M. LYUTIKOV
D. EICHLER
Y. LYUBARSKY
P. WOODS

MAGNETARS

$$\frac{d}{dt}\int \frac{B^2}{8\pi} dV \Rightarrow I\Omega\dot{\Omega}$$

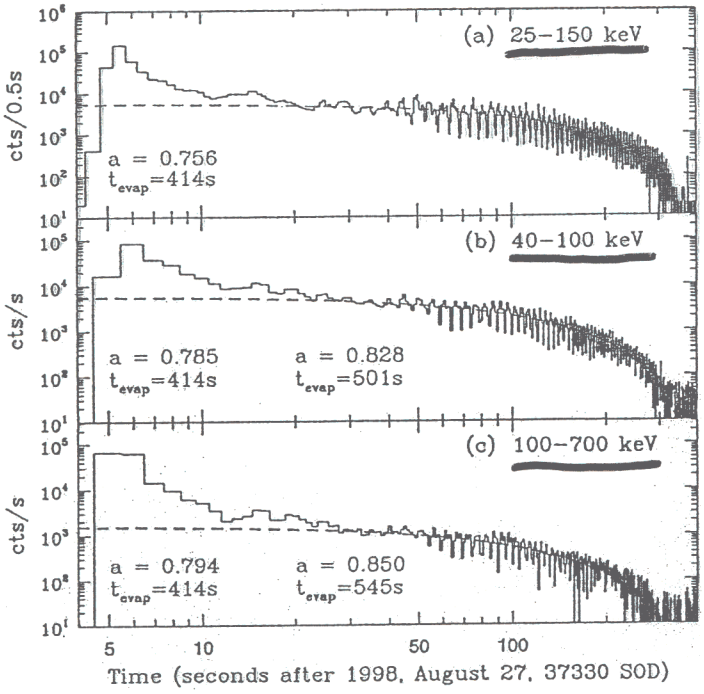
SGRs
AXPs
HYPERENERGETIC SNe ?
GRBs ?

KEY OBSERVATIONAL INPUT:

- SGR/AXP FLARES + BURSTS
- FLARE AFTERGLOW
- SPINDOWN, TORQUE NOISE
- X-RAY SPECTRA + PULSE PROFILES
- ACTIVE LIFETIME ~ 10^4 YRS

Tcn
- NUCLEON STARS? QUARK STARS?
- HOW DOES MAGNETIC FIELD DECAY?
- ORIGIN OF SECULAR CHANGES IN X-RAY PULSE PROFILE + TORQUE

EVIDENCE FOR A 'TRAPPED FIREBALL' IN THE 27 AUGUST 1998 FLARE



COUNTS/S →

TIME →

FEROCI ET AL 2001

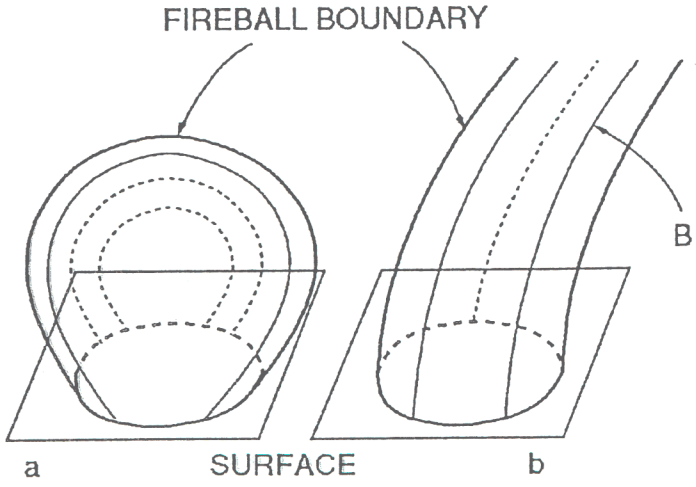
$$L_X = L_X(0)\left[1 - t/t_{EVAP}\right]^{3\chi}$$

HOMOGENEOUS FIREBALL:

$\chi = 1$ (CYLINDER)

$\chi = 2$ (SPHERE)

DIFFERENT FIREBALL GEOMETRIES:

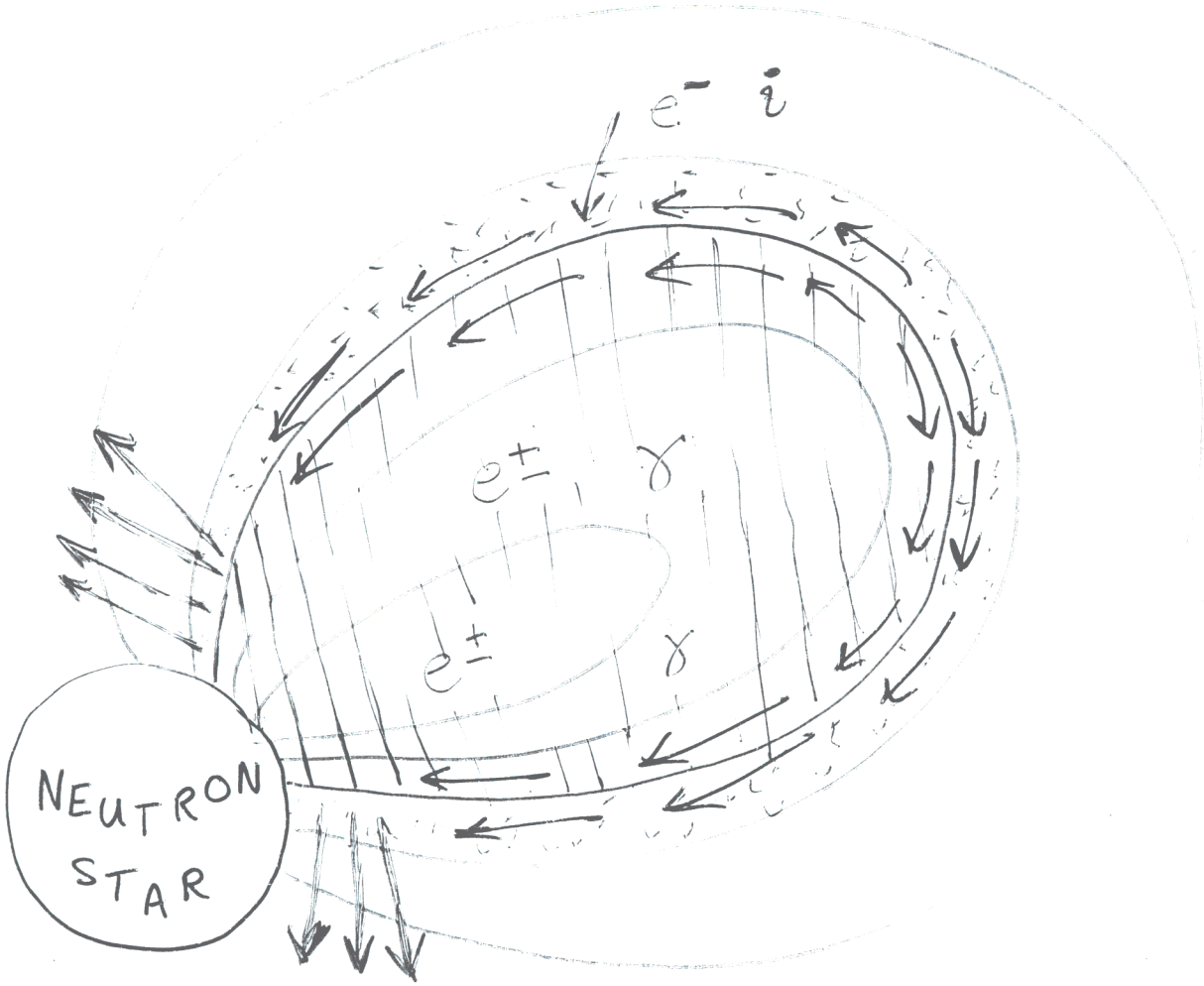


INHOMOGENEOUS FIREBALL:

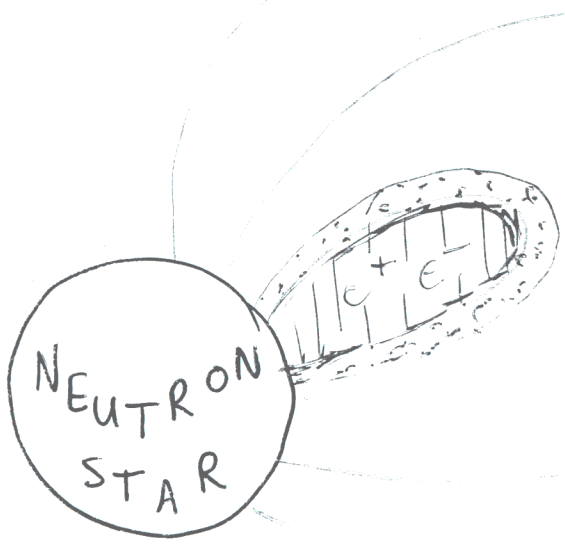
$$T \sim r^{-\gamma}$$

$$\chi = \frac{D_{CURVED} + \frac{5}{2}\gamma}{1 + 3/2\,\gamma}$$

$D_{CURVED} = 2$, $\gamma = +\frac{1}{2} \rightarrow \chi = 3$



'COOLING WAVE'



$e^+ + e^- \rightarrow \nu\bar{\nu}$:

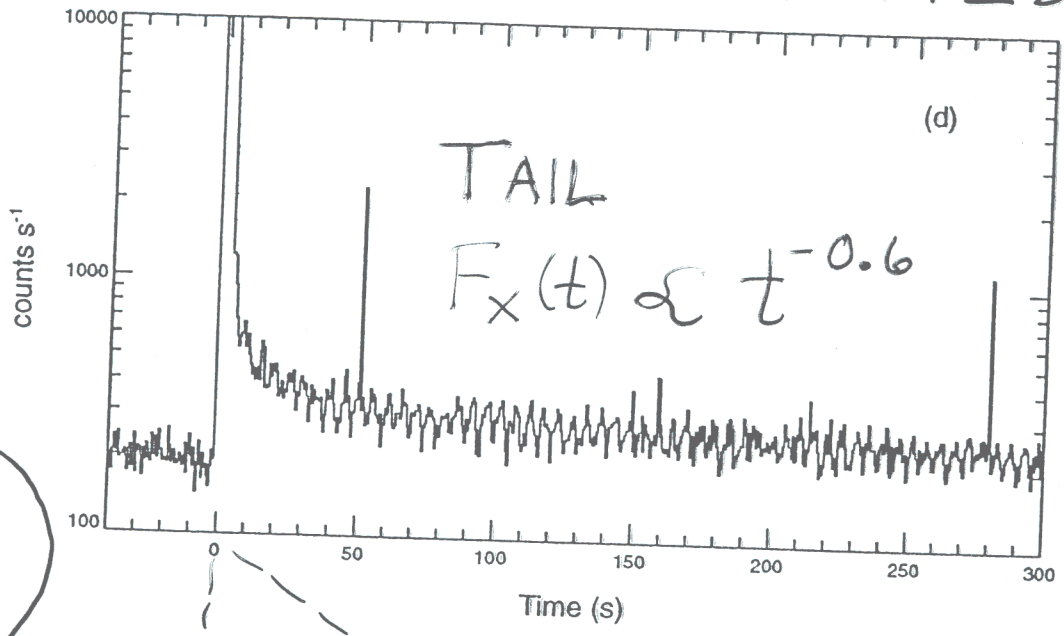
$t_\nu \sim 28\,s\; T_{MeV}^{-5}$

$T_{MeV} \sim 1 \left(\frac{R_{max}}{10\,Km}\right)^{3/4}$

[MARCH 5, 1979 SOFTTAIL]

SGR BURST AFTERGLOW

AUG 29 1998 (GIANT FLARE + 2 DAYS)



TAIL

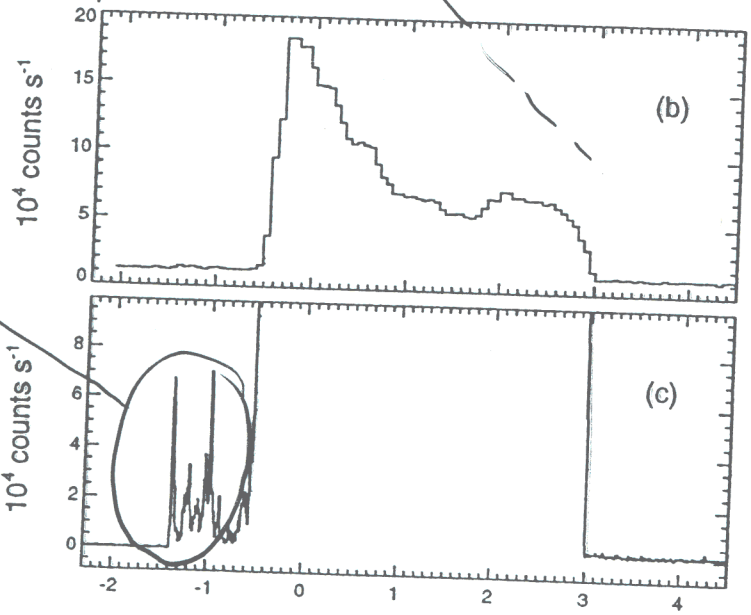
$F_x(t) \propto t^{-0.6}$

IBRAHIM ET AL. 2001

HOT SPOT

$\frac{A}{R^2_{NS}} \sim 10^{-2}$

~ 4 keV

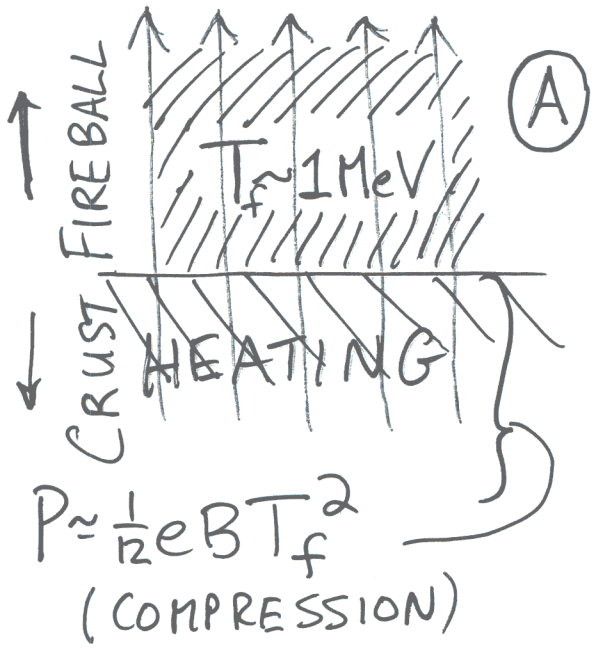


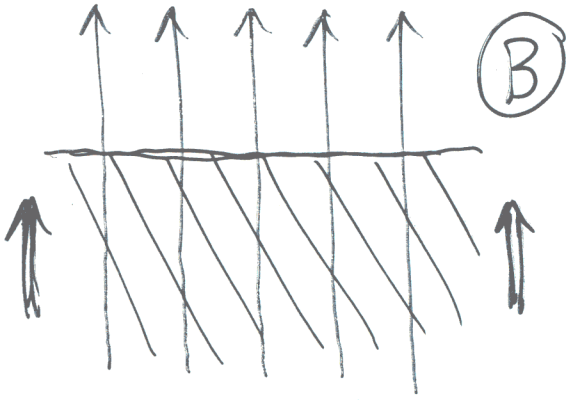
MAIN BURST

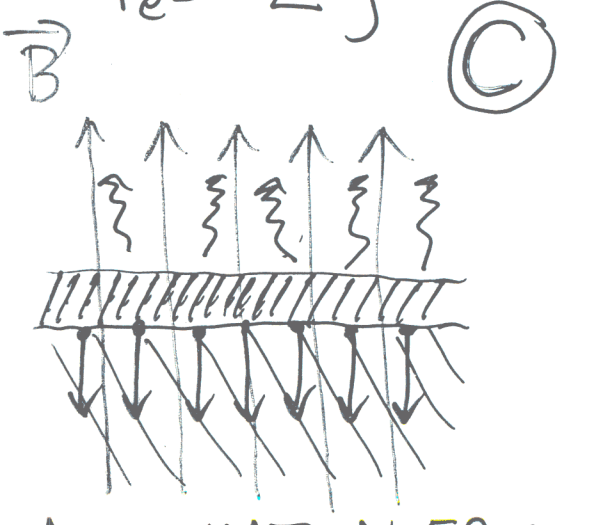
ECURSOR

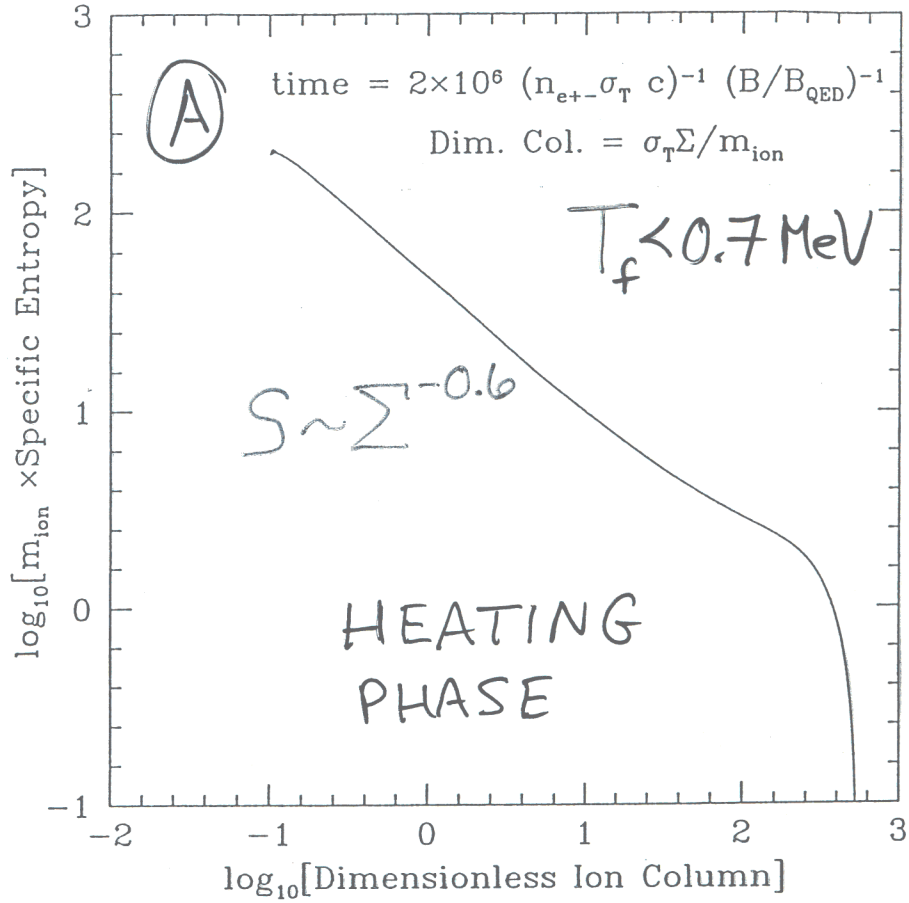
3.5 SECONDS

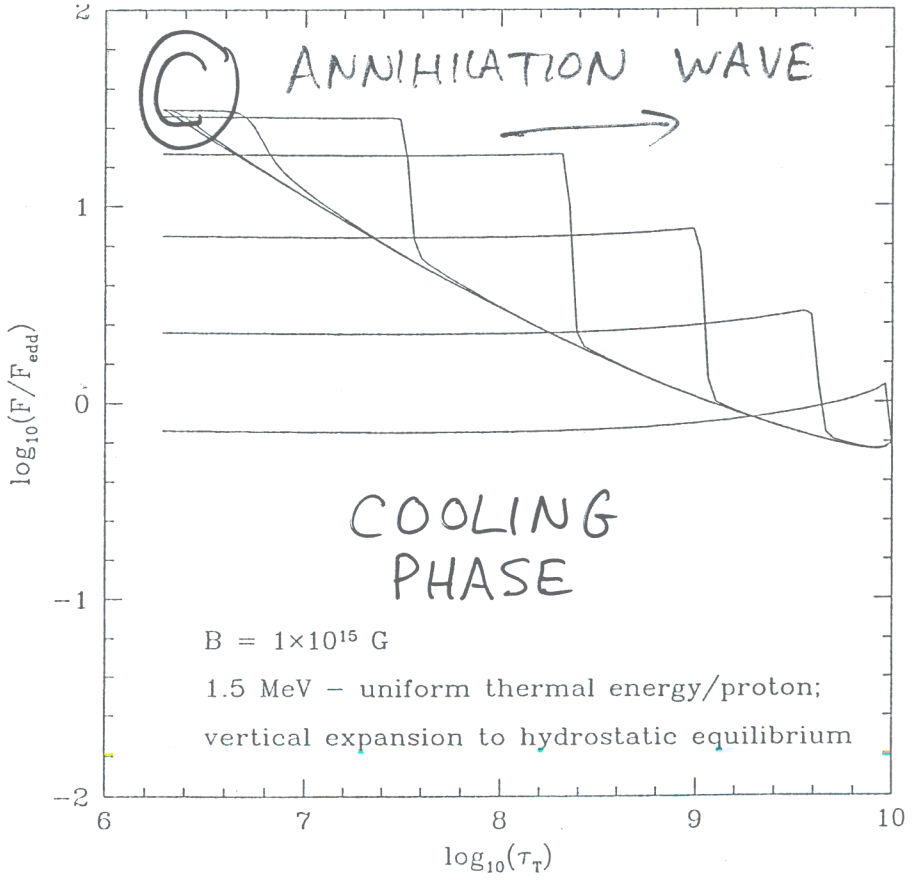
FORMATION / COOLING OF $e^{\pm}$ ATMOSPHERE











(A) INWARD RADIATIVE DIFFUSION

$$S_{e^\pm} + S_\gamma \simeq S_{e^\pm} \sim \Sigma^{-0.6} \qquad \Sigma \equiv \int \rho \, dz$$

UP TO $$\Sigma_{max} \simeq 1 \times 10^{10} \, B_{15} \left(\frac{T_{ex}}{MeV}\right)^{1/2} \left(\frac{t}{10s}\right)^{1/2} \frac{g}{cm^2}$$

^4He DISSOCIATION / RECOMBINATION

NEGLIGIBLE IF $T_{ex} < 0.7$ MeV

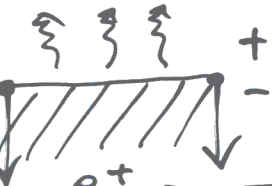
T, WOODS, EICHLER, LYUBARSKY

(C) COOLING VIA PAIR ANNIHILATION

FRONT

$$F^+_{RAD} = \frac{-c}{3 K_E(B,T) \rho} \frac{\partial}{\partial z} \left(\frac{1}{2} a T^4\right)$$

E-MODE $\rightarrow$ $K_E(B,T) = 4\pi^2 \sigma_T \left(\frac{kT}{mec^2}\right)^2 (B/B_Q)^{-2} Y_e/m_p$



$$F^+_{RAD} - F^-_{RAD} \simeq v_z (n_{e^+} + n_{e^-}) mec^2$$

$$F^+_{RAD} = 1 \times 10^{26} \frac{erg}{cm^2 - s} \, B_{15} \, (t/100s)^{-0.4} \left(\frac{m_p S_{e^\pm}}{2}\right)^{1/2}$$

POST AUGUST 29 1998 BURST: $B = 1 \times 10^{15} G$

$$S_{e^\pm} \sim \Sigma^{-\delta} \qquad F \sim t^{-3/(8-5\delta)} \sim t^{-0.6}$$

COOLING OF OUTER CRUST

LYBARSKY, EICHLER, T.

DECAYING X-RAY TAIL

$t^{-0.7}$ POST AUG. 27 FLARE

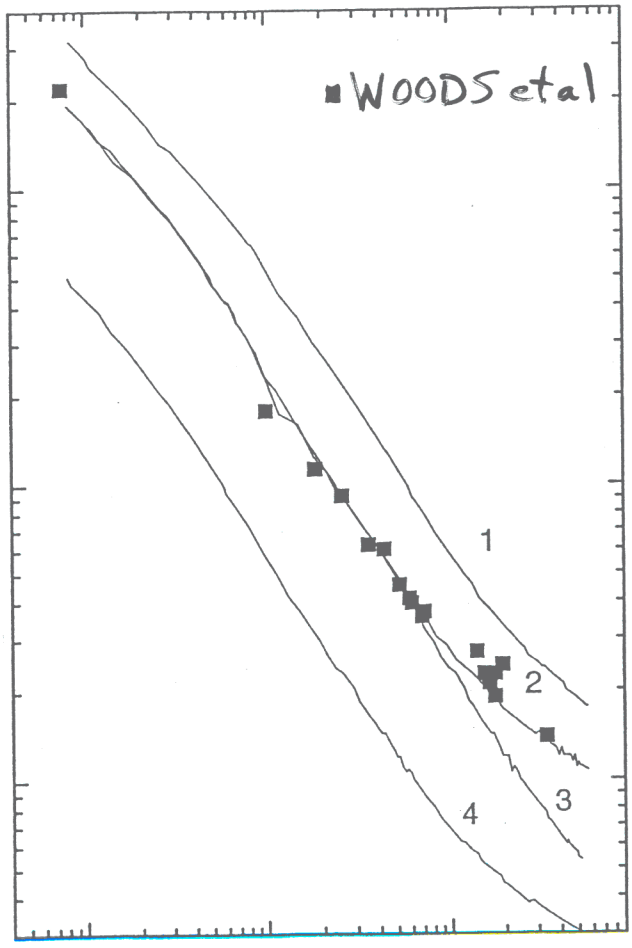
[TAIL ENERGY ~ 10^{-2} FLARE ENERGY]

$$U_{thermal} = \tfrac{1}{2} C_p T \propto B^2/8\pi \sim \text{constant}$$

$$C_p \propto n_e^{2/3} \propto (\text{DEPTH})^2$$

$$\Rightarrow T \propto \frac{1}{\text{DEPTH}}$$

$$U_{thermal} = \frac{E_{FLARE}}{\frac{4\pi}{3} R_{NS}^3} \Rightarrow$$

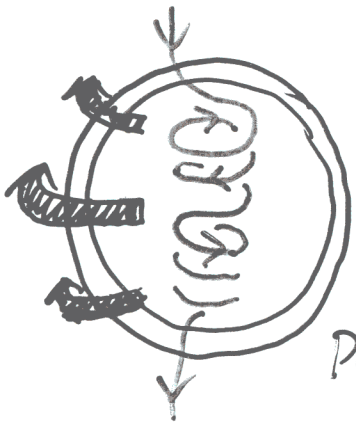


B-FIELD DECAY

MECHANISM, IMPLICATIONS FOR COMPOSITION + RADIATIVE MECHANISM

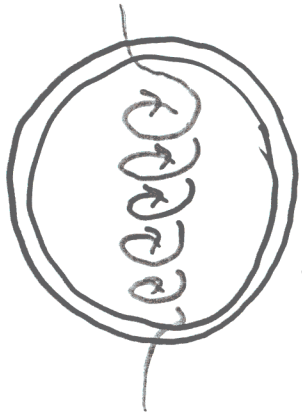
T + DUNCAN
T, LYUTIKOV, KULKARNI
ARRAS + T.

HELICITY - STABILIZATION



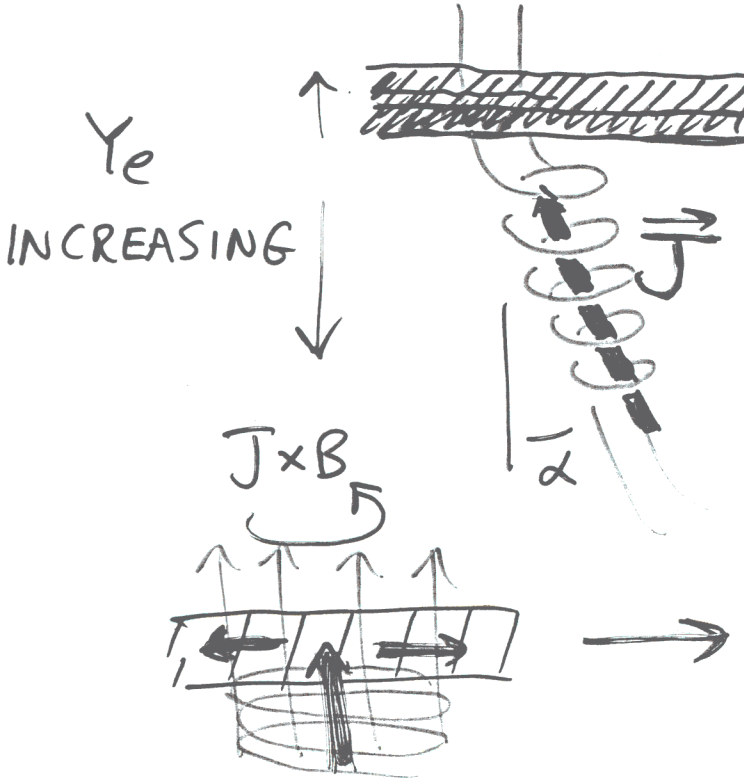
$$\int \vec{A}\cdot\vec{B}\, d^3x = 0$$

PURE DIFFERENTIAL ROTATION



$$\neq 0$$

$B > 10^{14}$ G: EXCHANGE OF HELICITY BETWEEN CRUST + MAGNETOSPHERE



$$\alpha > (B_\phi / B_z)^{-1}$$

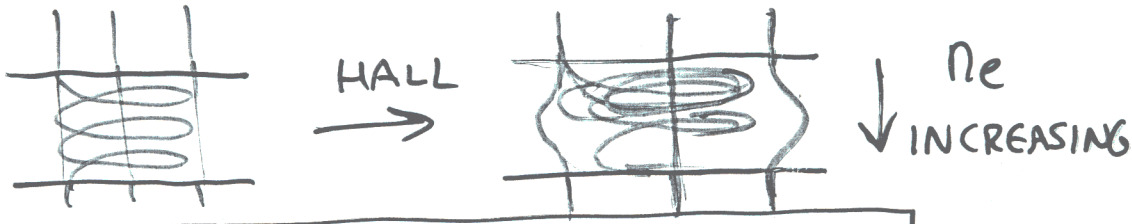
TWIST IS STABILIZED BY Y_e-GRADIENT

→ MAGNETOSPHERE IS TWISTED UP

$$\frac{1}{c}\,\partial B/\partial t = -\nabla \times E$$

$$E \sim \underbrace{J \times B / n_e e c}_{\text{HALL}} + \underbrace{J/\sigma}_{\text{OHMIC}} - \underbrace{\nabla \mu_e / e}_{e^-/\text{ION-NEUTRAL DRIFT}}$$

CRUST:



$$\left(\partial B_\phi/\partial t\right)_{\text{HALL}} \simeq -\left[\frac{\partial}{\partial z}\left(\frac{1}{n_e e}\right)\right]\hat{z} \times \left(\vec{J}_z \times \vec{B}_\phi\right)$$

ARRAS T.

CORE: HIGH FREQUENCY HALL WAVES SUPPRESSED

$$\left(\partial B/\partial t\right)_{\text{HALL}} \neq 0 \longleftrightarrow \text{STABLE MAGNETO-STATIC EQUILIBRIUM}$$

$$t_{\text{HALL}} \sim 1\times10^6\,\text{YR}\left(\frac{B_\phi}{10^{15}\,G}\right)^{-1}\left(\frac{w}{10\,\text{km}}\right)\left(\frac{l_{ne}}{1\,\text{km}}\right)\rho_{14}$$

GOLDREICH + REISENEGGER '92
PETHICK

e^-/ION-NEUTRAL DRIFT

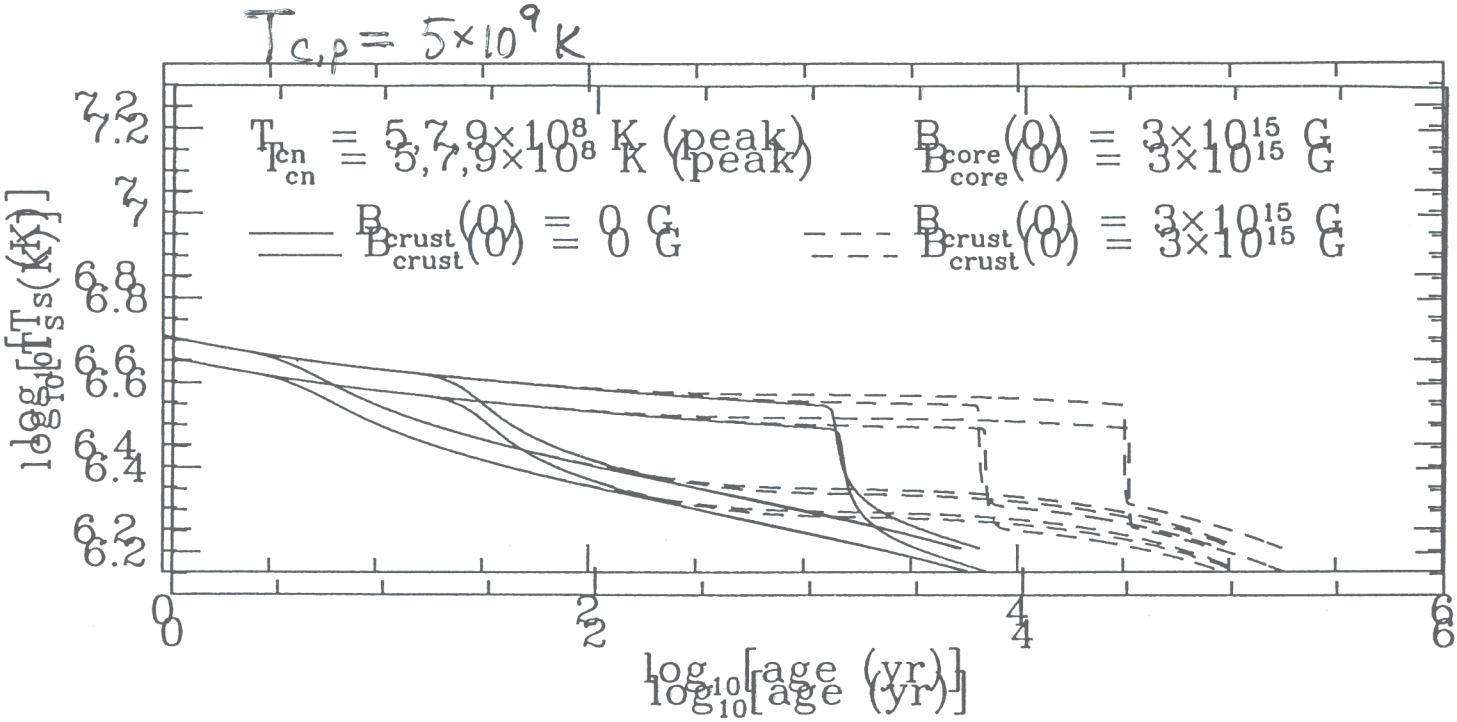
$$t_{\text{DRIFT}} \sim \frac{4\pi P_e}{B^2}\left(\frac{\Delta\mu}{\dot{\mu}}\right); \quad \Delta\mu \sim \frac{B^2}{4\pi n_e}$$

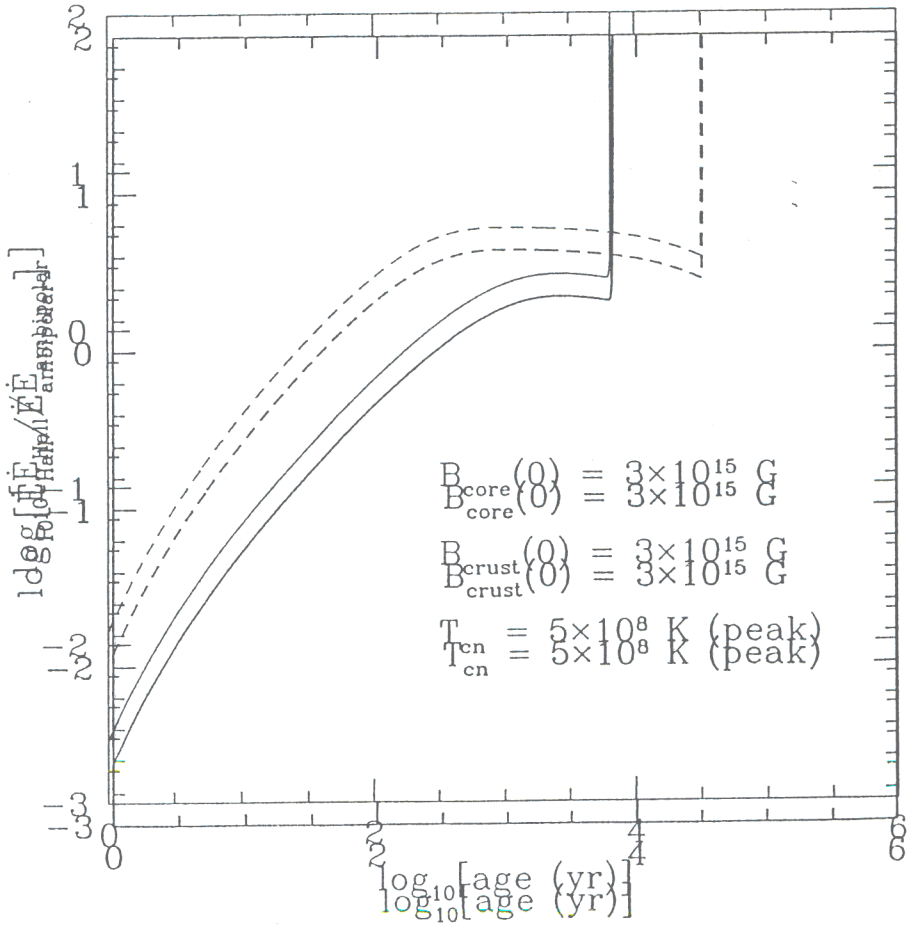
$B > 3\times10^{15}\,G \Rightarrow$ ACCELERATED DRIFT

$\Delta\mu \sim kT$

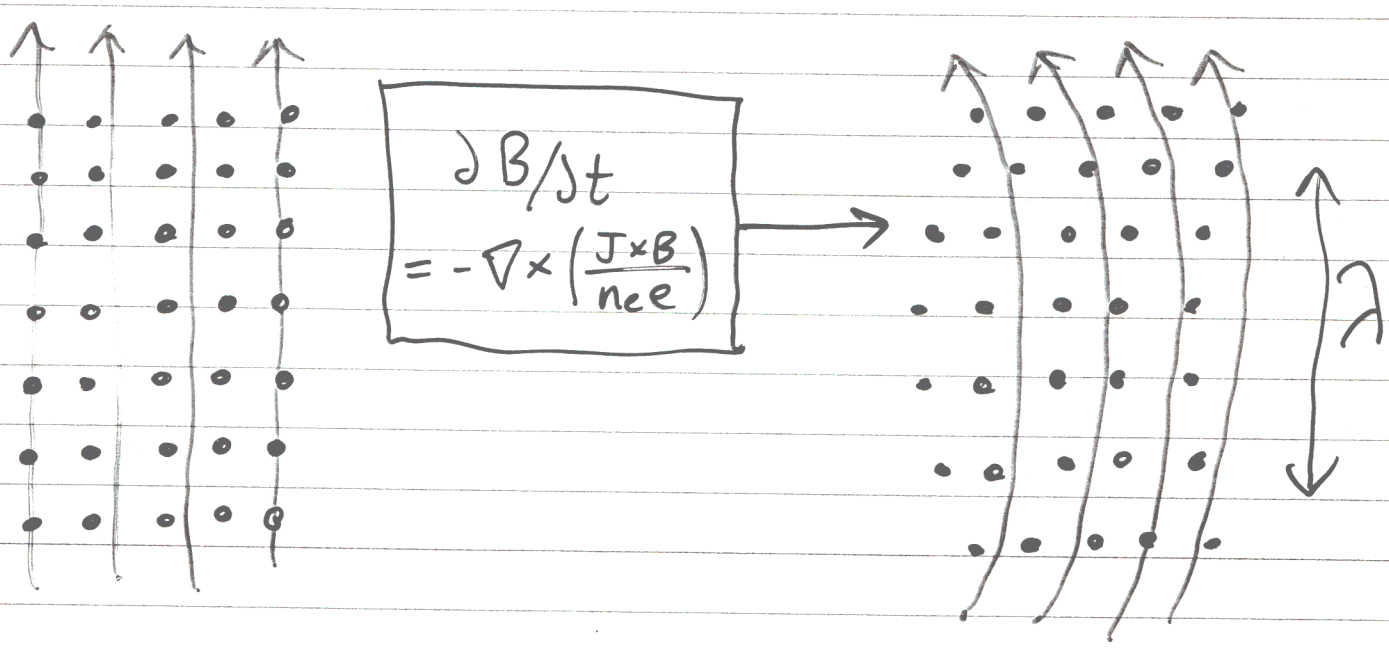
$$t_{\text{DRIFT}} \propto B^{-14}$$

T + DUNCAN '96


$T_{c,p} = 5\times10^9$ K
$T_{cn} = 5,7,9\times10^8$ K (peak)
$T_{cn} = 5,7,9\times10^8$ K (peak)
$B^{core}_{core}(0) = 3\times10^{15}$ G
$B^{core}_{core}(0) = 3\times10^{15}$ G
$B^{crust}_{crust}(0) = 0$ G
$B^{crust}_{crust}(0) = 0$ G
$B^{crust}_{crust}(0) = 3\times10^{15}$ G
$B^{crust}_{crust}(0) = 3\times10^{15}$ G
$\log_{10}[T_s(K)]$
$\log_{10}[\text{age (yr)}]$


$B^{core}_{core}(0) = 3\times10^{15}$ G
$B^{core}_{core}(0) = 3\times10^{15}$ G
$B^{crust}_{crust}(0) = 3\times10^{15}$ G
$B^{crust}_{crust}(0) = 3\times10^{15}$ G
$T_{cn} = 5\times10^8$ K (peak)
$T_{cn} = 5\times10^8$ K (peak)
$\log_{10}[\text{age (yr)}]$

BULK HEATING OF CRUST



$$\frac{B\,\delta B}{4\pi} < \theta_{max}\,\mu$$

$$\frac{\delta B}{B} < \theta_{max}\,\frac{\mu}{B^2/8\pi}$$

λ/v_μ << ohmic timescale

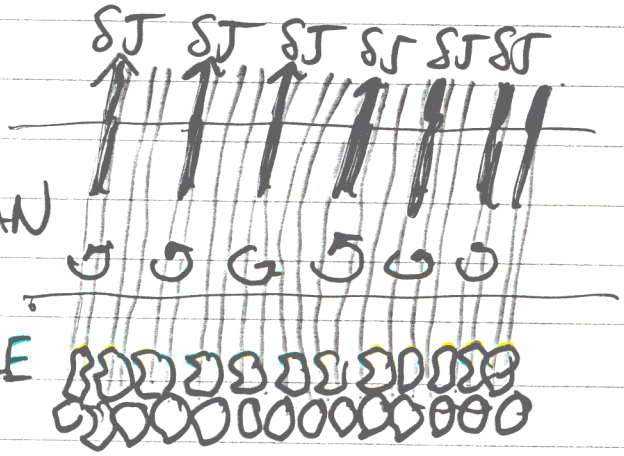
T. DUNCAN

STRESS RELAXATION REQUIRES LATTICE BREAKDOWN

BULK HEATING OF LIQUID OCEAN: OCEAN

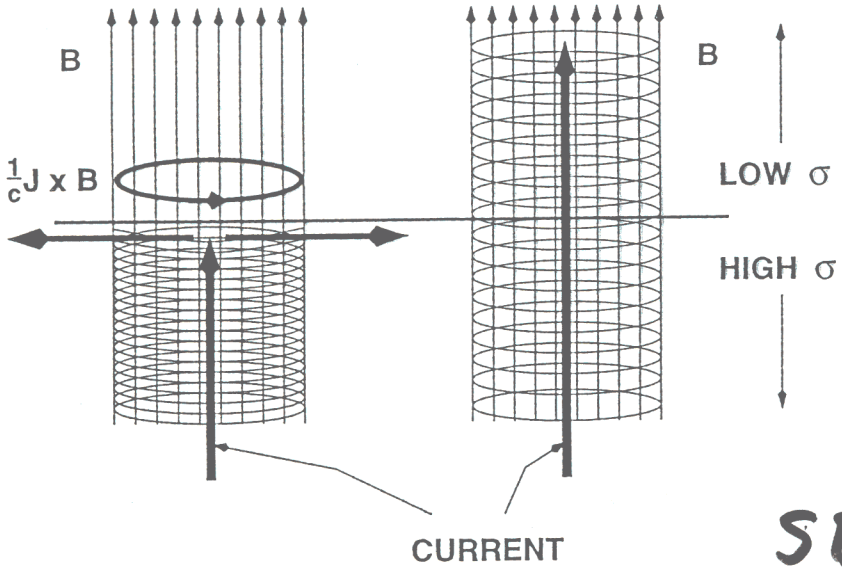
(LYUBARSKY EICHLER, T.)

SANDPILE



TWISTED MAGNETARS

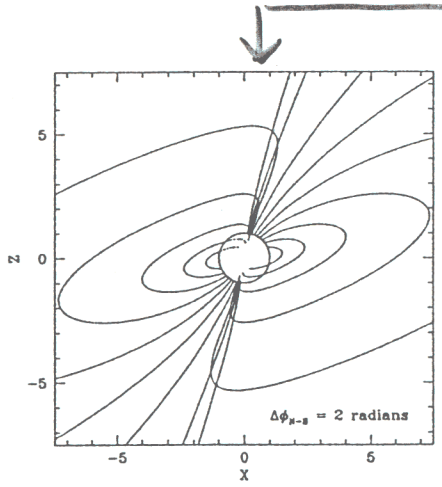
T. LYUTIKOV
KULKARNI



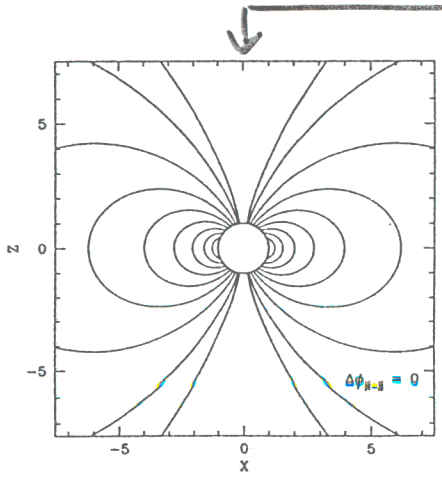
SELF-SIMILAR EQULIBRIA

$\vec{J} \times \vec{B} = 0$

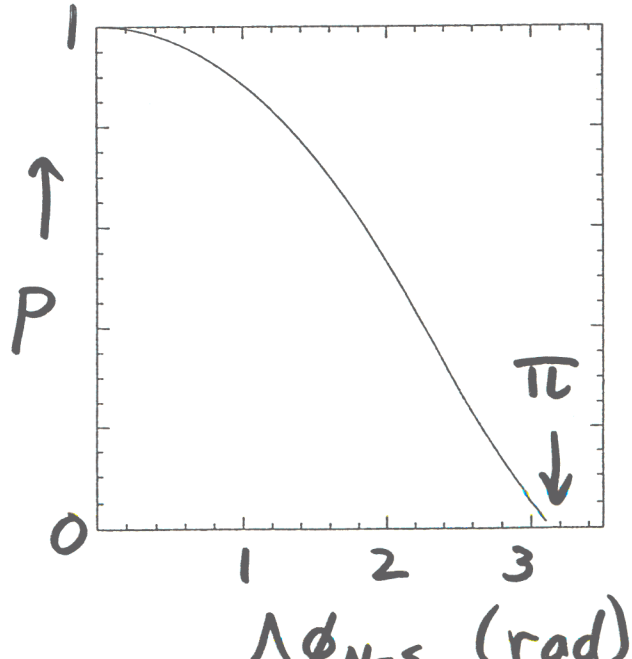
$\vec{B} \propto r^{-2-p}$



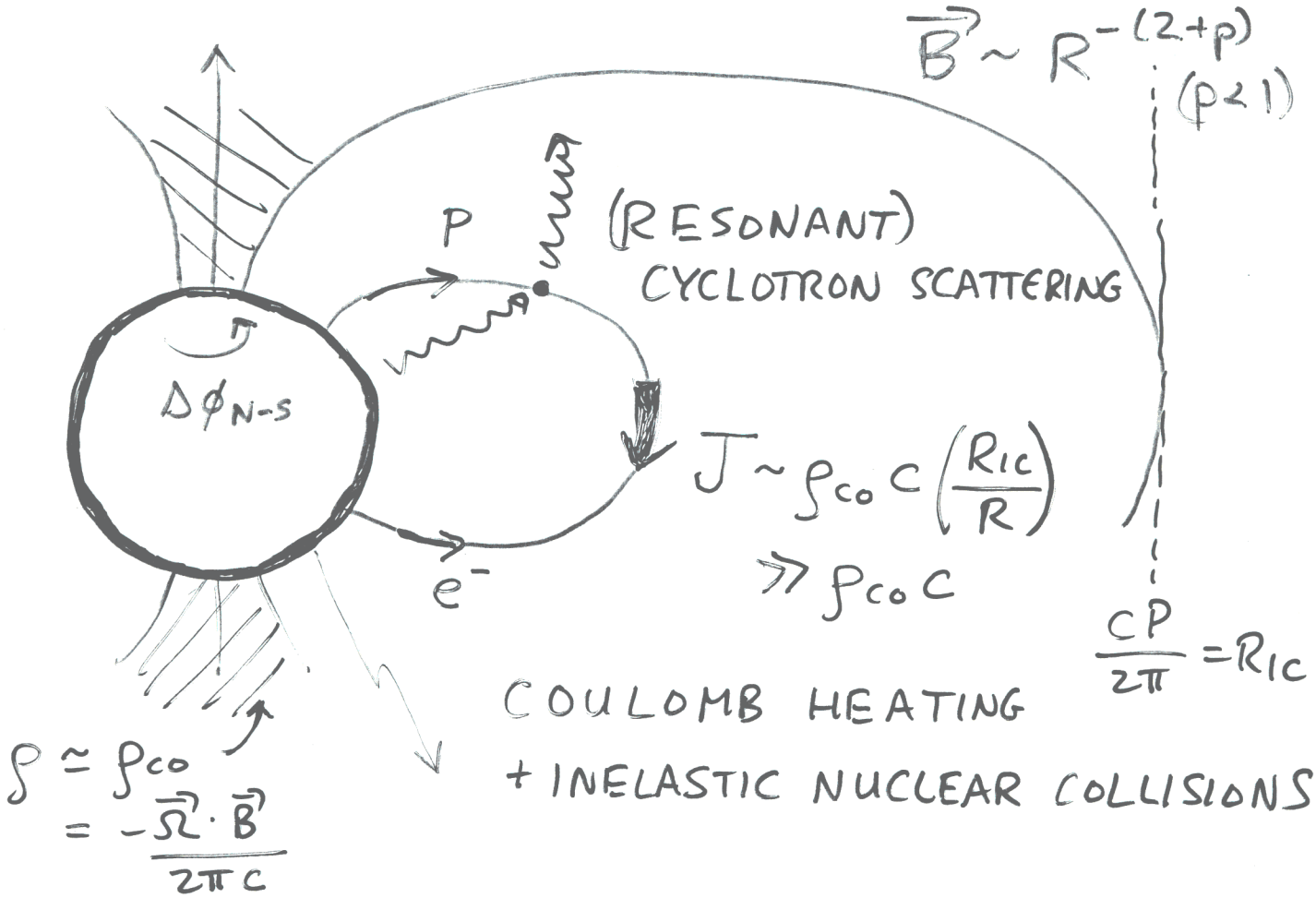
$\Delta\phi_{N-S}$ =2 RAD.



DIPOLE



PERSISTENT CURRENTS



SURFACE HEATING:

$$\dot{E}_{OHMIC} \sim \frac{I(R_{NS})}{e} \frac{G M_{NS} m_p}{e}$$

$$= 1 \times 10^{35} \left(\frac{B_{POLE}}{10^{14}\,G}\right) \left(\frac{\Delta\phi_{N-S}}{\text{radian}}\right) \frac{ERG}{s}$$

COMPARE SPIN DOWN POWER:

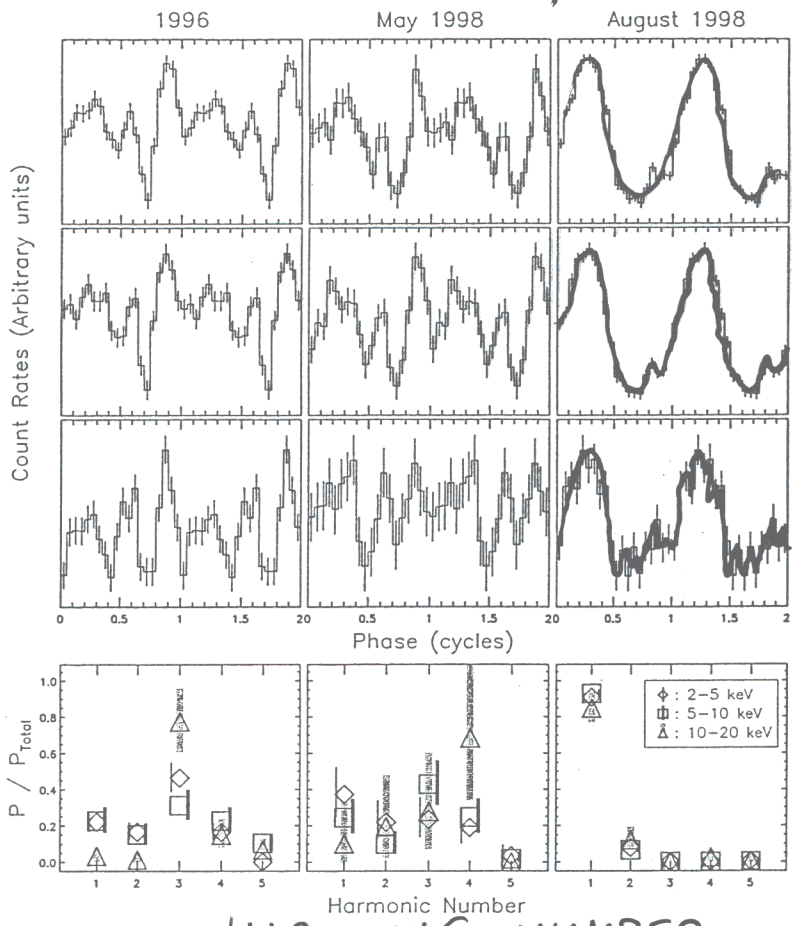
$$I \Omega \dot{\Omega} \sim \frac{I^2(R_{NS})}{c} \left(\frac{R_{NS}}{R_{lc}}\right)^{-2(1+p)}$$

$$\sim 10^{-2}\, \dot{E}_{\text{'OHMIC'}}$$

CHANGING X-RAY PULSE PROFILES

SGR 1900+14
GIANT FLARE
27 AUGUST 1998

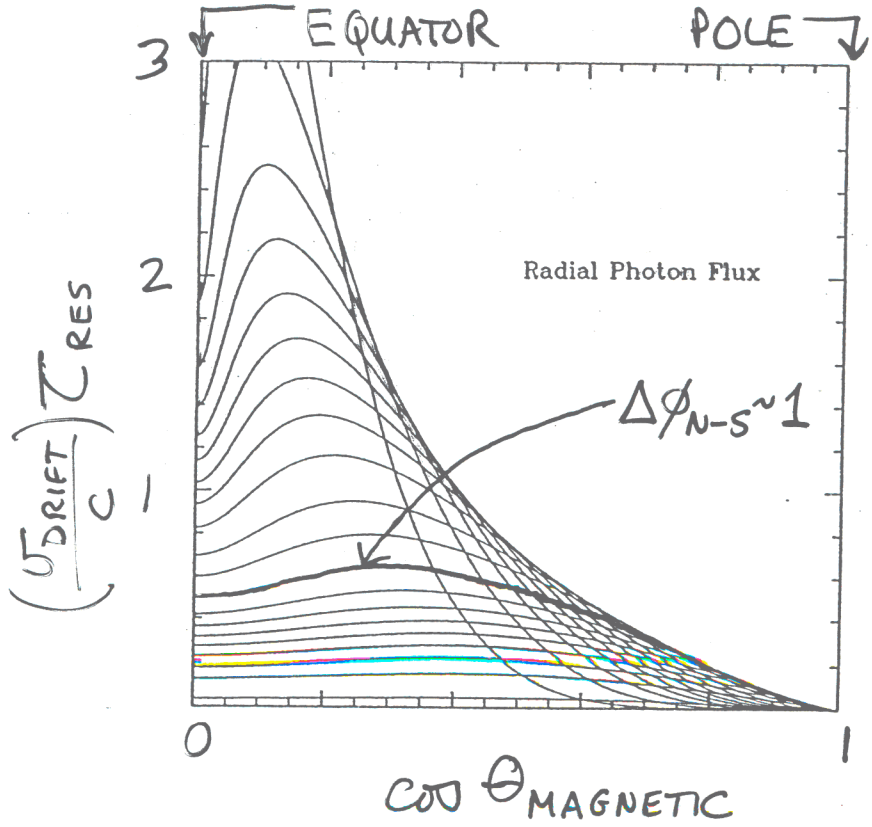
BEFORE ← → AFTER
GIANT FLARE



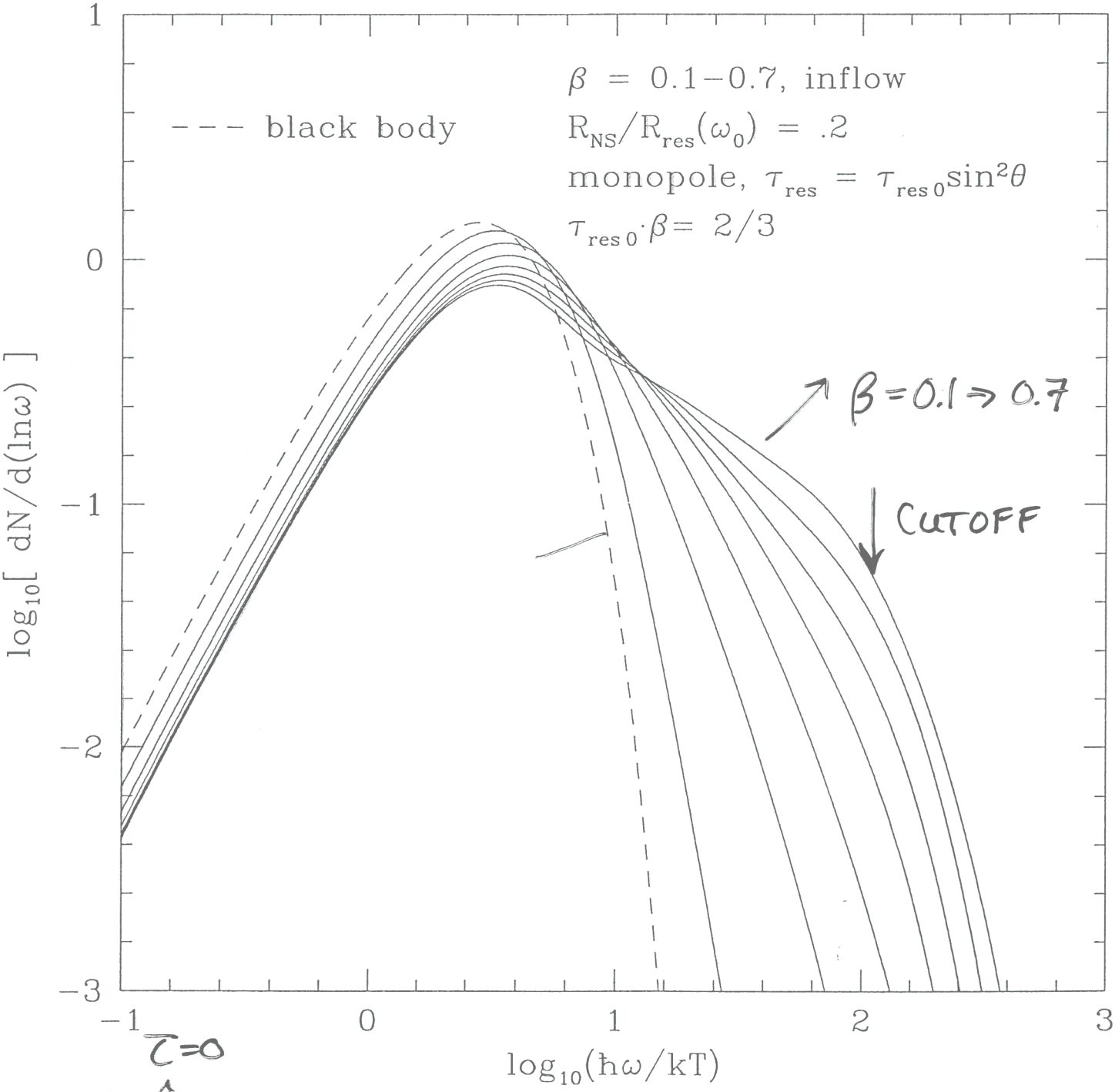
WOODS ET AL 2001

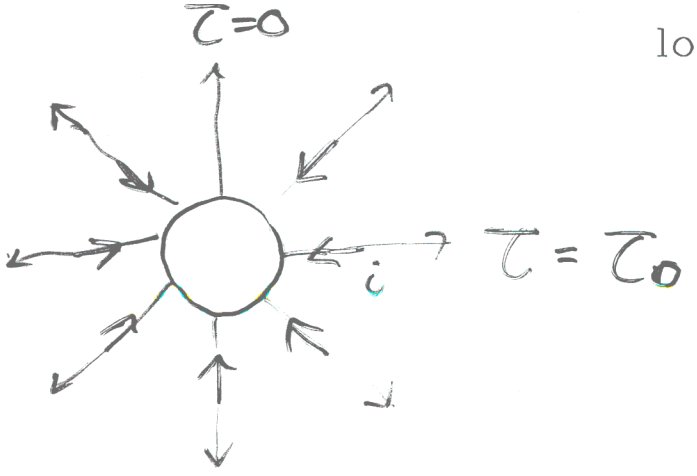
HARMONIC NUMBER

CYCLOTRON SCATTERING SCREEN



THOMPSON ET AL 2002





T + LYUTIKOV

IN PREP.

- MODE EXCHANGE
- SURFACE ABSORPTION OF E-MODE