Thermal emission areas of heated neutron-star polar caps

M. Ruderman

A. Beloborodov

Dept. of Physics

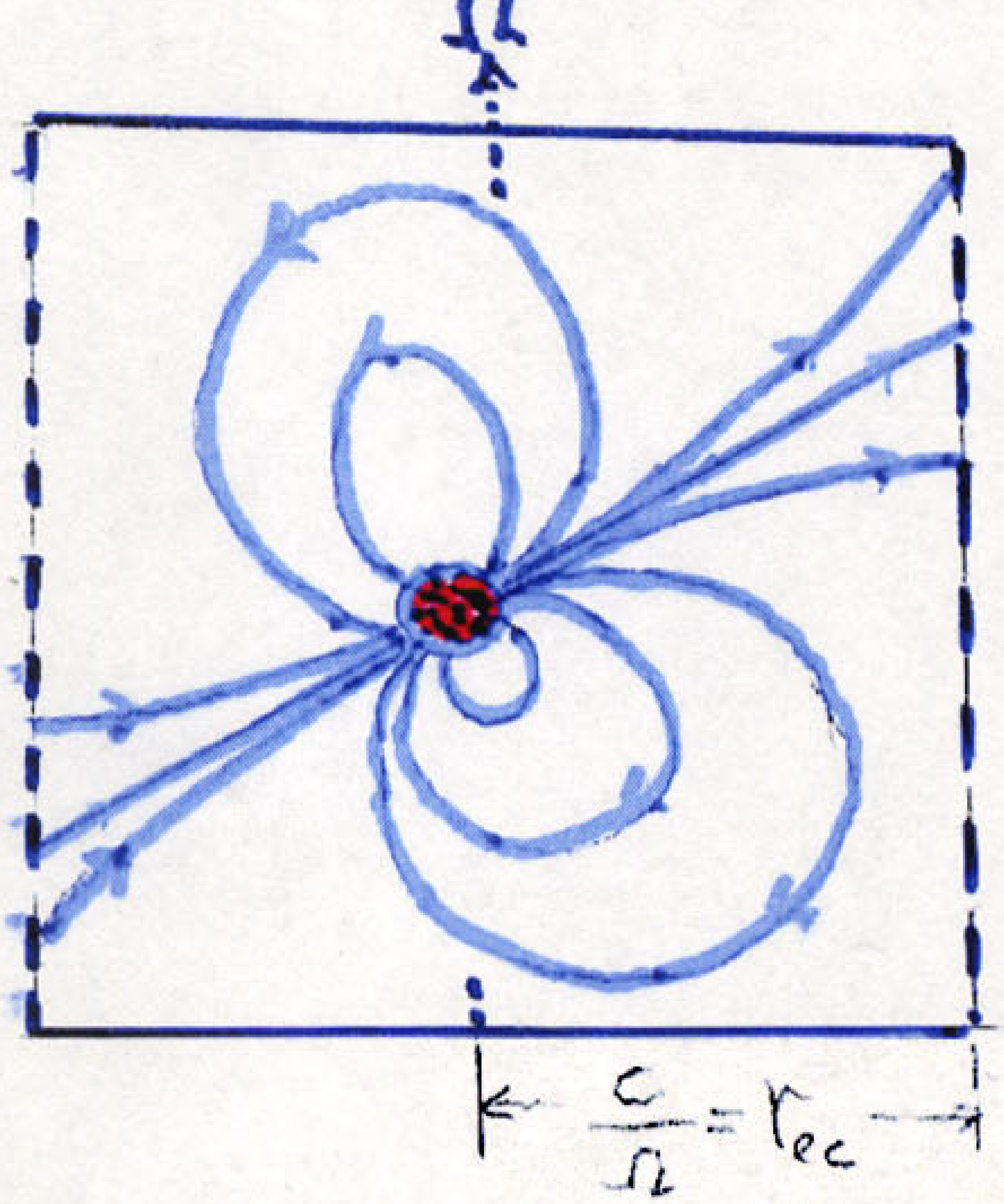
Columbia Univ.

Why are the areas of Neutron Star polar caps inferred from observations of their blackbody emission generally very much smaller than the canonical (central dipole) $\frac{\Omega R}{c} R^2$?

Already established at NS birth ?

A consequence of magnetic field evolution as a NS spins-down or is spun-up ?

Caused by the processing of thermal X-ray emission from the NS surface during its passage through the inner magnetosphere ?



"Open" field line **flux** (Φ) conservation

between $r = R_{NS}$ and $r_{lc} \equiv c/\Omega$;

① $\Phi \sim r_{lc}^2 \, B(r_{lc}) = A_{pc} B_s$ (at polar cap)

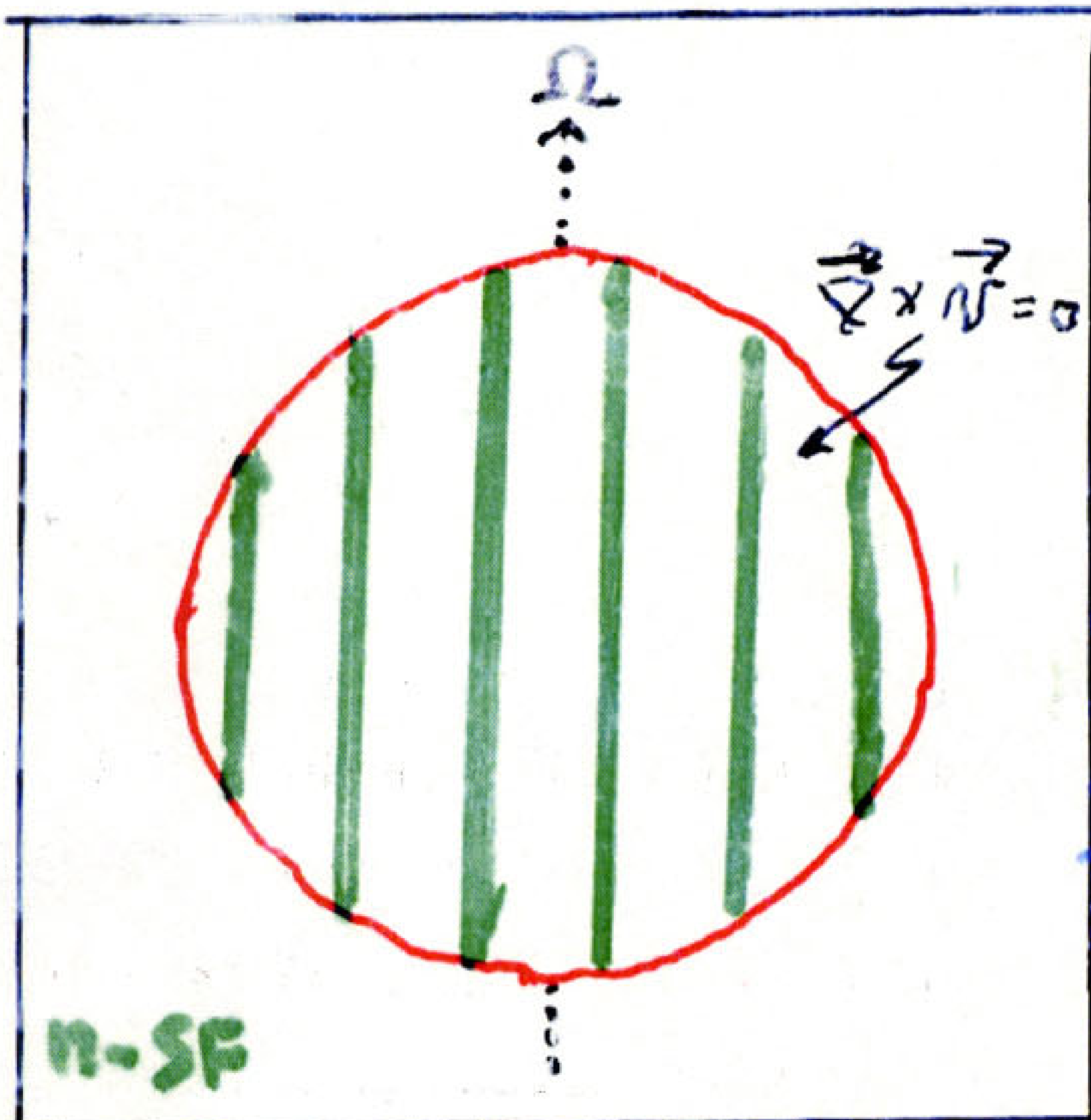
Dipole dominance ($R_{NS} \lesssim r \to c/\Omega$)

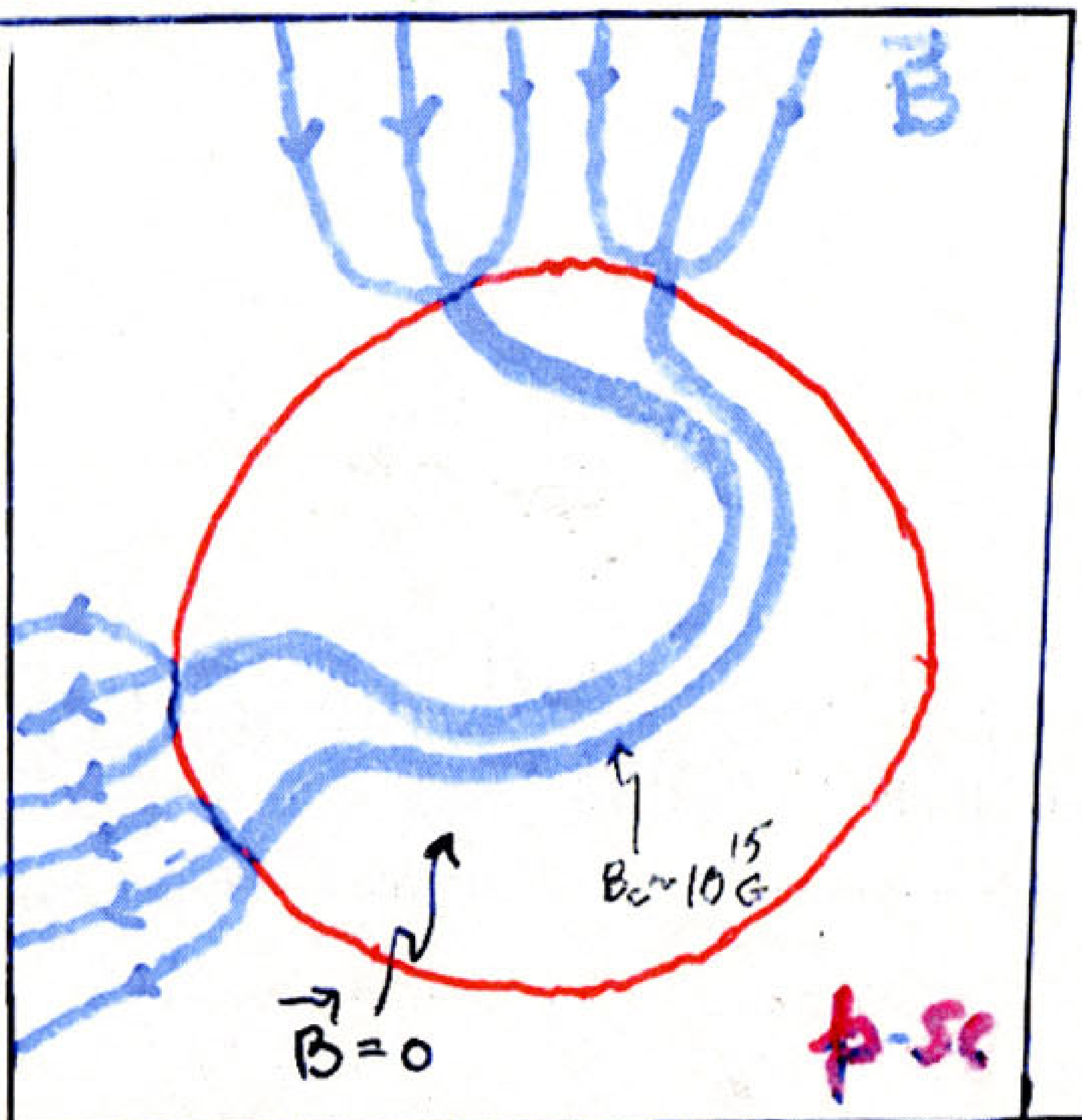
② $\dfrac{B_d R^3}{r_{lc}^3} = B(r_{lc})$

$$\boxed{A_{pc} = \left(\frac{\Omega R}{c}\right) R^2 \left(\frac{B_d}{B_s}\right)}$$

$\tau \sim$ 1–10 yrs : p become superconducting

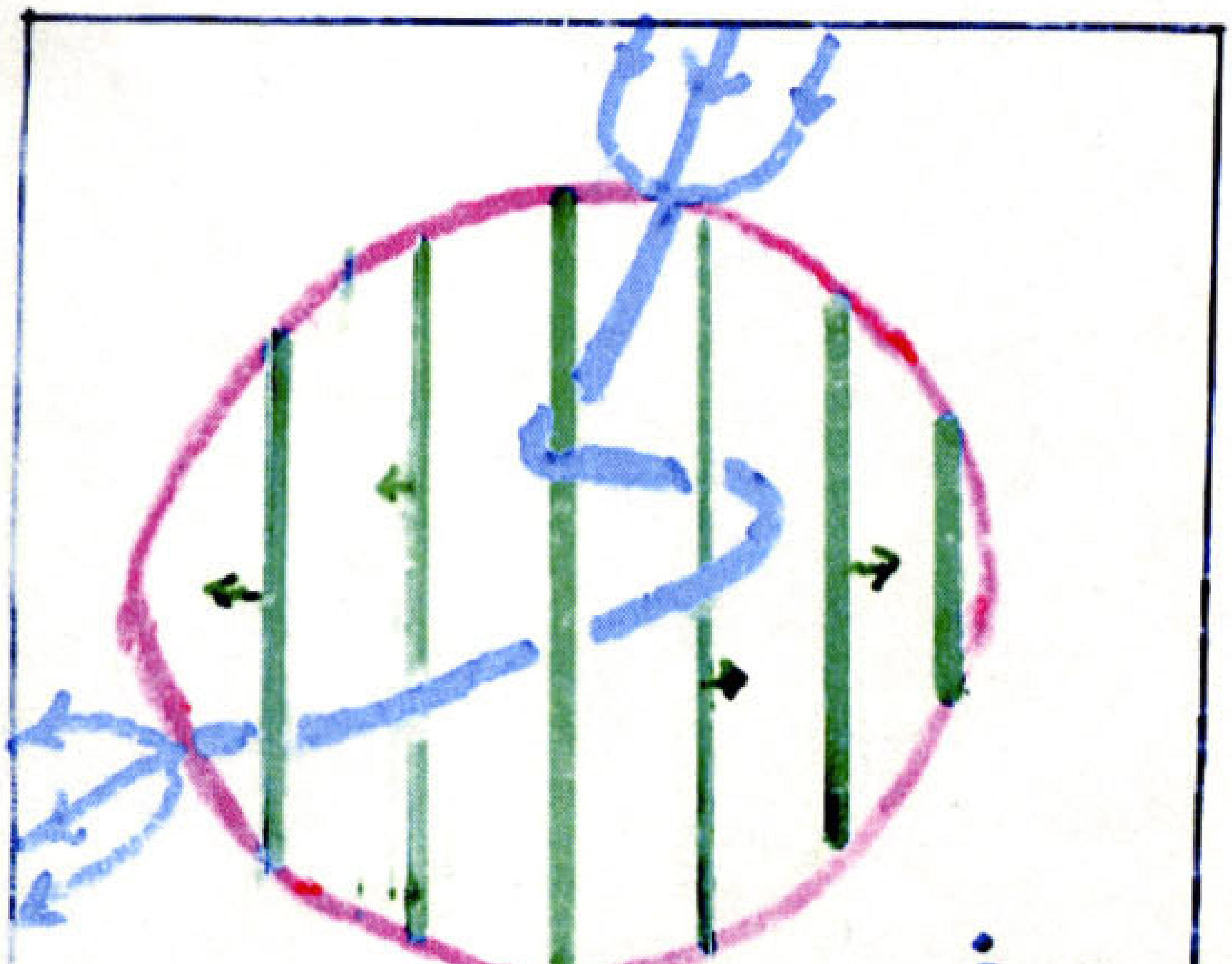
$\tau \sim$ 1000 yrs : n become superfluid

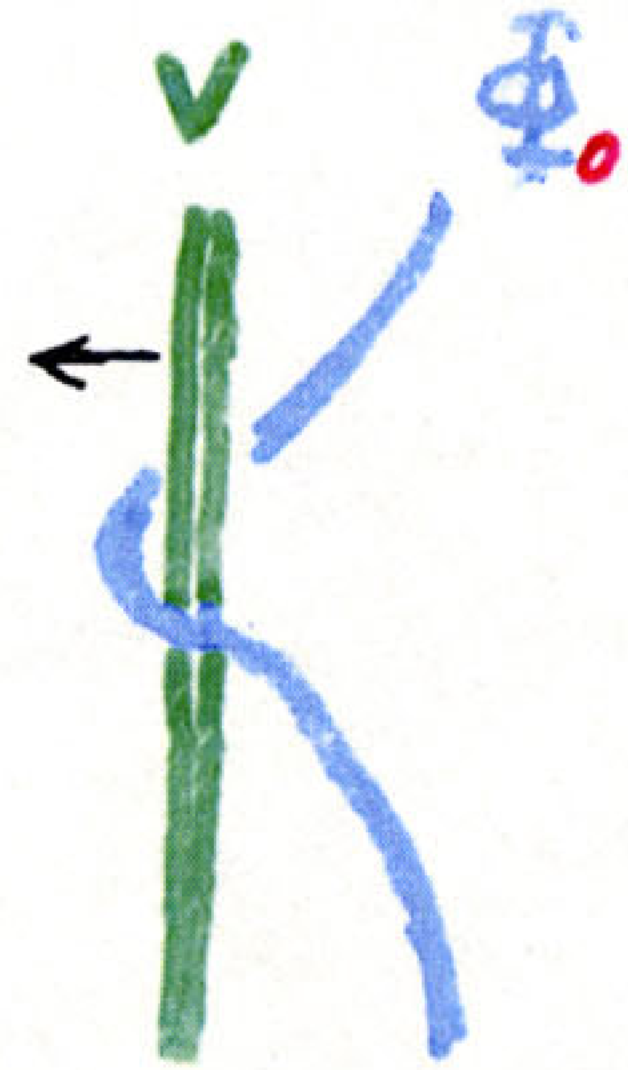




$$n_v = \frac{2m_n}{\pi\hbar}\Omega \sim \frac{10^4}{P_{(sec)}}\ \text{cm}^{-2}$$

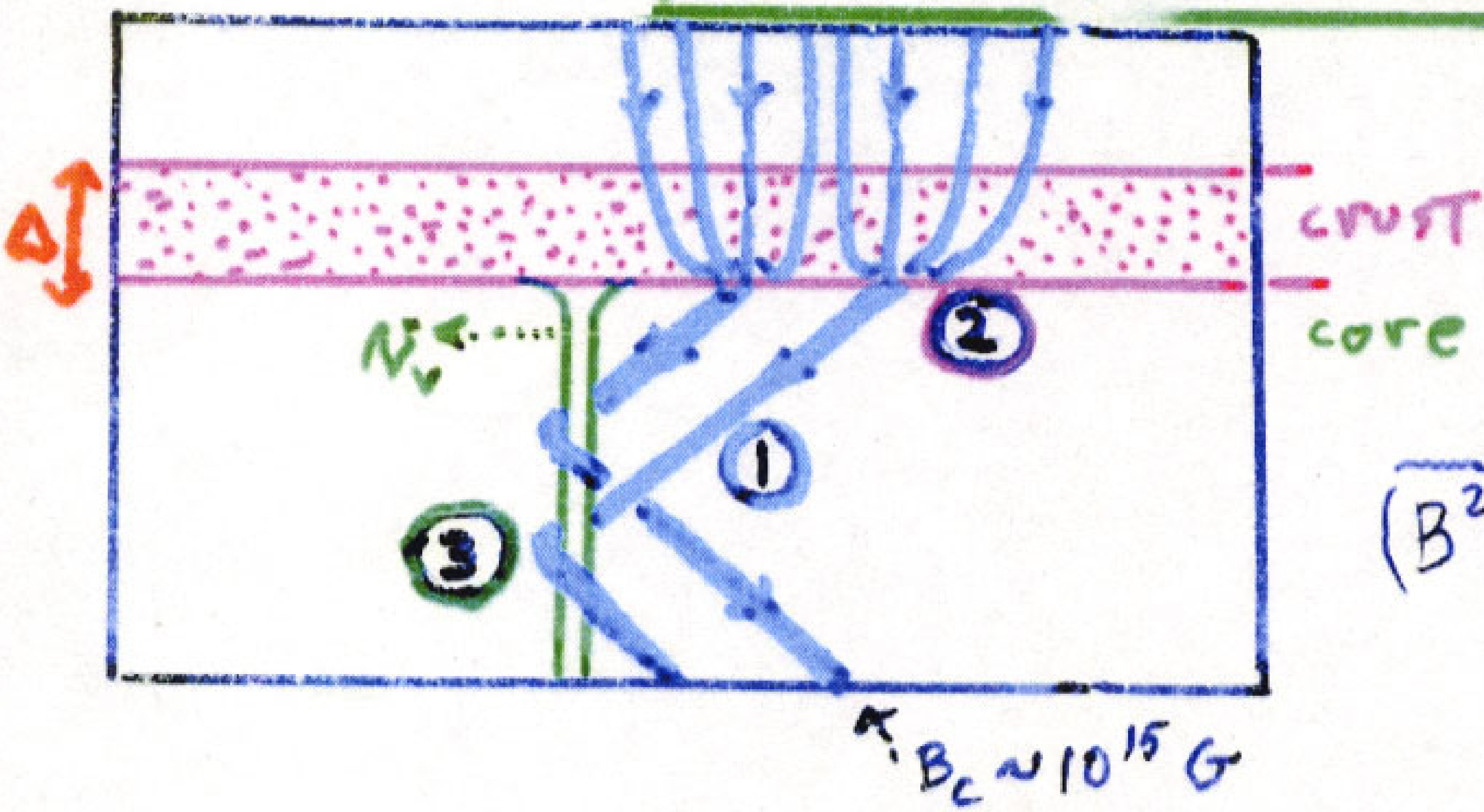
$$n_\Phi = \left(\frac{2e}{2\pi\hbar c}\right) B \sim 2\cdot 10^{19} B_{12}$$





Ding, Sheng, Chau (1993)

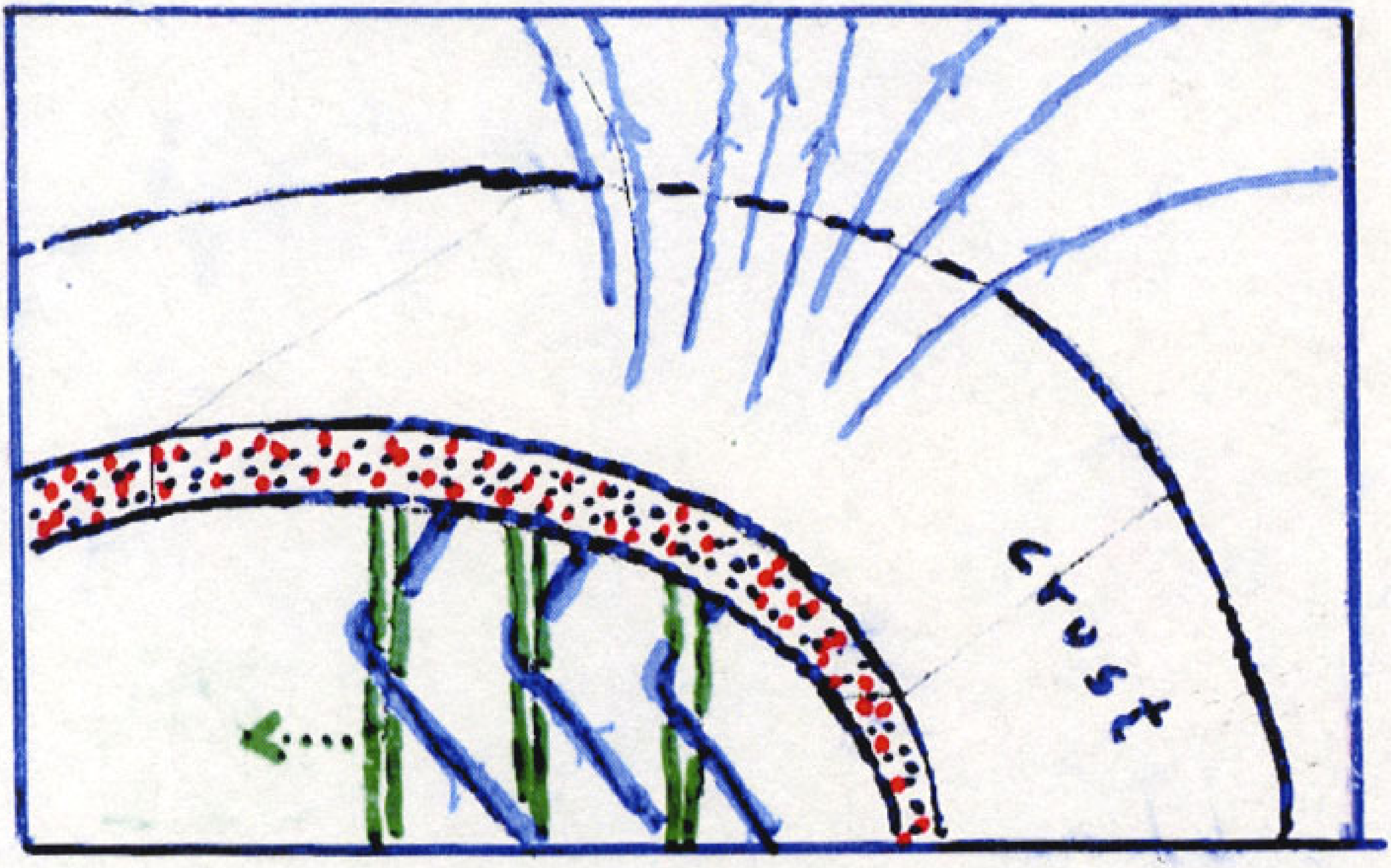
spin-down Crab $v_v \sim 1$ cm/day
Spin-up MSP $v_v \sim 1$ cm/10^{3} yrs



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

<u>slow spin-up</u>: local crust surface B_s (and B_d) follows local core vortex array just below it.

"<u>rapid" spin-down</u>: crust surface B_d follows large scale core vortex movement through plastic "creep" and "sudden breaking" as crust shear strength is exceeded.



$$\vec{v}_{SFnv} = \frac{\vec{r}_{\perp}\dot{\Omega}}{2\Omega}$$

$B_s \propto \Omega$

$B_d \propto 1/\Omega^{1/2}$

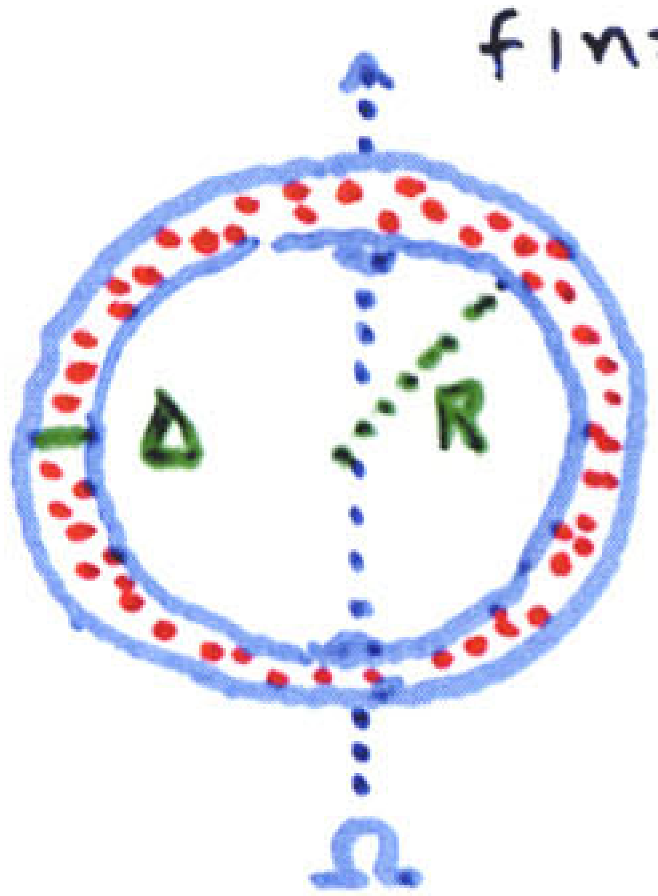
$A_{pc} \propto 1/\Omega^{1/2}$

Spin-up of a NS to a MSP

$B_d \downarrow \qquad B_s(pc) \uparrow \qquad \text{as } \Omega \uparrow$

initial $\quad P_0 \sim 10\ \text{s}$?

final $\quad P \sim$ several ms



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

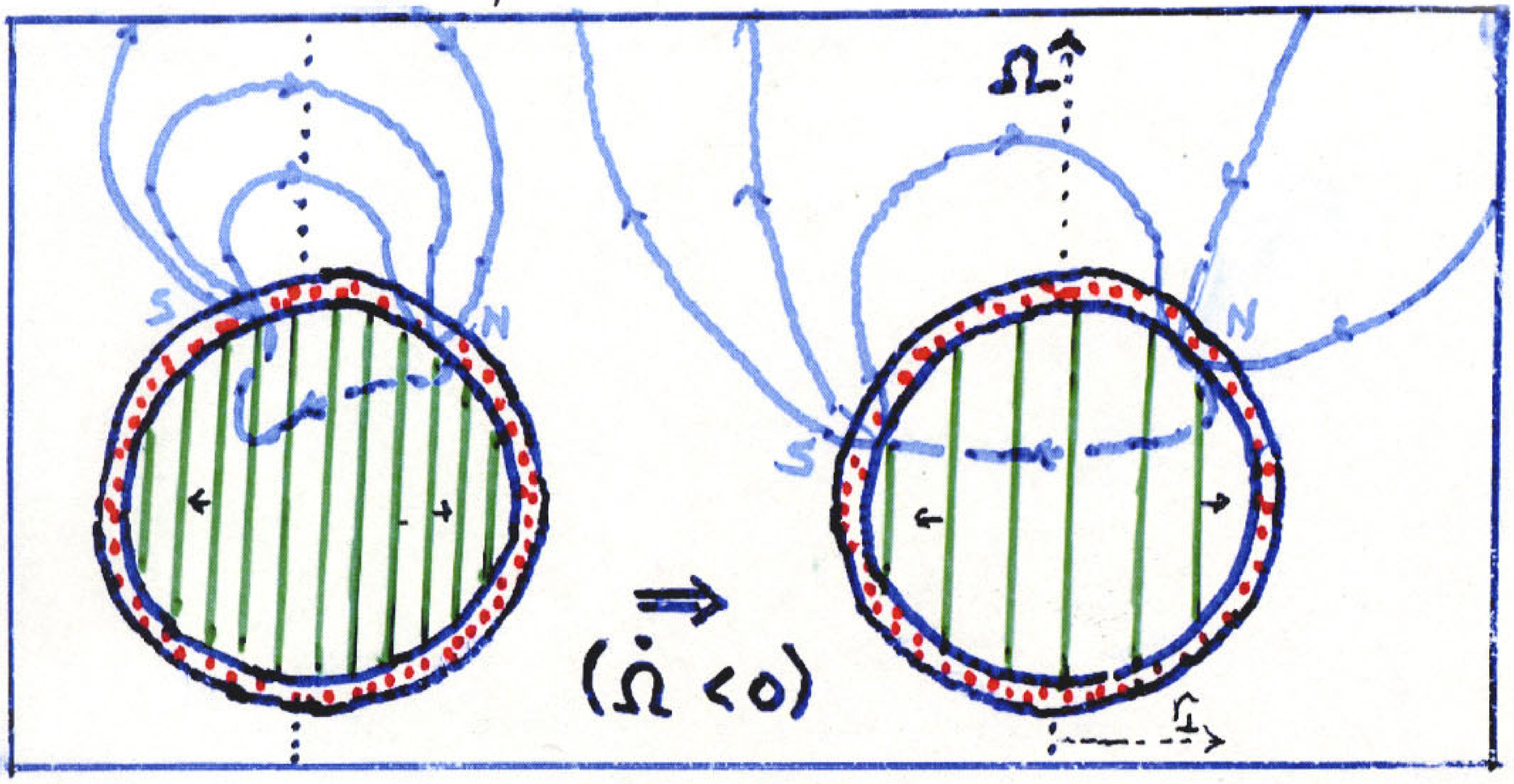
$$\boxed{\bar{R}_{pc} \sim \left(\frac{\Delta}{2R}\right) \times \left(\frac{\Omega R}{c}\right)^{1/2} R \sim 10^{-1}\ \text{km}}$$

R_{pc} inferred from blackbody fits to observations

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

(Zavlin 2006)

Early spin-down



$$\frac{\mu_\perp}{R^3} = \boxed{B_d(\perp) \propto r_\perp \propto \frac{1}{\Omega^{1/2}} \quad \text{if } r_\perp < R}$$

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

$n \equiv$ "braking index"

$$\boxed{B_d \propto \frac{1}{\Omega^{\hat{n}}} \qquad \hat{n} = \frac{3-n}{2}}$$

PSR	$\frac{P}{2\dot{P}}$ (yrs)	$\hat{n}$
J1846	720	~~0.9~~ → 0.2††
B0531	1240	0.25
B1509	1550	0.1
J1119	1,610	0.05
B0540	1,670	0.5
B0833	11,300	0.8
model		0.5

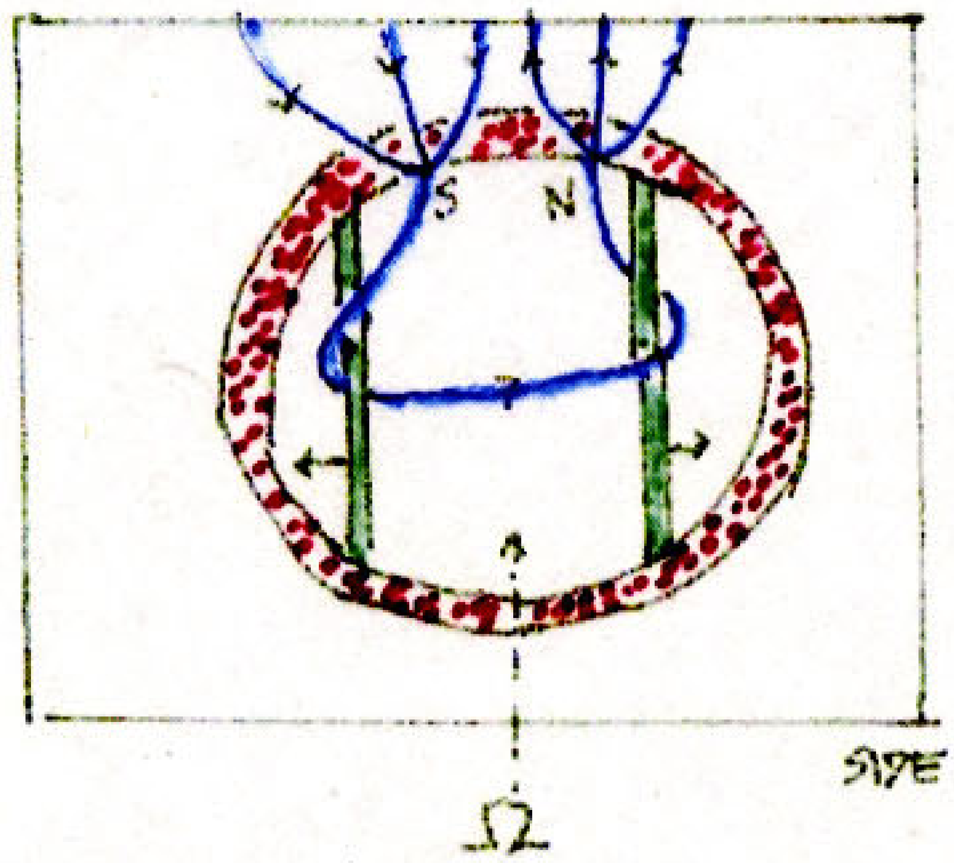
$\hat{n}$: $\frac{1}{2} \to 0$
n: $2 \to 3$

$r_\perp \to R$

†† Livingstone (2006)

$$\boxed{\frac{A_{pc}(P)}{A_{pc}(P_0)} \sim \left(\frac{\Omega}{\Omega_0}\right)^{1-2\hat{n}}}$$

... followed by slow reconnection of flux expelled from core (allowed by crust conductivity after 10^5–10^6 yrs)



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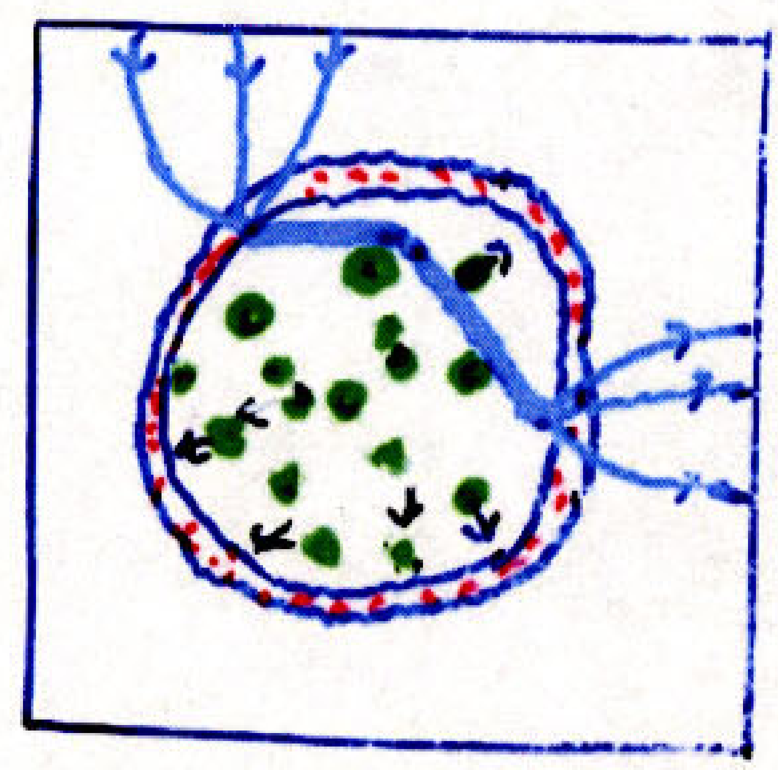

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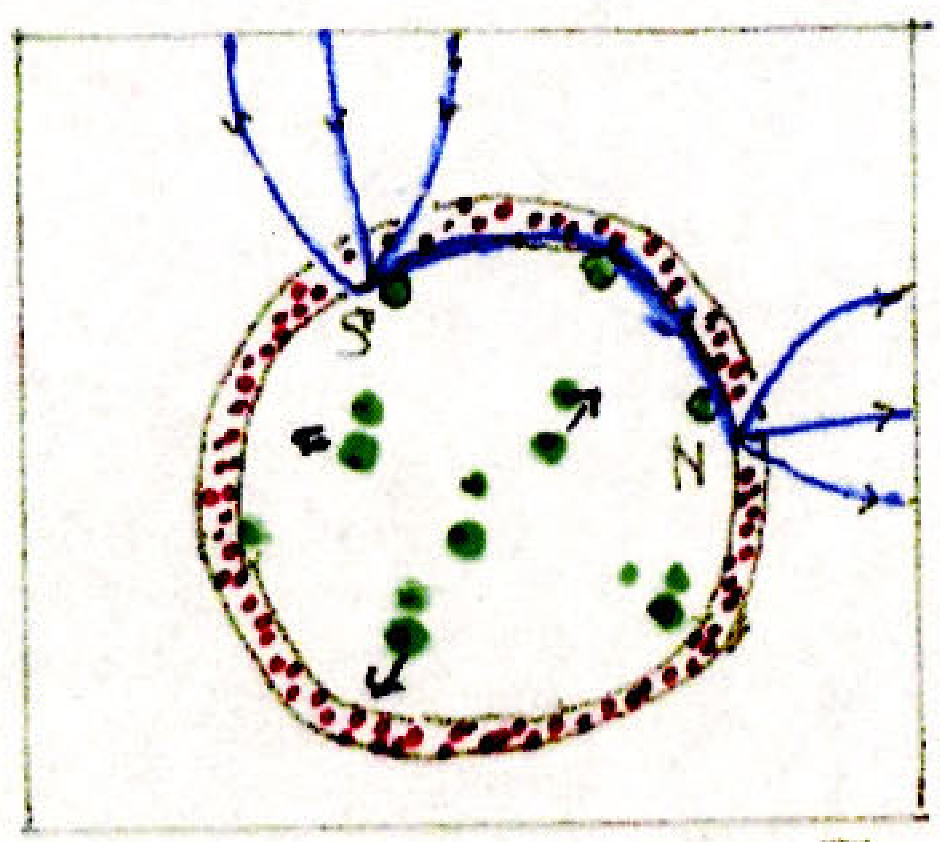


Top

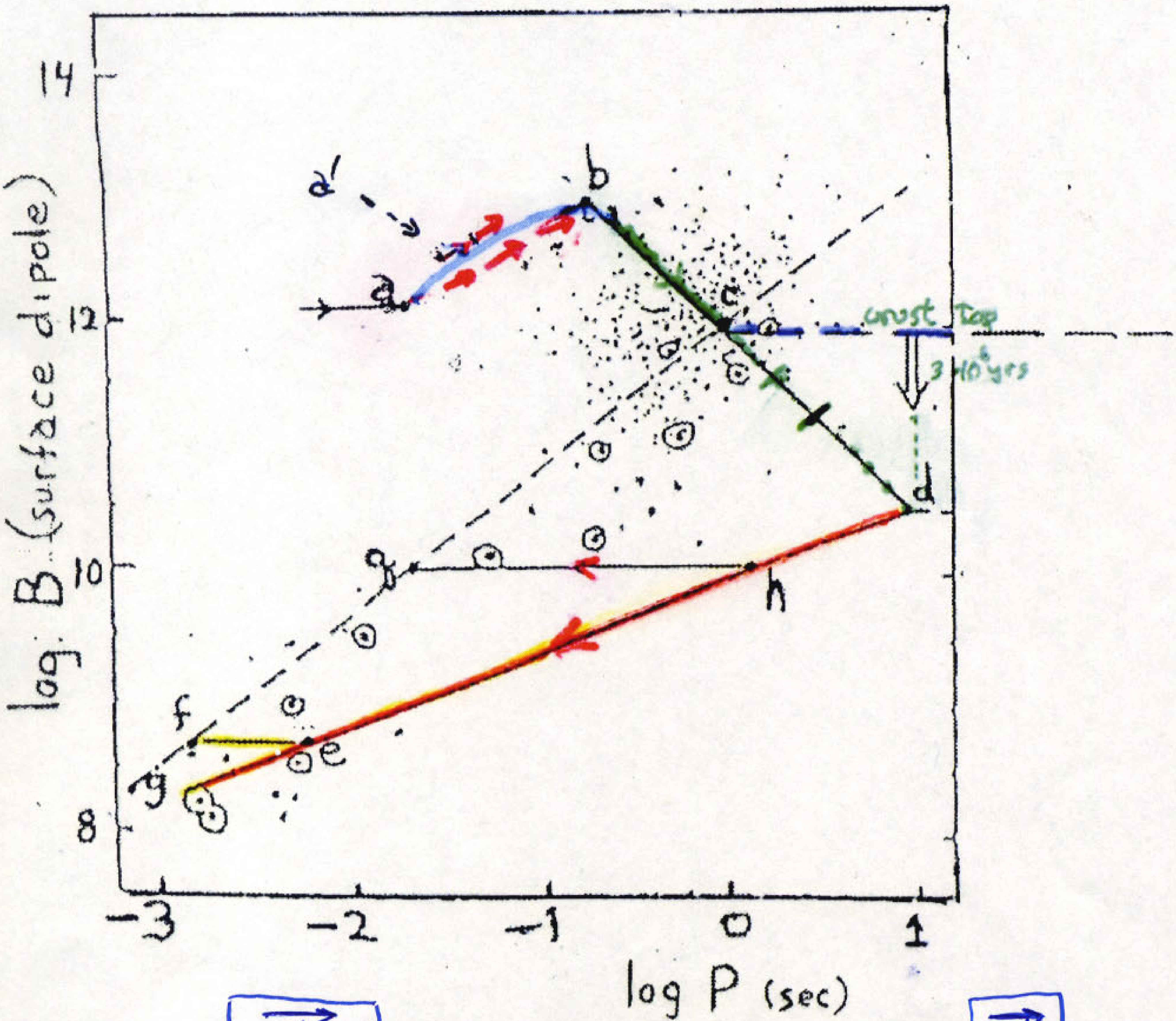
reconnection —

$B_d(\perp) \propto \Omega$

$B_d \propto \Omega^{0.8 \pm 0.2}$

Cordes & Chernoff (1990)

$$I\Omega\dot{\Omega} \simeq -(B_d R^3)^2\,\Omega^4/c^3$$
$$\Omega \equiv \frac{2\pi}{P}$$



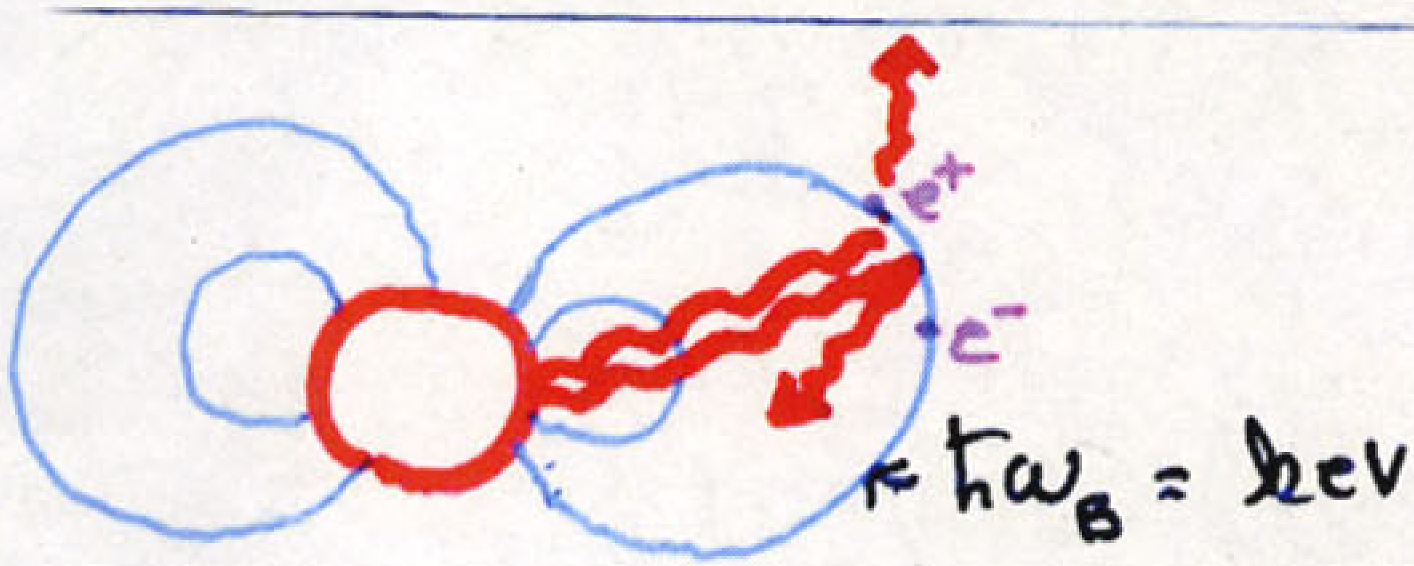
$\overrightarrow{abc}$

$$A_{pc} \sim A_{pc}(a)\left(\frac{P_a}{P}\right)\frac{B_d}{B_d(a)}$$

$\overrightarrow{cd}$

$$A_{pc} \sim \frac{\Omega R}{c}\,R^2$$

Inverse Compton boosting of L_x (surface) by resonant scattering in the inner magnetosphere of young NSs



OD $\gg$ 1 $\quad X + e^{\pm} \to X' + e^{\pm}$

$(\gamma_{\pm} E_x = \hbar\omega_B)$

$\left(\begin{array}{l} \frac{1}{2} \text{ scatter out} \\ \frac{1}{2} \text{ scatter back} \end{array}\right)$

$$L_x \to L_x(\text{surface}) + L_{\parallel}(e^{\pm}) \overset{?}{\sim} L_{BB}$$

$\dot{N}_x$ unchanged

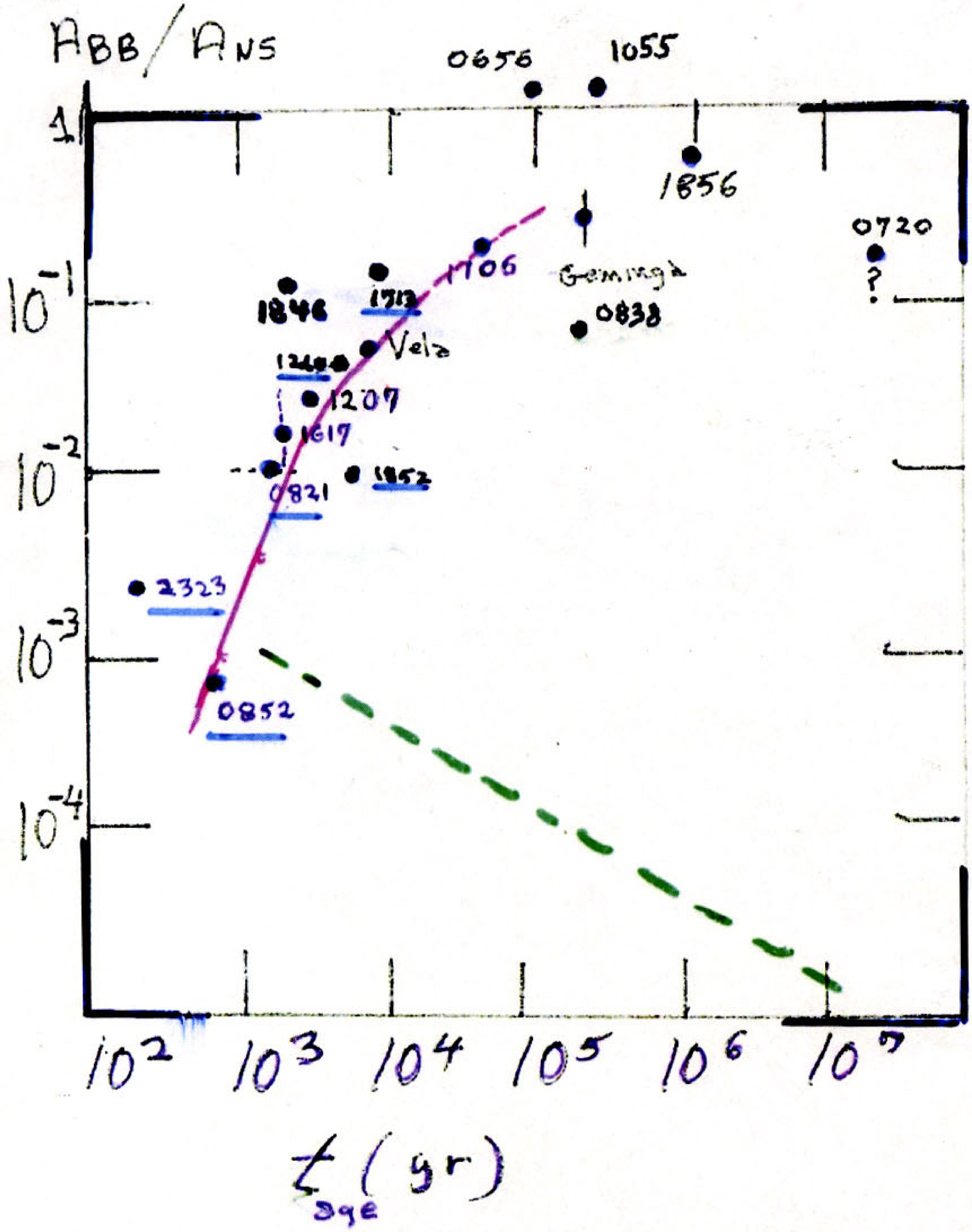
$$\boxed{\frac{A_{BB} \text{ inferred}}{A_{\text{surface emission}}} \sim \left[\frac{L_x(\text{surface})}{\underbrace{L_{\parallel}(e^{\pm}) + L_x(\text{surface})}_{L_{BB} \text{ observed ?}}}\right]^3}$$

$$L_x\left(\begin{array}{c}\text{surface}\\ \text{cooling}\end{array}\right) \sim 1 \cdot 10^{32} \left(\frac{10^4}{t}\right)^{0.3} \frac{\text{erg}}{s}$$

Yakovlev et al (2002)

$$L_{\parallel}(e^{\pm}) \sim 2 \cdot 10^{32} \left(\frac{10^4}{t}\right) \frac{\text{erg}}{s}$$

(Goldreich-Julian scaled from Vela L_{pc})



Ratio of Black Body emission area (A_{BB})
to Neutron Star surface area ($A_{NS} = 10^3$ Km^2)

$$\boxed{\frac{A_{pc}}{A_{NS}} \sim \frac{5 \times 10^{-5}}{P(\mathrm{sec})}}$$ canonical

Such inferred area decreases may be applicable to polar cap emission. ?

$L_x \rightarrow$ polar cap emission $\propto \dot{N}_{GJ}$.

- All inferred A_{pc} would then be reduced by the same factor (estimated as 10^{-2}–10^{-1}).

- Because all observed polar cap X-rays would have been diffusively scattered at $r \sim 3R$ (where $\gamma_{\pm}(\parallel) E_x \sim \hbar\omega_B$) their spin-phase modulation would be greatly diminished.