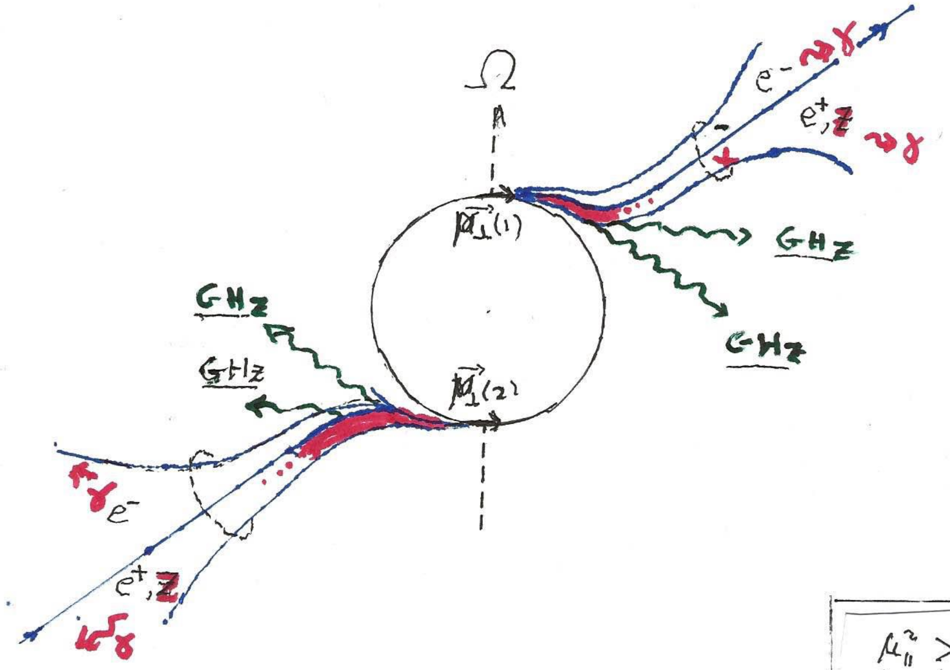
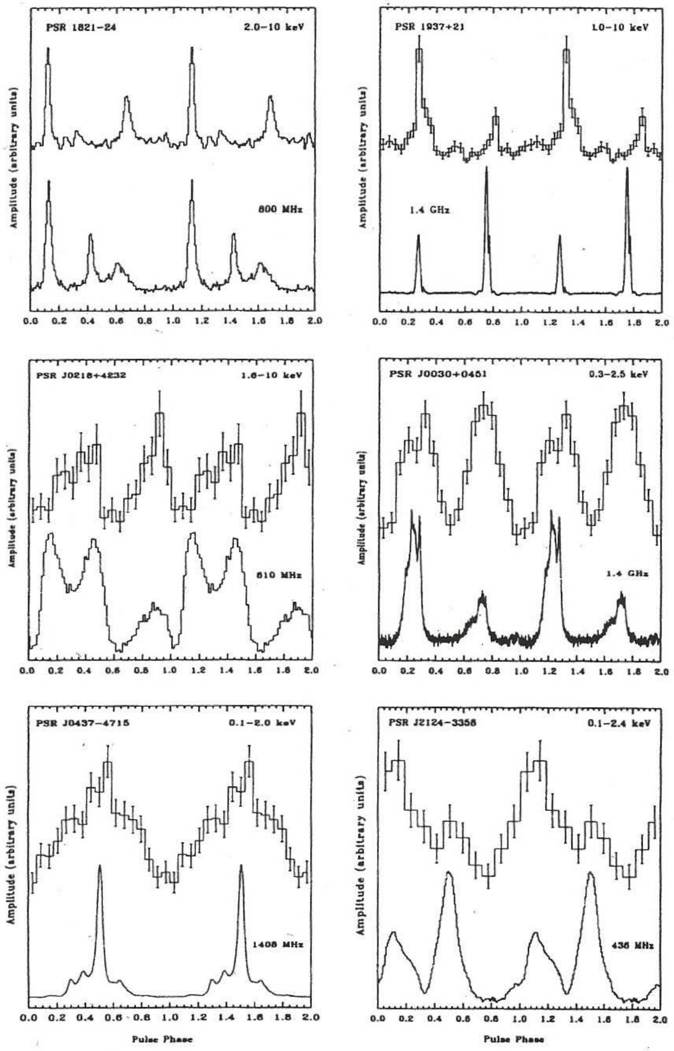
0.1
1
10



$\mu_\parallel^2 < \mu_\perp^2(1) \sim \mu_\perp^2(2)$



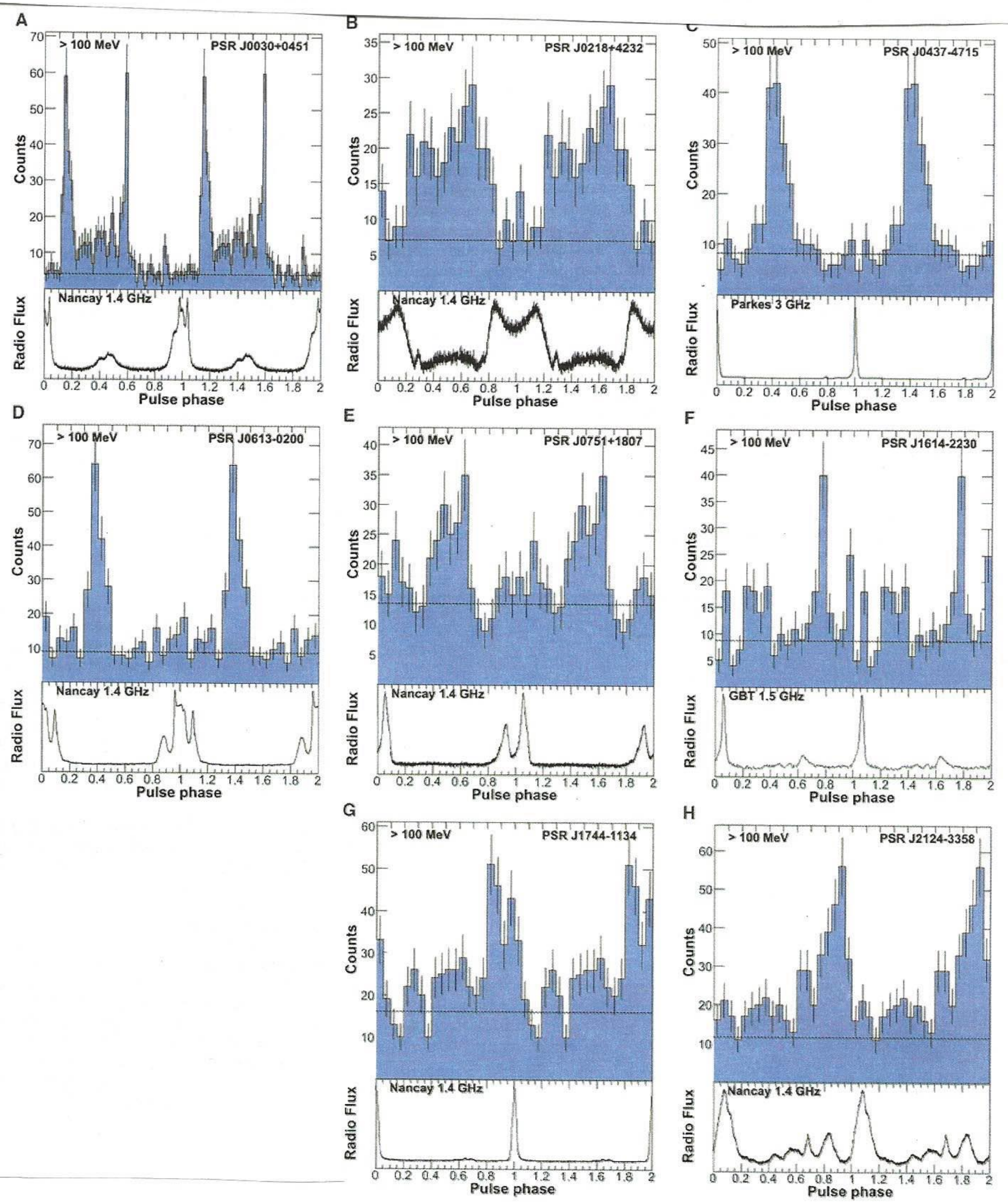
$\mu_\parallel^2 > \mu_\perp^2(1) - \mu_\perp^2(2)$

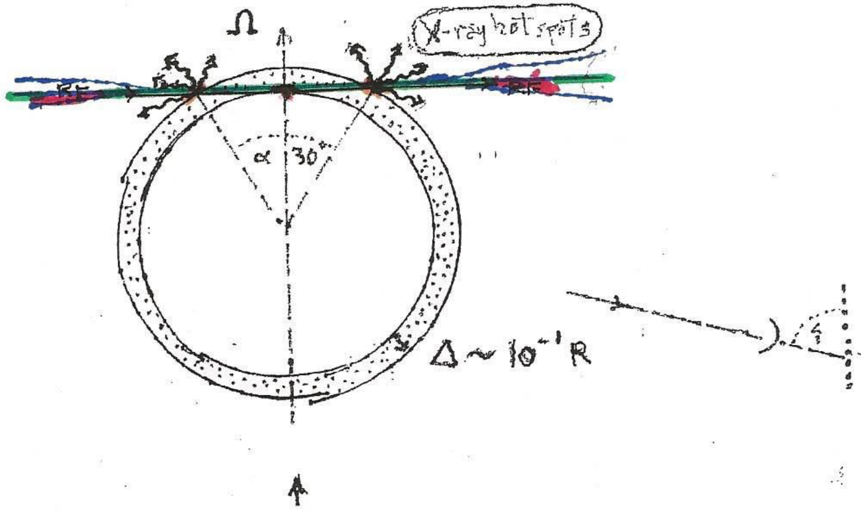


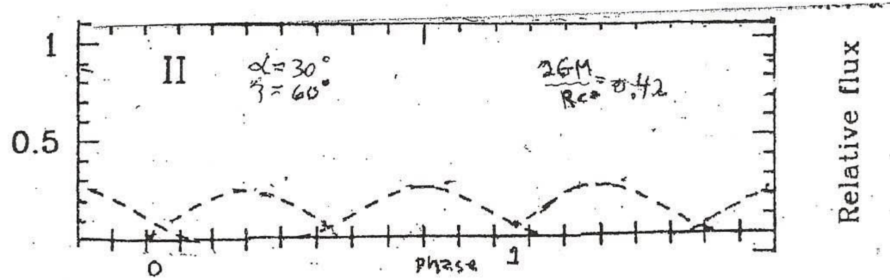
X-ray and radio pulse profiles for the six brightest ms-pulsars.

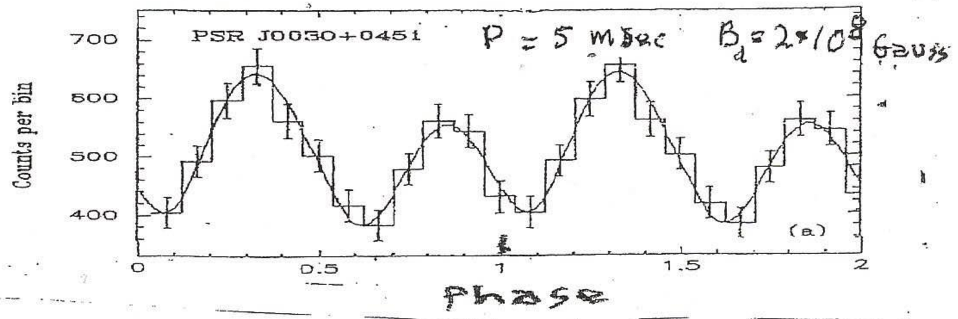
Becker (2009)

Two full pulse cycles are shown for clarity. The relative phase between the radio and X-ray pulses is only known for PSR 1821−24, B1937+21, 0218+4232 and PSR J0437−4715 with sufficient accuracy. The phase alignment in all other cases is arbitrary


A
> 100 MeV
PSR J0030+0451
Counts
Nancay 1.4 GHz
Radio Flux
Pulse phase
B
> 100 MeV
PSR J0218+4232
Counts
Nancay 1.4 GHz
Radio Flux
Pulse phase
C
> 100 MeV
PSR J0437-4715
Counts
Parkes 3 GHz
Radio Flux
Pulse phase
D
> 100 MeV
PSR J0613-0200
Counts
Nancay 1.4 GHz
Radio Flux
Pulse phase
E
> 100 MeV
PSR J0751+1807
Counts
Nancay 1.4 GHz
Radio Flux
Pulse phase
F
> 100 MeV
PSR J1614-2230
Counts
GBT 1.5 GHz
Radio Flux
Pulse phase
G
> 100 MeV
PSR J1744-1134
Counts
Nancay 1.4 GHz
Radio Flux
Pulse phase
H
> 100 MeV
PSR J2124-3358
Counts
Nancay 1.4 GHz
Radio Flux
Pulse phase

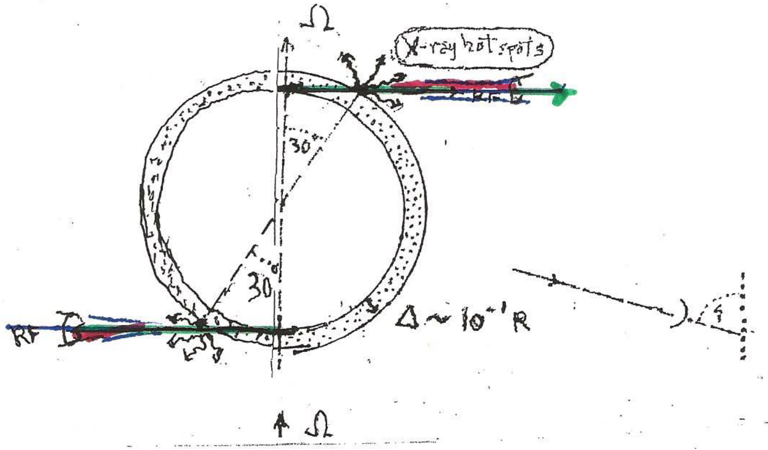


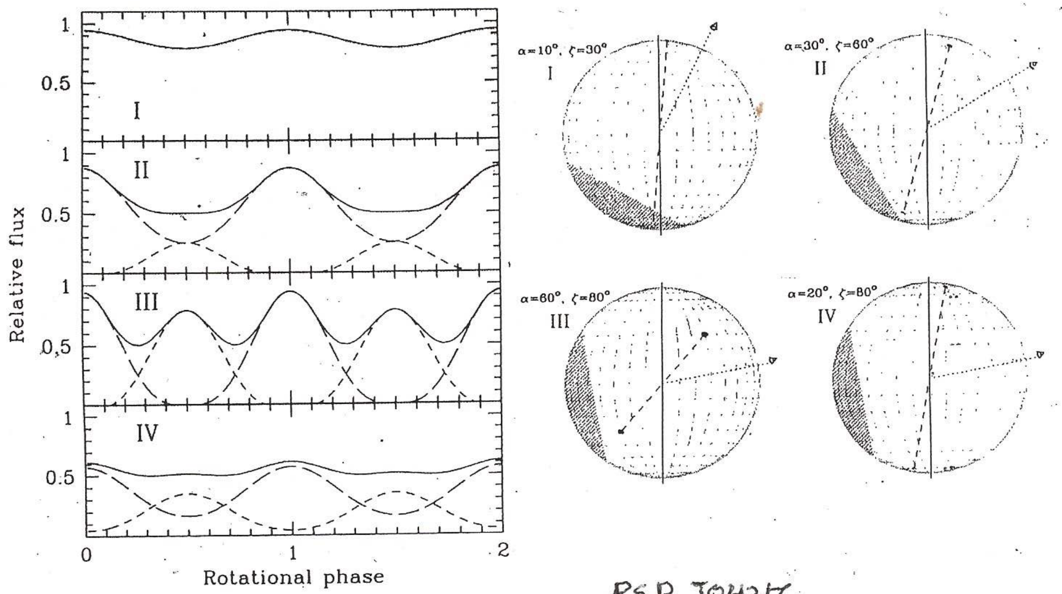




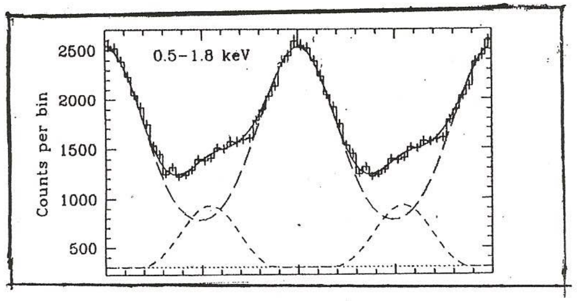
$P/\dot{P} \approx 10^{10}$ yrs

BOGDANOV, GRINDLAY, & RYBICKI (2008)

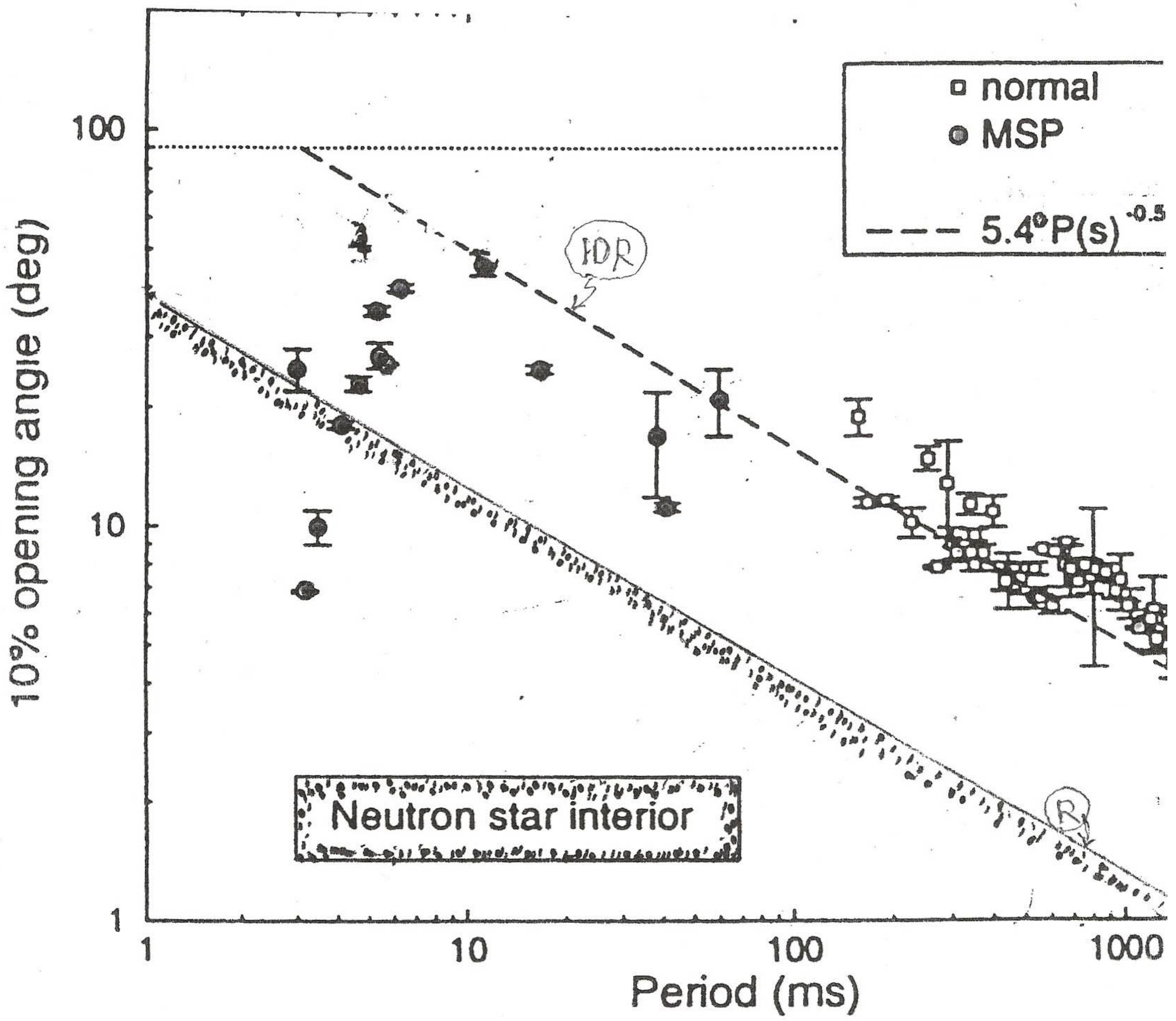




PSR J0437

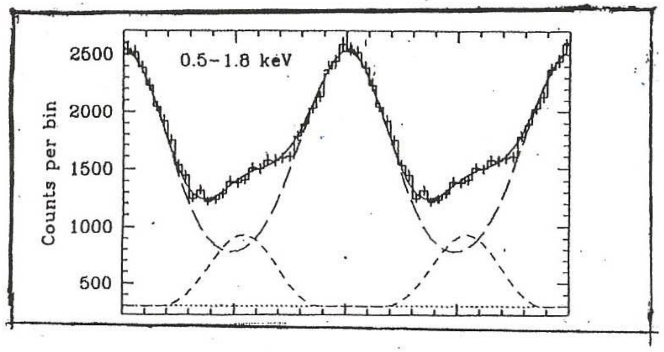


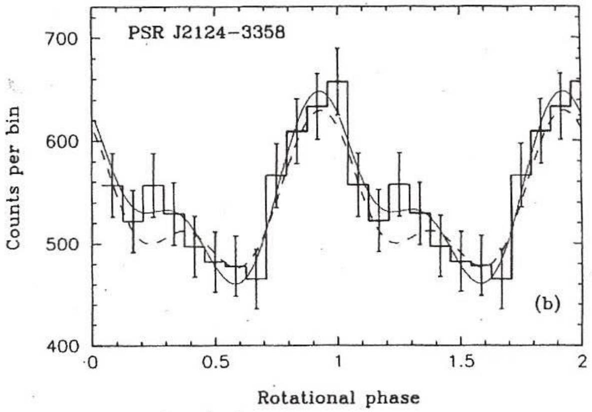
Bogdonov (2013)

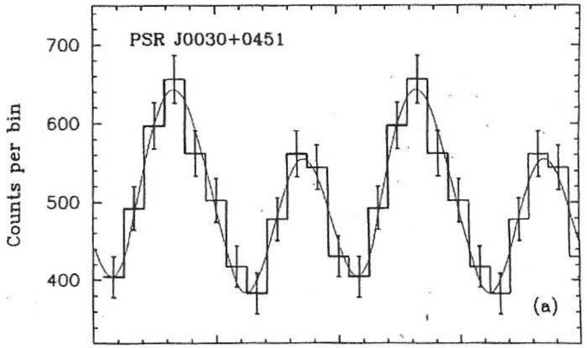


normal
MSP
5.4°P(s)^-0.5
IDR
R
Neutron star interior
10% opening angle (deg)
100
10
1
1
10
100
1000
Period (ms)

PSR J0437


0.5–1.8 keV
Counts per bin
2500
2000
1500
1000
500


PSR J2124–3358
Counts per bin
700
600
500
400
(b)
0
0.5
1
1.5
2
Rotational phase


PSR J0030+0451
Counts per bin
700
600
500
400
(a)