How neutron star magnetic fields should change with stellar spin: predictions and comparisons with observations

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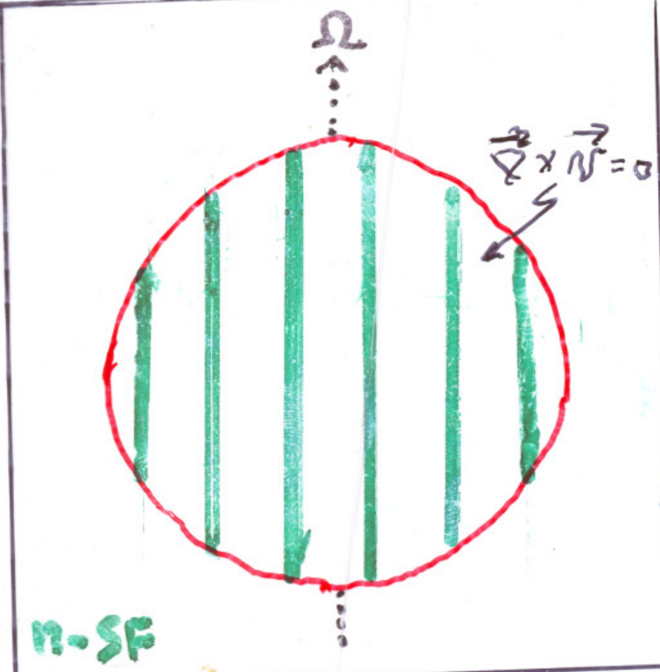
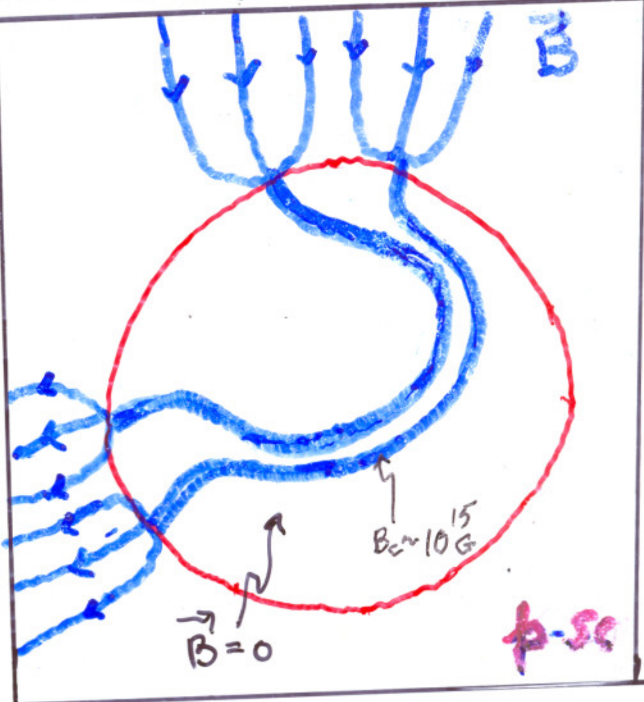
$t \sim 1\text{-}10$ yrs : p become superconductor

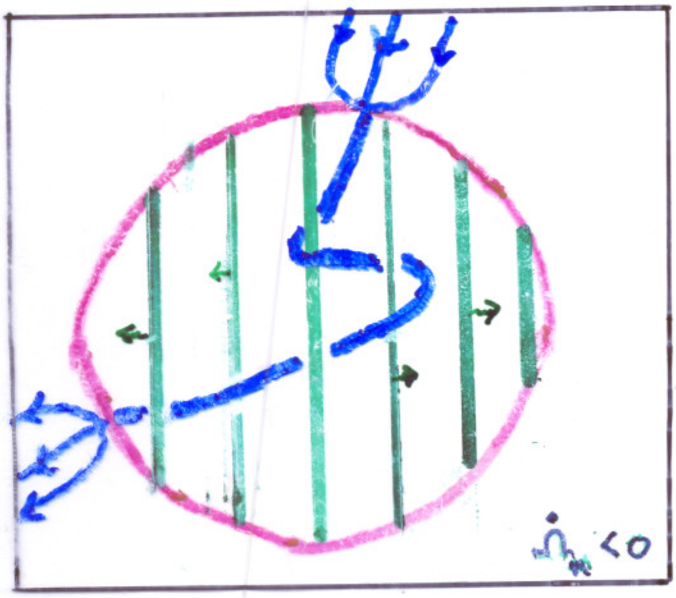
$t \sim 1000$ yrs : n become superfluid

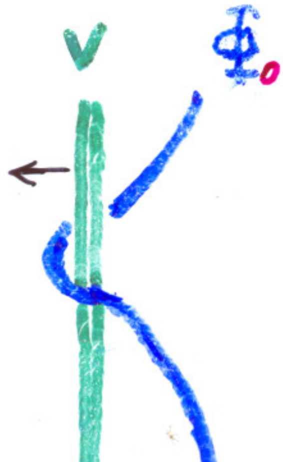




$$n_v = \frac{2m_n}{\pi\hbar}\Omega \sim \frac{10^4}{P_{(sec)}}\ cm^{-2}$$

$$n_\Phi = \left(\frac{2e}{2\pi\hbar c}\right)B \sim 2\cdot 10^{19} B_{12}\ cm^{-2}$$





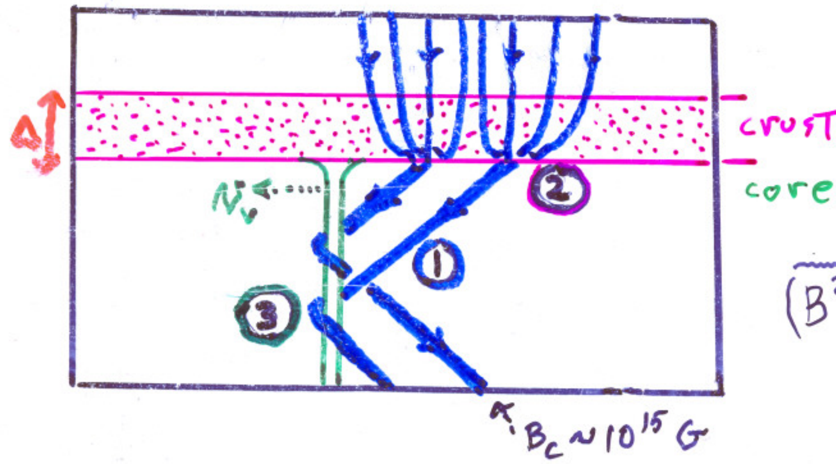
Ding, Cheng, Chau (1993)

Constraints $\vec{\Omega}$, $\vec{B}$

No cut through with Jones! days

$$T_{\parallel} = \frac{\overline{B^2}}{8\pi} \sim \frac{B_c}{B}\frac{\overline{B}^2}{8\pi} \sim 10^3 \frac{\overline{B}^2}{8\pi}$$

$$T_{\perp} = 0$$



$$\overline{(B^2)} \gg (\bar{B})^2$$

①	②	③
Maximum flux-tube shear stress on crust ($BB_c/8\pi$)	Maximum shear stress sustainable by crust ($\sigma_s \frac{\Delta}{L} \theta_{max}$)	Maximum vortex line push (pull) before cut-through ($\omega_{max} \Omega R^2 \rho_n$)
$10^{26} B_{12}$	$\sim 10^{26} \left(\frac{R}{L}\right)$	$10^{27} \Omega_2$
. . . . dyne/cm² . . .		. . .

↑ Ding, Cheng & Chau (1993)

$$\boxed{F_{1,3} > F_2}$$

(if $L \sim R$)

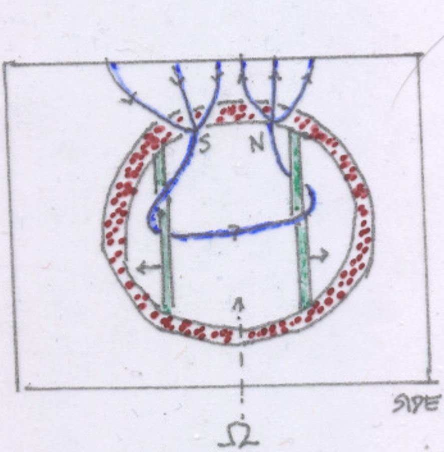
$$\boxed{\sigma \sim 10^{23} - 10^{24}\ \mathrm{sec}^{-1}}$$

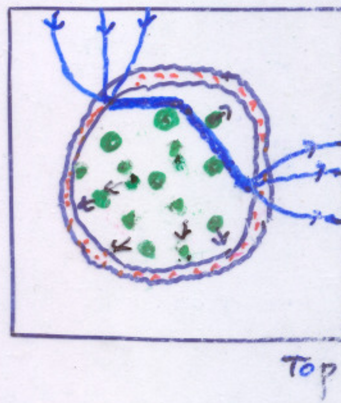
(Jones 2006)

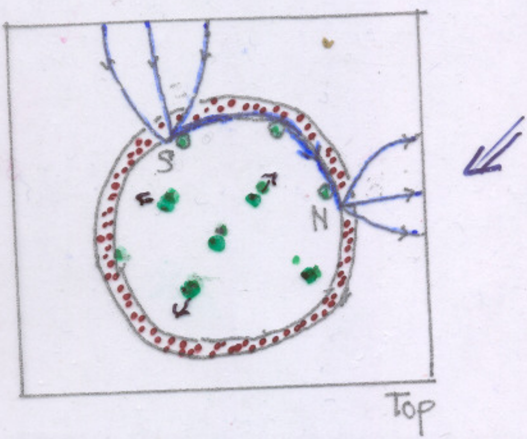
$\left(T_{core} \lesssim 3 \times 10^8 \mathrm{K}\right)$

$\left(\theta_{max} \overset{?}{\sim} 10^{-3} - 10^{-4}\right)$

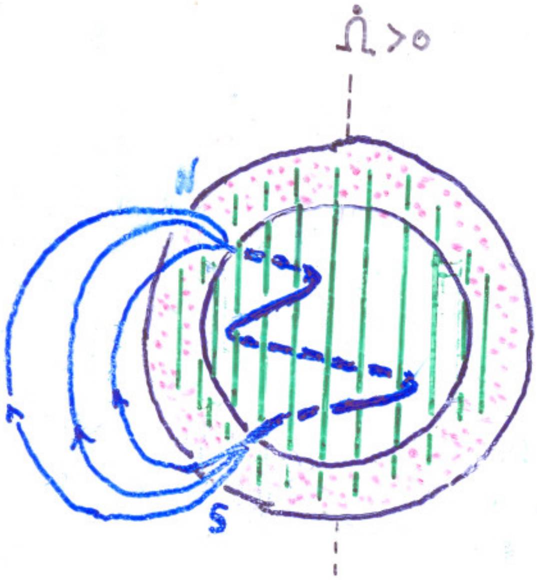
spin-down



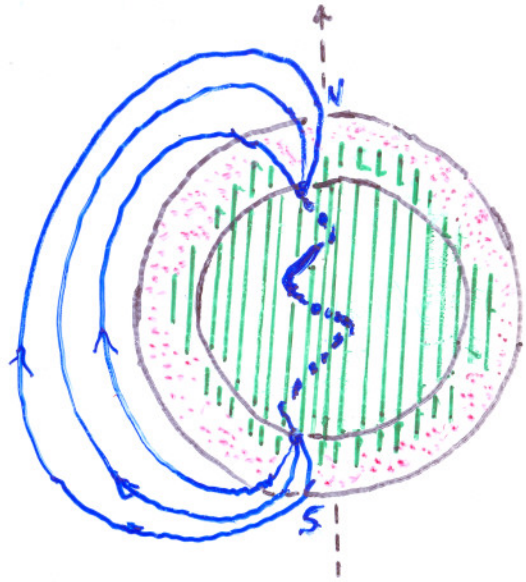




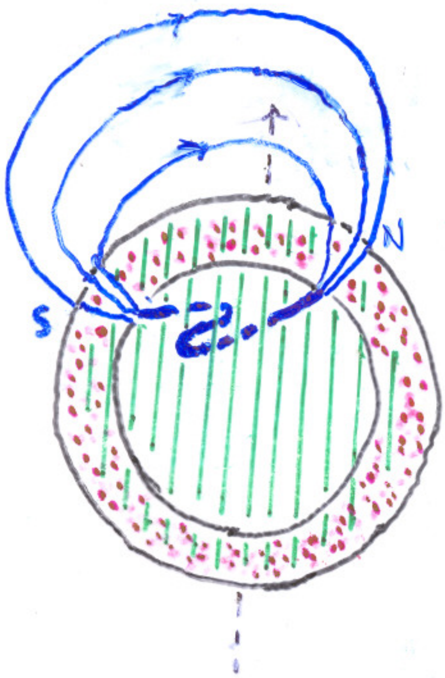
"slow" - **Spin-up** ⇒



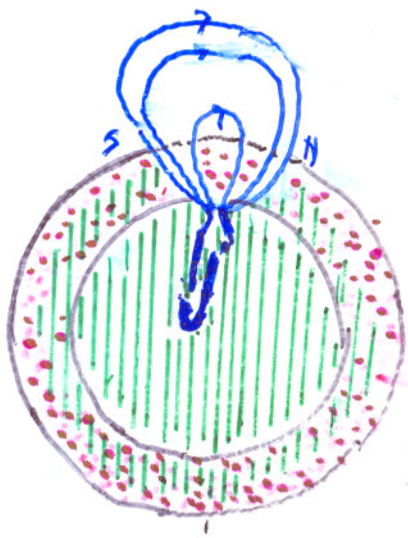
⇒



aligned rotator



⇒

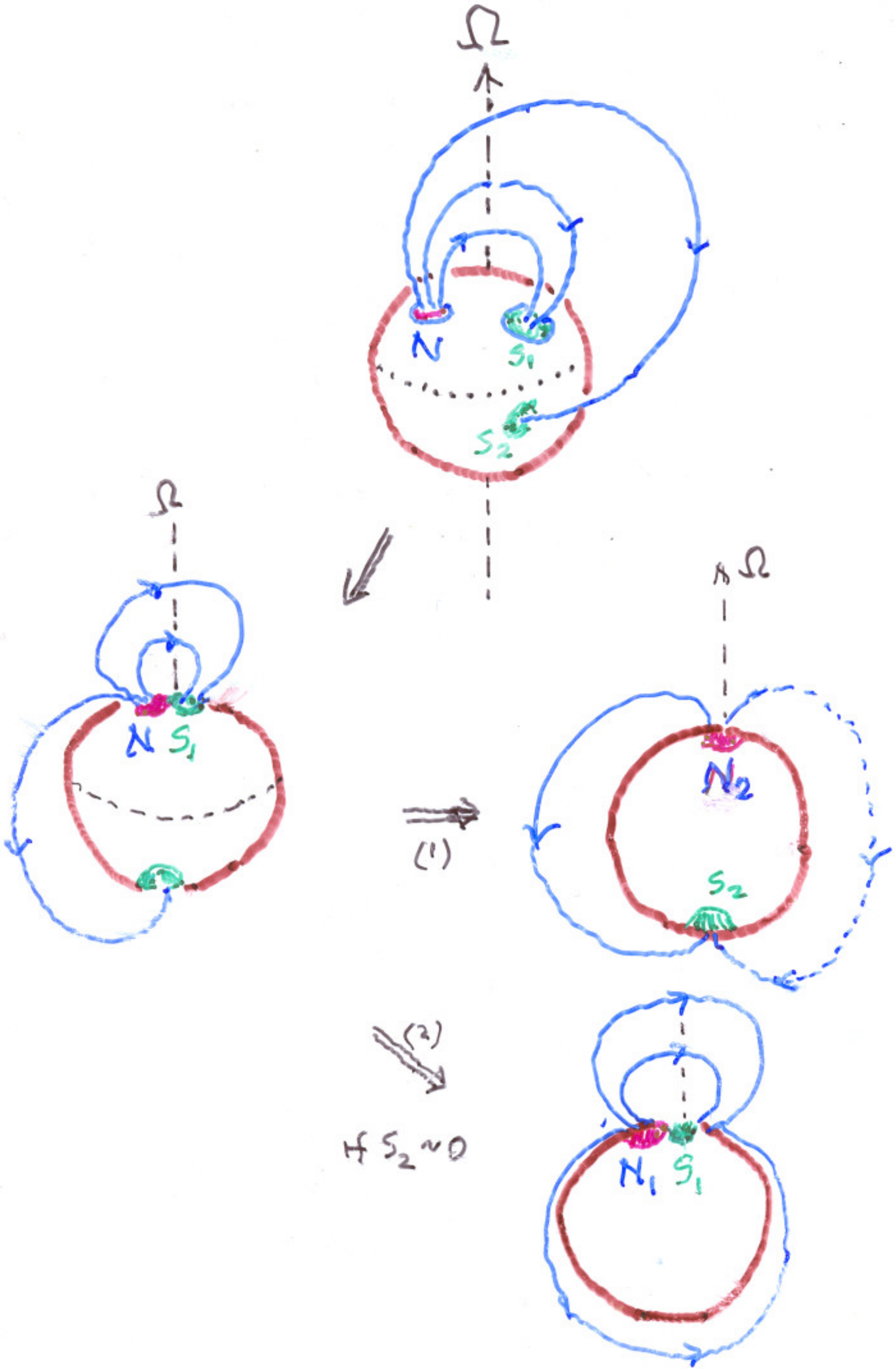


↑ orthogonal rotator

① aligned rot ↑
② orthogonal rot ↑ ③ Areas of fC.

cf
ZAVLIN

$\dot{\Omega} > 0$

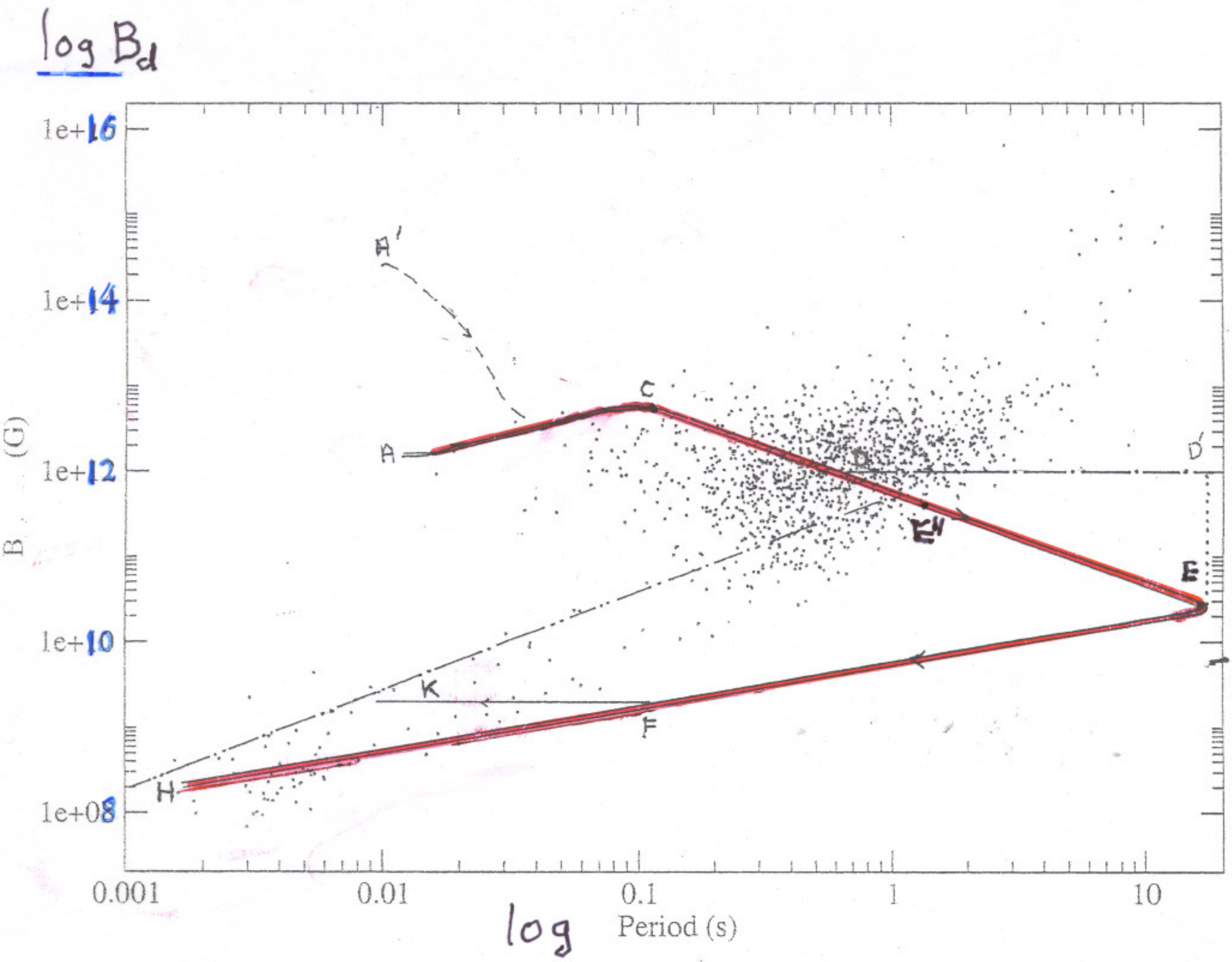


if continued $\dot{\Omega} > 0$

(1) aligned rotator (PSR 0437)

if $S_2 \ll S_1$ (PSR 1937)

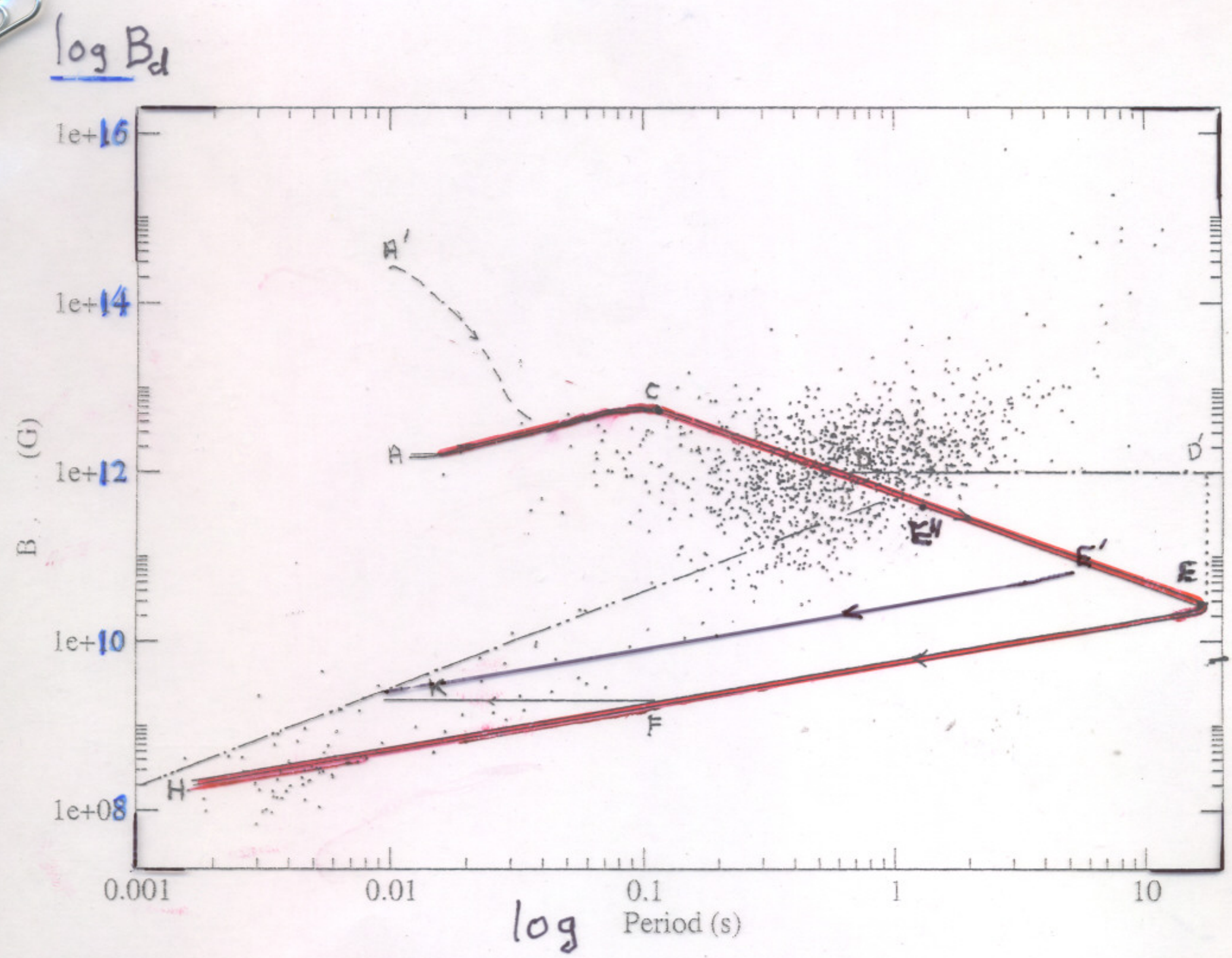
(2) orthogonal rotator



$$I\dot{\Omega} \equiv - B_d^2 R^6 \Omega^3 \equiv - A\Omega^n$$

	model	observed
a → c	2 → 3	2.5 2.1 1.8 2.2 2.9 (1.4)
C → D → E''	$\bar{n} = 5$	$\bar{n} = 4.5 \pm 0.8$ Cordes Chernov (1990)
E → F → H	n = 2	—

braking index



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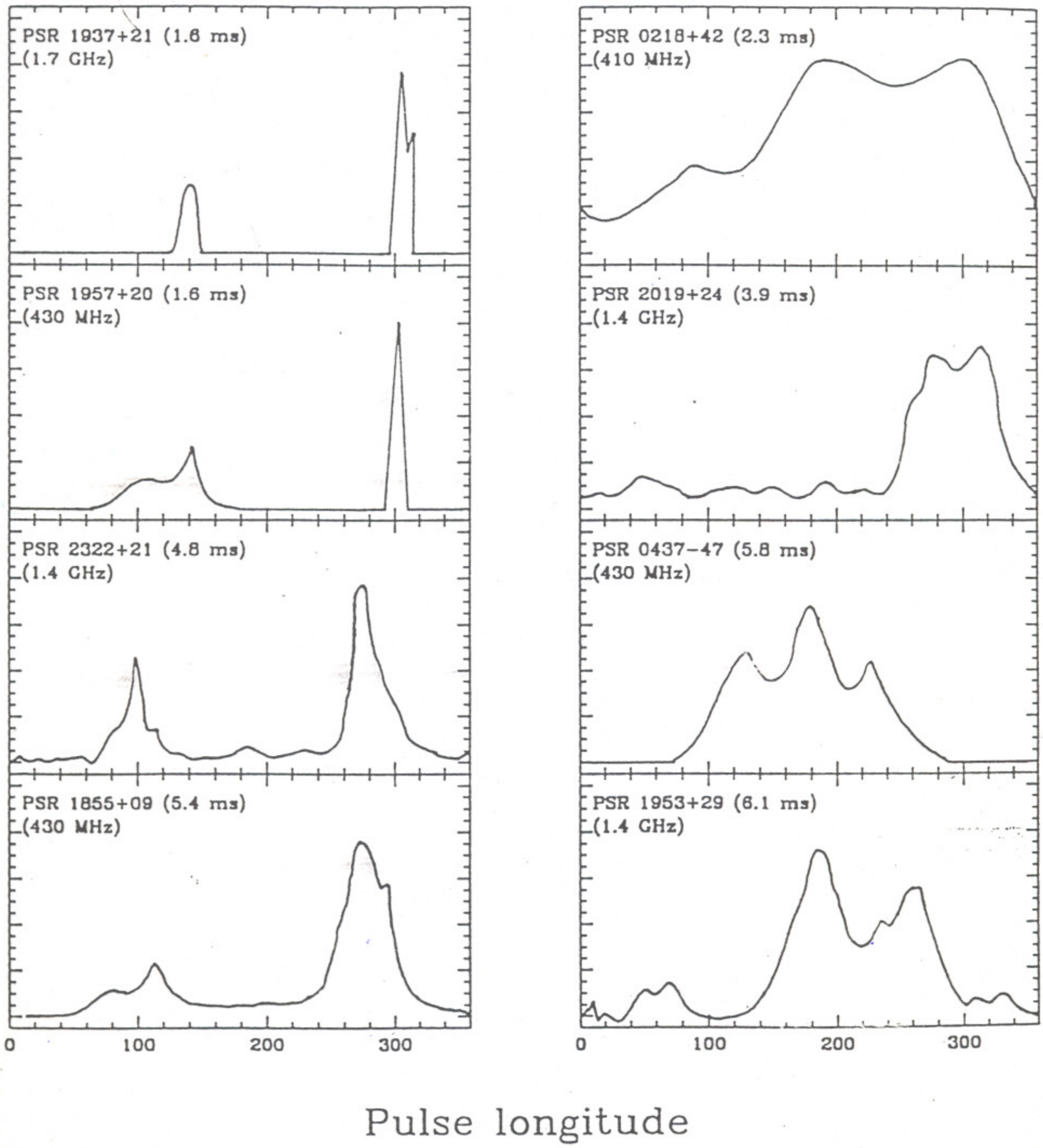
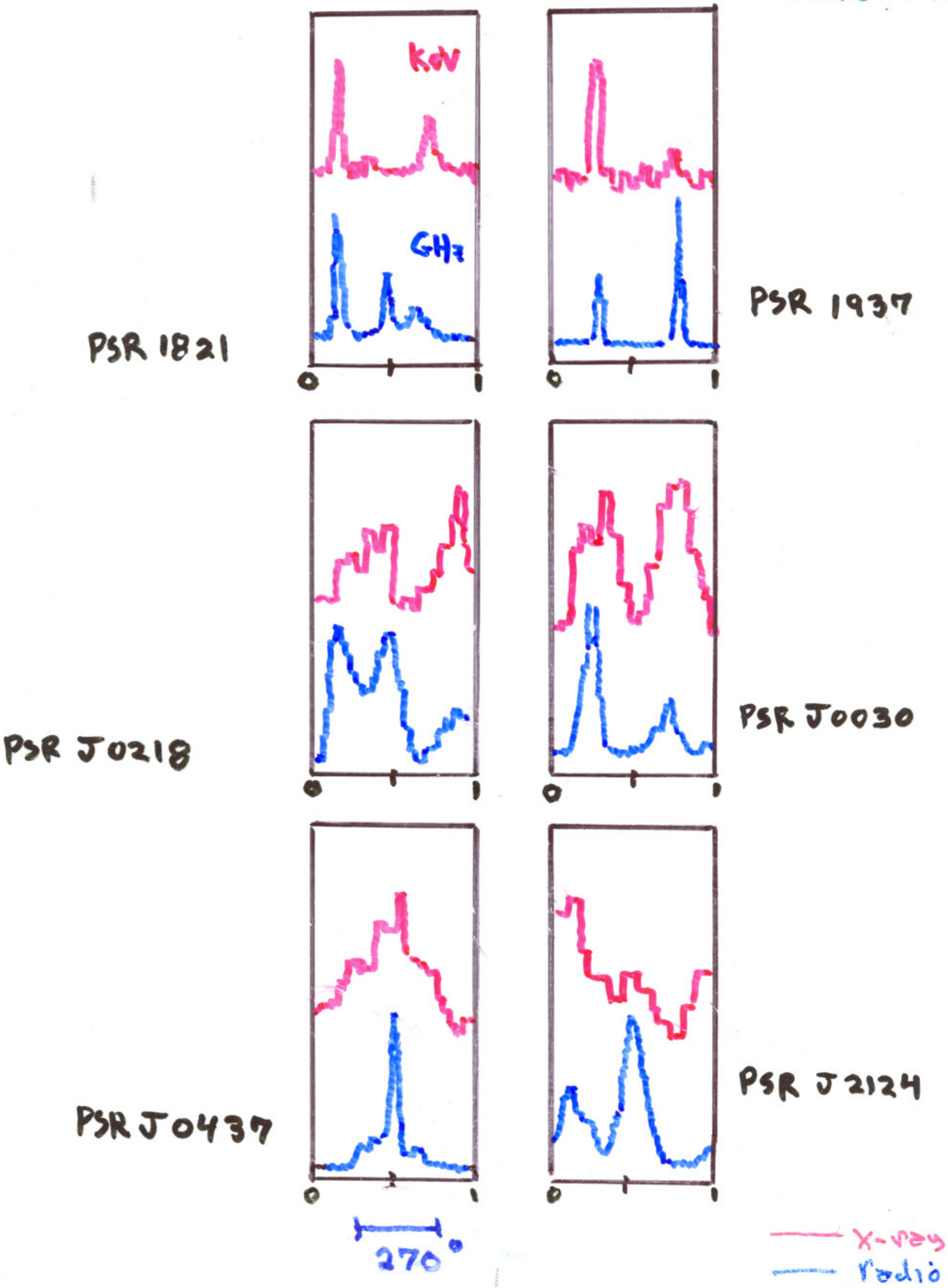


.— Radio pulse profiles of eight of the fastest eleven disk population millisecond pulsars (1997)

Grindlay et al
K. Chen MR

X-rays from Millisecond Pulsars

Becker + Aschenbach (2002)



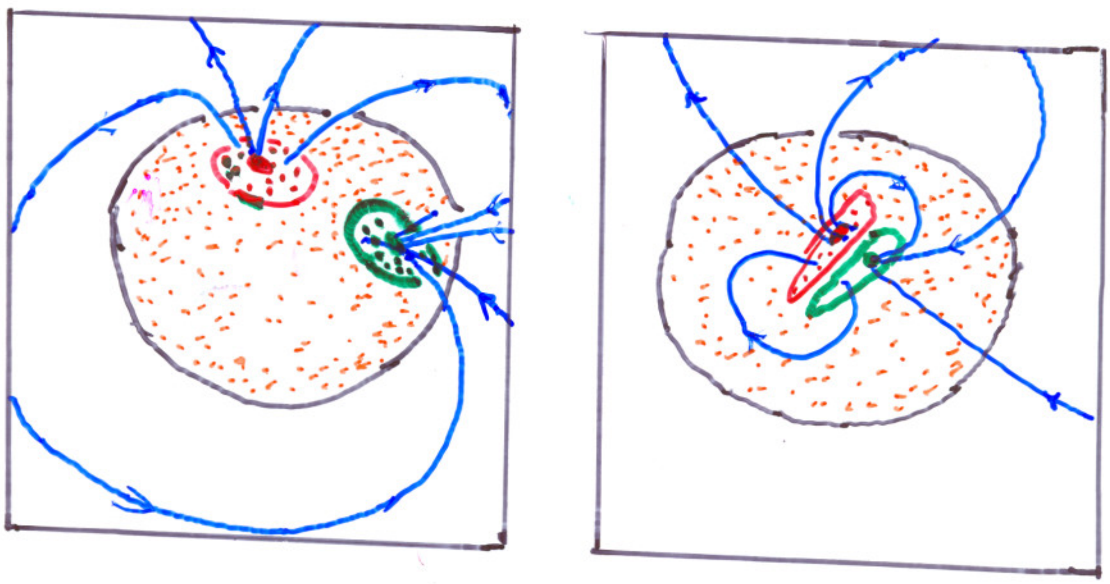
Polar cap areas (A_{pc})

$$A_{pc} \sim \left(\frac{\Omega R}{c}\right) R^2 \left(\frac{B_d}{B_{pc}}\right)$$

if $B \sim \frac{B_d R^3}{r^3}$ out to $r \sim \frac{c}{\Omega}$

$\tau \gg 10^6$ yrs $\quad B_{pc} \propto \Omega$

$\tau \ll 10^6$ yrs $\quad B_{pc}$ not sensitive to Ω

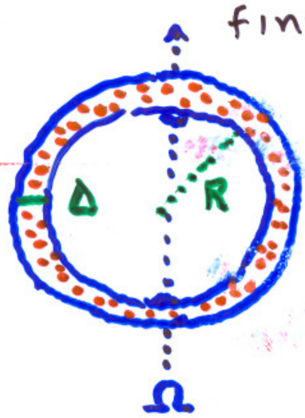


"slowly" spun-up MSP : $A_{pc} \sim \left(\frac{\Omega R}{c}\right) R^2 \left(\frac{\Omega_0}{\Omega}\right)^{3/2}$

MSP : $B_d \downarrow$ $B_{(pc)} \uparrow$ as $\Omega \uparrow$

initial $P_0 \sim 10$ s ?

final $P \sim$ several ms



If $\left(\frac{P}{P_0}\right)^{1/2} << \frac{\Delta}{R} \sim 10^{-1}$

$$\bar{R}_{pc} \sim \left(\frac{2\Delta}{2R}\right) \times \left(\frac{\Omega R}{c}\right)^{1/2} R \sim 10^{-1} \text{ km}$$

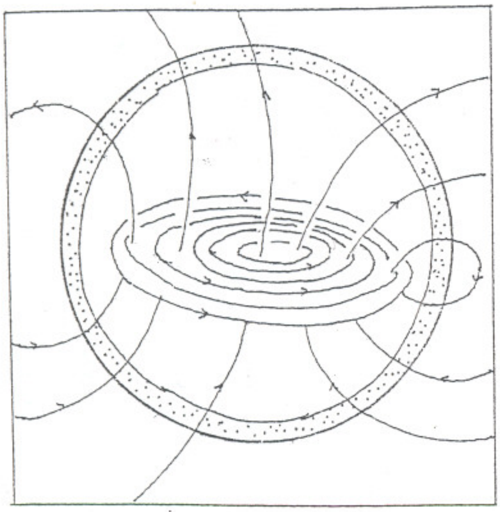
PSR		R_{pc}	
J0437	(aligned)	~ 0.1 km	?
J0030	(orthog.)	~ 0.1 km	?
J2124	(orthog.)	~ 0.1 km	?

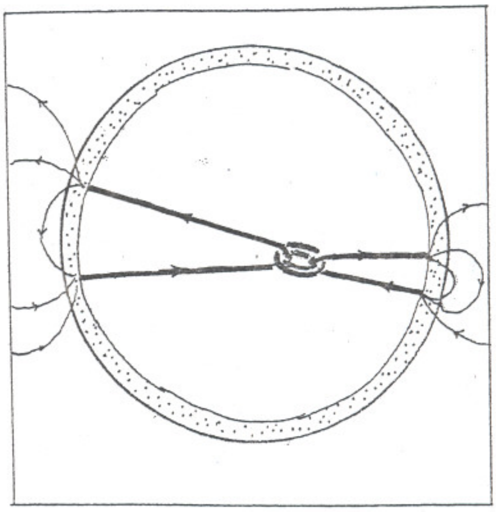
(Zavlin 2006)

1937
rad. Polarization ✓
0437
x-ray modulation ✓

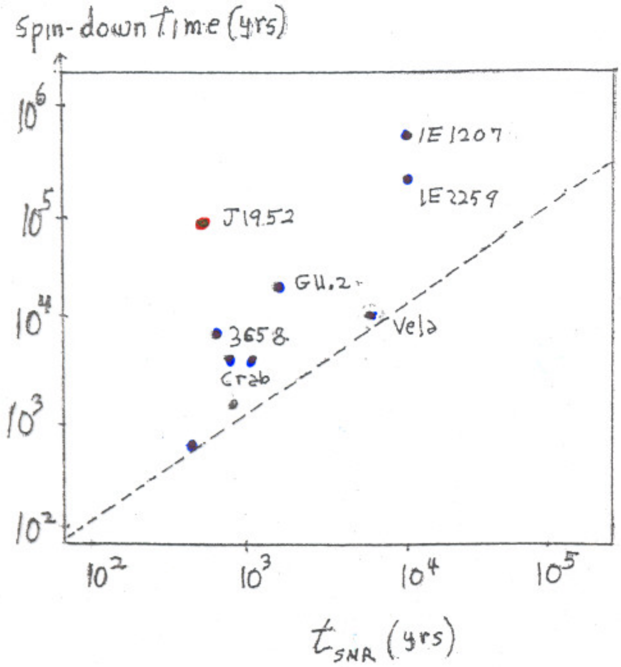
pulse width narrowing at $P \sim 3$ ms ✓

($t \sim$ 1yr – 10^3 yrs)

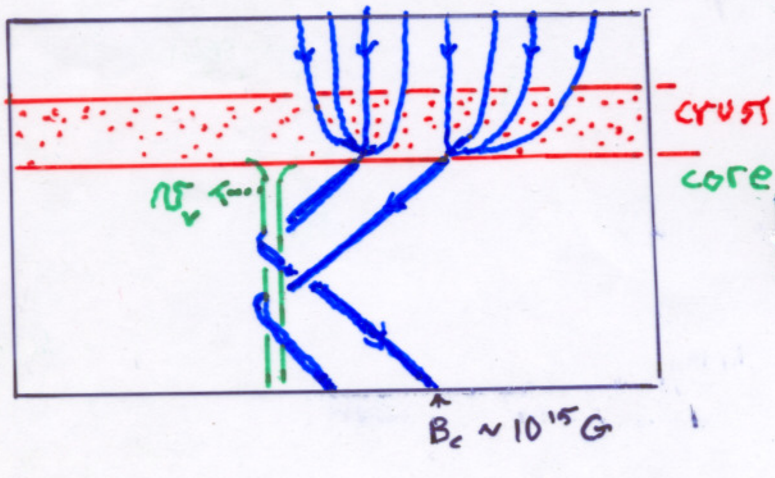




($T_{core} \to 3\times10^8$ K)



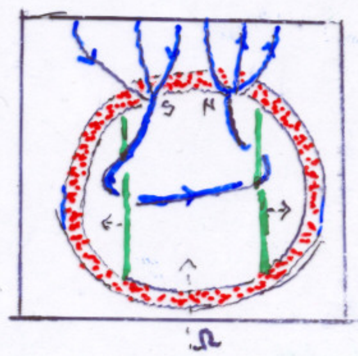
← Δs displacement in yield-events (glitches)



ω cut through $\sim 3\cdot 10^{-2}\, s^{-1}$

$$\overline{B^2} = B_c \overline{B} \gg \langle \overline{B} \rangle^2$$

Crab-like "glitches"



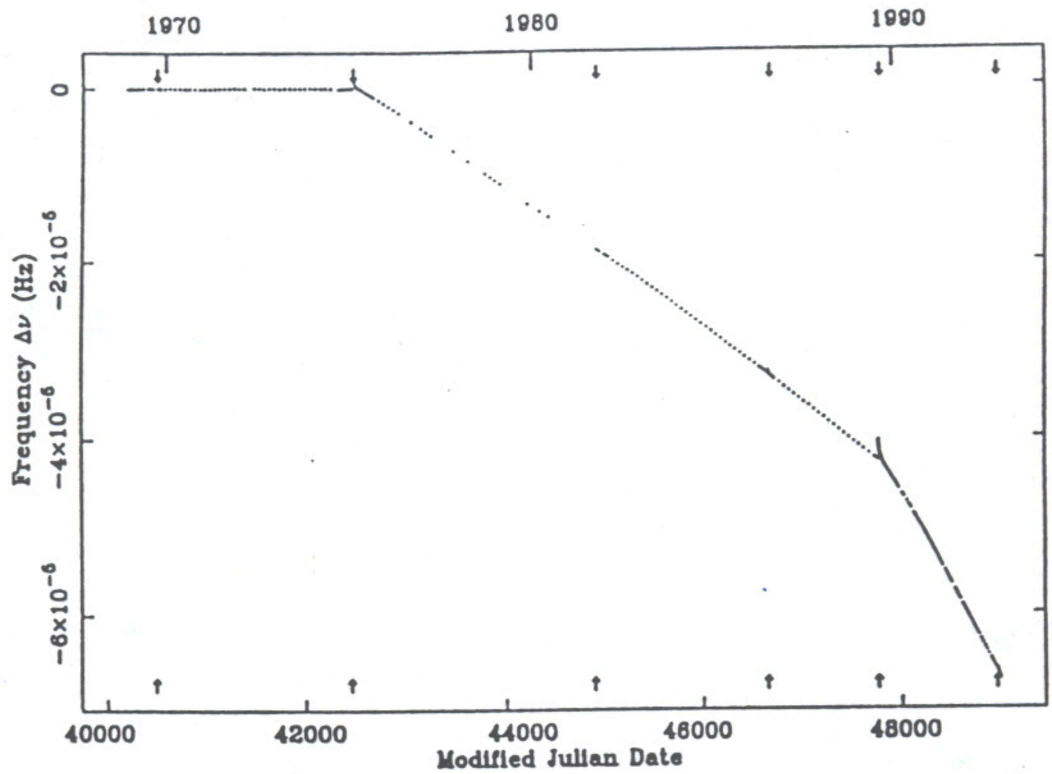
$$\frac{\Delta \dot{\Omega}}{\dot{\Omega}} \sim \frac{\Delta B_d^2}{B_d^2} \sim \frac{\Delta s}{R}$$

$$\Rightarrow \frac{\Delta \Omega}{\Omega} \sim \frac{B B_c}{8\pi \rho R^2 \Omega^2} \left(\frac{\Delta s}{R}\right) \sim 10^{-5} \left(\frac{\Delta \dot{\Omega}}{\dot{\Omega}}\right)$$

(Lyne, Backer, et al)

$\left(\frac{\Delta s}{R}\right)_{max} \sim 3\cdot 10^{-4}$: plausible but not predictable

Crab pulsar "glitches"



Lyne (1994)

The rotation frequency of the Crab pulsar, PSR 0531+21, over a 23-year period, relative to a slow-down model fitted to the first few years of data.

$\frac{\Delta\dot{\Omega}}{\dot{\Omega}} \sim 5\cdot10^{-4} \Leftarrow$ crust movement $\frac{\Delta R}{R} \sim$ few $\times 10^{-4}$ per crack

{Backer et al
Lyne ...
(2001

22 yrs of Crab data

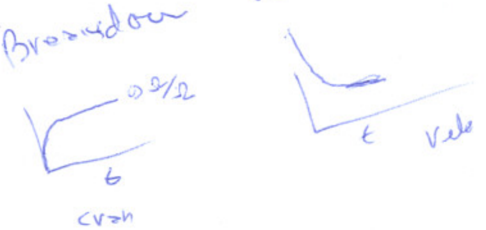
$\frac{\Delta\Omega}{\Omega} \propto \left| \frac{\Delta\dot{\Omega}}{\dot{\Omega}} \right|$

$\frac{\Delta\dot\Omega}{\dot\Omega} \propto \frac{\Delta\Omega}{\Omega}$ in Crab glitches

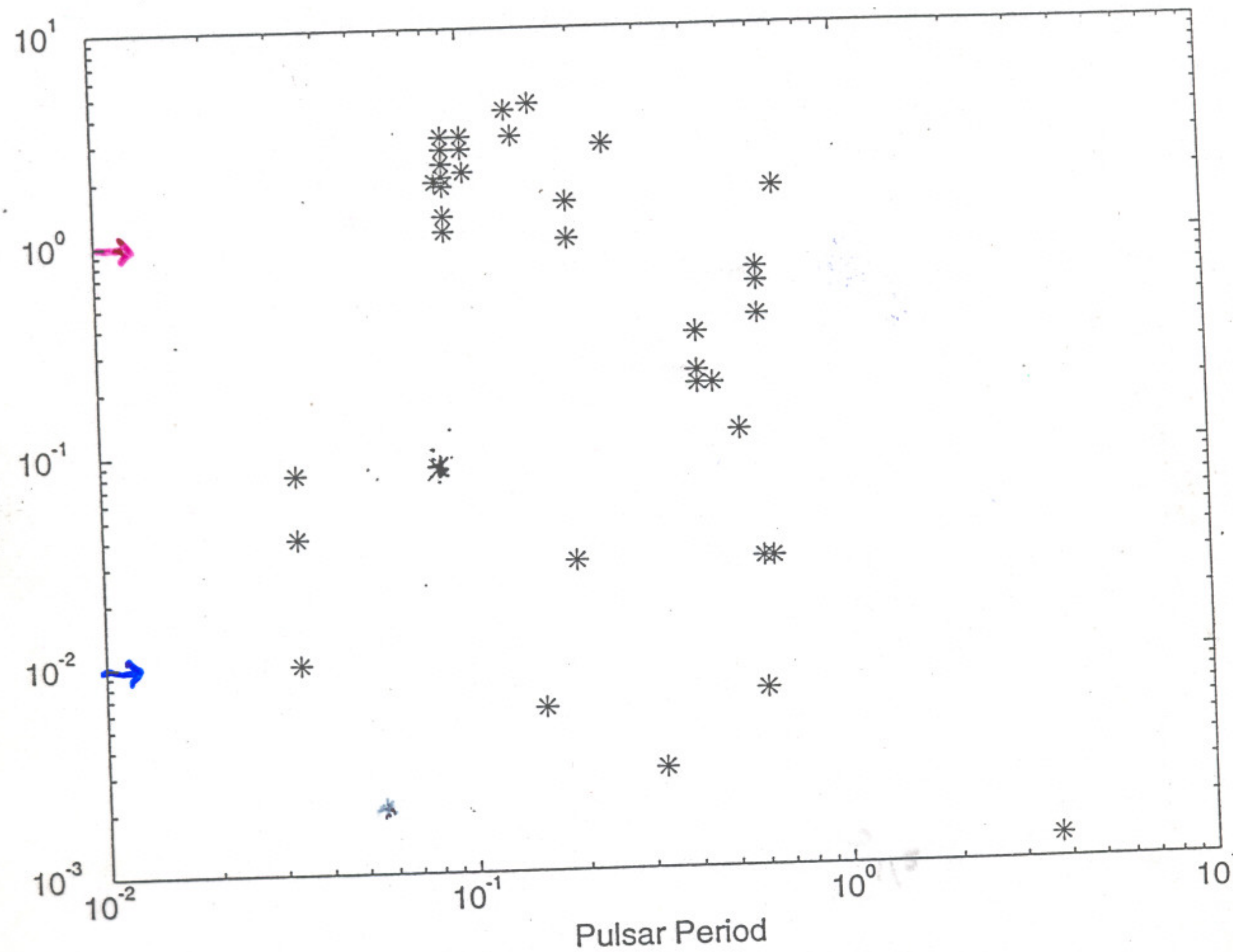
"crack"

for Vela!

1) Breakdown
2)



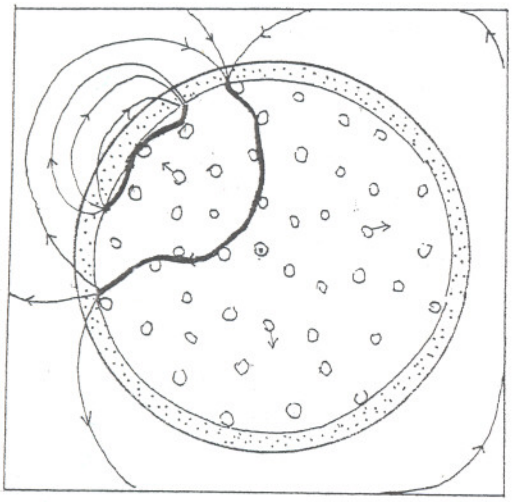
GLITCHES



V →

C →

(Lyne 1995)



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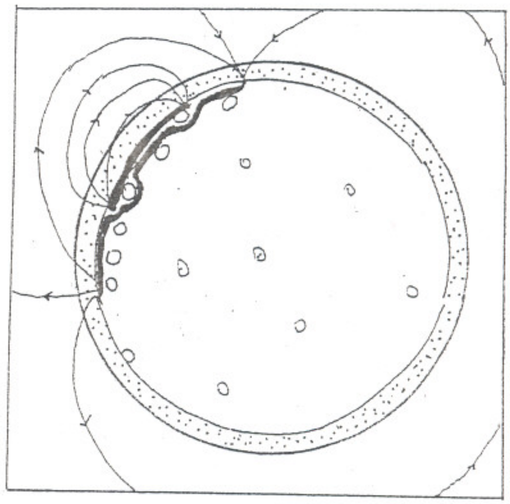

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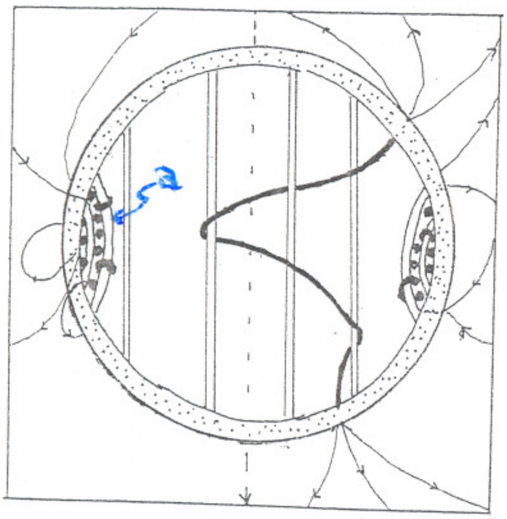

side

$$\Omega_a - \Omega_c \equiv \omega_a \sim 3 \times 10^{-2}\ s^{-1}$$

$$\left(\frac{\Delta \Omega}{\Omega}\right)_g \sim \left(\frac{\omega_a}{\Omega}\right) \times \left(\frac{B}{B_c}\right) \sim 2 \times 10^{-6} \text{ (Vela) ?}$$

$$\tau_g \sim \frac{\omega_a}{\dot{\Omega}} \sim \frac{\omega_a}{\Omega} \tau_{SD} \sim 5 \text{ yrs (Vela) ?}$$

Some important questions

- What are the consequences of the processing in the inner magnetosphere of thermal X-ray emission from an "active" neutron star's surface?

- Could the radiobeam precession inferred for some radiopulsars be only a precession of magnetospheric current patterns rather than precession of the whole neutron star?

- What happens to surface B in a very young neutron star between the onset of proton superconductivity (several years after birth) and that of neutron superfluidity (several-many centuries later)?