Solving the Mysteries of Ultra-Magnetized Neutron Stars

Heat Transport inside the Crust

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Neutron Stars

General characteristics:
- masses between 1.1 and 2.1 $M_{\odot}$
- corresponding radii between 20 - 10 km
- central density $\sim 10^{15}$ g cm$^{-3}$
- core: superfluid of degenerate neutrons + superconductor of degenerate protons
- inner core ?
- crust $\rightarrow$ envelope $\rightarrow$ atmosphere
Magnetic Breaking

Magnetic Dipole Model:

\[
\dot{E} = -\frac{2}{3c^3} \mid \dot{m} \mid^2 = \frac{-B_p^2 R_{NS}^6 \Omega^4 \sin^2 \alpha}{6c^3}
\]

Rotation Energy:

\[
E = \frac{1}{2} I \Omega^2 \quad \rightarrow \quad \dot{E} = I \Omega \dot{\Omega}
\]

Compare the two:

\[
B_p^2 \Omega^4 \propto \Omega \dot{\Omega}
\]

Get the relations:

\[
P = \frac{2\pi}{\Omega} \quad \dot{P} = -\frac{\dot{\Omega}}{\Omega^2}
\]

\[
B \simeq 10^{12} \sqrt{PP_{-15}} \text{G}
\]
Relation $P - \frac{dP}{dt}$


**HBPSR**

(“High Field Pulsars”)

Critical quantum field:

$$B_{CR} \sim 4.4 \times 10^{13} G$$

Cyclotron energy = electron rest energy

$B > B_{CR} \rightarrow$ “magnetic photon splitting” dominates “pair production” $\rightarrow$ no emission in the radio

Before the Parkes Multibeam Pulsar Survey (1999):

Largest inferred $B \sim 2.1 \times 10^{13} G$ for a radio pulsar.

AFTER: $B \sim 1e13 - 1e14 G$

(Gonzalez et al. 2005)
Relation $P - \frac{dP}{dt}$


**General Characteristics:**
- low, but persistent emission in x-rays, $L_x \sim 10^{30} - 10^{34}$ ergs$^{-1}$
- no emission in the radio
- Black Body with $kT \sim 40 - 110$ eV $\Rightarrow r = 3 - 5$ km
- broad absorption line $\Rightarrow$ proton cyclotron
- optical excess $\Rightarrow r > 10$ km
- pulsations in 6 sources $\Rightarrow B \sim 10^{13} - 10^{14}$ G
- $10^5 - 10^6$ years old
- close, $d \sim 100 - 300$ pc

**XDINS**

(“X-Ray Dim Isolated Neutron Stars”)
Relation P - dP/dt

SGRs

("Soft Gamma-Ray Repeaters")

- short bursts (~100ms) en soft γ rays ν x-rays with energies of ~10^{41} ergs and rise times of ~10ms
- 4 - (6?) in the Galactic and the LMC (1)
- optically thin Bremsstrahlung emission, kT ~ 20-50 keV
  + power law with n ~ 2-3
  (quiescence)
- giant bursts, ~ 4x10^{44} erg (3)
- 3 sources with pulsations in quiescence → B ~ 10^{15} G

X-rays: surface origin
Bursts: crustal breaking and plasma excitation

Relation $P - \frac{dP}{dt}$

AXPs
(“Anomalous X-Ray Pulsars”)
- pulsations in x-rays, $L_x \sim 10^{33} - 10^{35}$ ergs$^{-1}$, $P \sim 6 - 12$ s
- Soft x-ray spectrum with (i) Black Body $kT \sim 0.4$keV y (ii) hard power law, $n \sim 2.5 - 4$
- Similar to the SGRs: wide profiles and $P - \frac{dP}{dt}$ en quiescence
- Different to the SGRs: softer spectrum, less noisy, lower B, association with SN
- Bursts in 2 cases but with a correlation with the rotation
- “Anomalous” - X-ray pulsars: NS accreting from a massive companion, fluctuations in the emission, $L_x \sim 10^{37} - 10^{38}$ ergs$^{-1}$
- lack of Doppler shift $\rightarrow$ no companion
- associations with SNRs $\rightarrow$ young

Anisotropic Heat Transport: magnetic field effects in the crust

Energy Balance:

$$C \frac{\partial T}{\partial t} = Sources - Sinks - \nabla \cdot F$$

General relativistic effects + heat transport:

$$e^\Phi F = -\kappa \cdot \nabla (e^\Phi T)$$
Anisotropic Heat Transport: magnetic field effects in the crust

Thermal conductivity of the electrons

\[ \mathbf{\kappa} = \begin{pmatrix} \kappa_{\parallel} & 0 & 0 \\ 0 & \kappa_\perp & \kappa_\wedge \\ 0 & -\kappa_\wedge & \kappa_\perp \end{pmatrix} \]

\[ \kappa_{\parallel} = \kappa_0 \]

\[ \kappa_\perp = \frac{\kappa_0}{1 + (\omega_B \tau)^2} \]

\[ \kappa_\wedge = \frac{\kappa_0 (\omega_B \tau)}{1 + (\omega_B \tau)^2} \]

Electron gyrofrequency

\[ \omega_B = \frac{eB}{m^*c} \]
Surface Temperature Distribution
With Magnetic Field:

Only considering the effect of the magnetic field in the envelope:

\[ T^4_s(\Theta_B) = T^4_s(\Theta_B = 0) \sin^2 \Theta_B + T^4_s(\Theta_B = 90) \cos^2 \Theta_B \]

Greenstein & Hartke, 1983

Best present version: Potekhin & Yakovlev, 2001
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Purely Poloidal Dipolar

Poloidal Dipolar + Quadrupolar

D. Page & A. Sarmiento,"Surface temperature distribution in magnetized neutron stars. II" 1996
Dipolar Fields: Crust + Core Currents

Crustal Poloidal
Core Poloidal

Crustal Poloidal
Core Poloidal
Fig. 7. Representation of both field lines and temperature distribution in the crust whose radial scale \((r(\rho_n) \leq r \leq r(\rho_b))\) is stretched by a factor of 5, assuming \(B_0 = 3 \times 10^{12} \text{ G}\) and \(T_{\text{core}} = 10^6 \text{ K}\). Left panel corresponds to a crustal field, right panel to a star-centered core field. Bars show the temperature scales in units of \(T_{\text{core}}\).
Poloidal + Toroidal Components
Surface Temperature Distribution
With Magnetic Field:

Geppert, Kueker & Page, 2006
Surface Temperature Distribution
With Magnetic Field:

Fig. 10. Fit of the spectrum of RX J1856.5-3754. Dotted lines show the two blackbodies fit to the data from Trümper et al. (2004). The continuous line show our results: the star has a radius $R = 14.4$ km and $R_\infty = 17.06$ km for a 1.4 $M_\odot$, at a distance of 122 pc ($N_H = 1.6 \times 10^{20}$ cm$^{-2}$ for interstellar absorption) and the observer is assumed to be aligned with the rotation axis. The magnetic field structure corresponds to model c of Figure 6 adjusted to the 14.4 km radius with $T_b = 6.8 \times 10^7$ K, resulting in $T_{\text{eff}} = 4.62 \times 10^9$ K and $T_{\text{max}} = 8.54 \times 10^5$ K.

Geppert, Kueker & Page, 2006

- \( P = 7.05514 \pm 0.00007 \text{s} \)
- \( \dot{P} < 1.9 \times 10^{-12} \text{s/s} \)
- \( B < 1.2 \times 10^{14} \text{G} \)
- \( T > 6 \times 10^4 \text{ years} \)
- \( PF = 1.6\% \pm 0.2\% \)

\( \alpha = 90^\circ \rightarrow PF \sim 18\% \)   previous model

\( \alpha = 8^\circ \rightarrow PF \sim 1.5\% \)
**RX J1856.5-3754: Quark Star?**

(Henderson & Page. 2007. *Ap&SS.tmp.* “RX J1856.5-3754 as a Possible Strange Star Candidate.”)

[Diagram showing neutron star and strange star density profiles with corresponding radii and densities.]
RX J1856.5-3754: Quark Star?

\[ B_{\text{tor}} = 1 \times 10^{15} \text{ G} \]

\[ \Delta r = 250 \text{ m} \]

But the magnetic sheer stress \( \frac{B_r B_\theta}{4\pi} \) is too large for such a thin layer

→ NOT PROBABLE

PSR J1119-6127: High Field Pulsar

Model:
T1 = 3.6e6K
T2 = 4.2e6K \( \alpha = 90^\circ \rightarrow \text{PF} \sim 68\% 
Ts = 2.7e6K

Observations:
P = 0.408s
t = 1700 years
B = 4.1e13 G
Tbb,\( \infty \) = 2.4e6 K
PF = (74 +/- 14) %
