Magnetic fields and Neutron Star Surface

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Neutron Stars: Interiors - Surface(s)

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- Neutron stars exist and have strong magnetic fields.
- Neutron stars do not exit: what are they ?
- How to find "exotic" matter: cooling.
- How to find "exotic" matter: stellar radii.
- Conclusions.

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Neutron stars do exist !

Let's consider the fastest known pulsar:

PSR J1748-2448ad in Terzan5: rotational period **P = 1.39 msec.**

(Previous fastest pulsar was PSR 1937+21: P = 1.558 msec.)

Velocity at equator < light velocity:

$$v_{\mathrm{equator}} = \Omega R = \frac{2\pi R}{P} \leq c \quad \Rightarrow \quad R \leq 2\pi c P = 65 \text{ km}$$

If the star is bound by gravity: $a_{\mathrm{gravity}} > a_{\mathrm{centrifugal}}$ at equator:

$$a_{\mathrm{gravity}} = \frac{GM}{R^2} \geq a_{\mathrm{centrifugal}} = \Omega^2 R = \frac{4\pi^2 R}{P^2} \quad \text{or} \quad \frac{M}{R^3} \geq \frac{4\pi^2}{GP^2}$$

$$\Rightarrow \quad \bar{\rho} = \frac{M}{\frac{4}{3}\pi R^3} \geq 8 \bullet 10^{13} \ \ \text{g/cm}^3$$

Pulsar spin-down

Spin-down power: $\dot{E} \equiv \frac{d}{dt}\left[\frac{1}{2} I\Omega^2\right] = I\Omega\dot{\Omega}$

Magneto-dipolar power: $\dot{E}_{md} = -\frac{R^6 B_p^2 \Omega^4 \sin^2\alpha}{6c^3}$

Spin-down law: $\dot{E} = \dot{E}_{md} \Rightarrow \dot{\Omega} = -\frac{R^6 B_p^2}{6c^3 I}\Omega^3 = -K\Omega^3$

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$$\Rightarrow P\dot{P} = -4\pi^2 \frac{\dot{\Omega}}{\Omega^3} = -\frac{2\pi^2}{3}\frac{R^6 B_p^2}{c^3 I}$$

$$\Rightarrow B_p = 3\times 10^{13}\left(P\dot{P}_{-13}\right)^{1/2}\ \mathrm{G}$$

$$\dot{\Omega} = -K\Omega^3 \Rightarrow \frac{d\Omega}{\Omega^3} = -Kdt \Rightarrow \frac{1}{2}\left(\frac{1}{\Omega_0^2} - \frac{1}{\Omega^2}\right) = Kt$$

$$\Rightarrow \tau_{sd} = \frac{P}{2\dot{P}}$$

Rough estimates

Pulsar spin-down

Spin-down power: $\dot{E} \equiv \frac{d}{dt}\left[\frac{1}{2} I\Omega^2\right] = I\Omega\dot{\Omega}$

<u>Magneto-dipolar power:</u> $\dot{E}_{md} = -\frac{R^6 B_p^2 \Omega^4 \sin^2 \alpha}{6c^3}$

It is essentially a dimensional analysis estimate:

At the light cylinder:

$r_{LC} \equiv \frac{c}{\Omega}$

Magnetic field: $B_{LC} = B_p \times \left(\frac{R}{r_{LC}}\right)^3 = \frac{B_p R^3 \Omega^3}{c^3}$

Magnetic energy density: $E_{m(LC)} = \frac{B_{LC}^2}{8\pi} = \frac{B_p^2 R^6 \Omega^6}{c^6}$

$$\dot{E}_{md} \sim -c\, E_{m(LC)} \cdot 4\pi\, r_{LC}^2 = -c \frac{B_p^2 R^6 \Omega^6}{8\pi\, c^6} 4\pi \frac{c^2}{\Omega^2}$$

Pulsar P-Ṗ diagram and X-ray detected pulsars

1403 known rotation-powered pulsars:

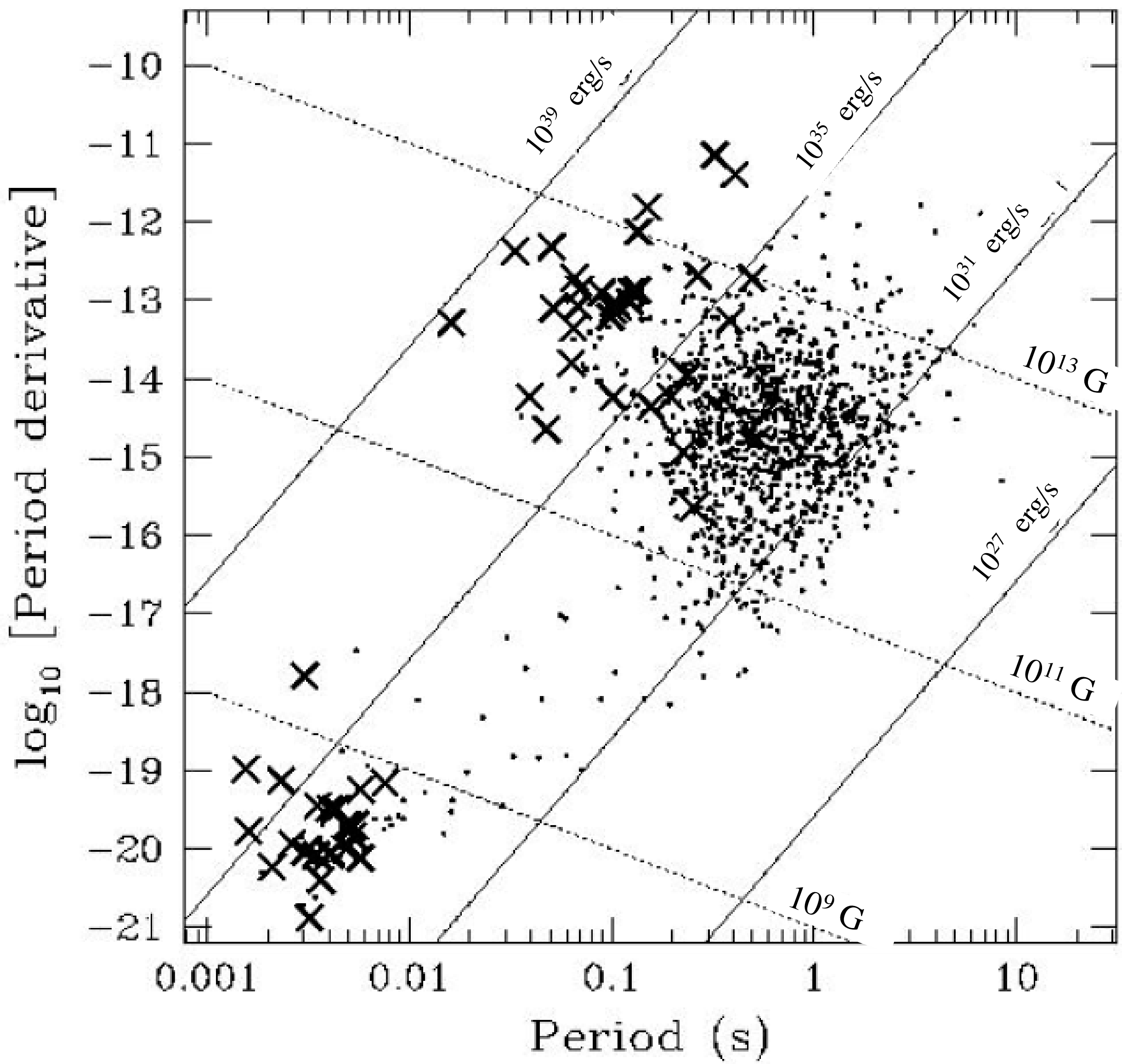
66 detected in X-rays:

pulsed, unpulsed or

nebular emission,

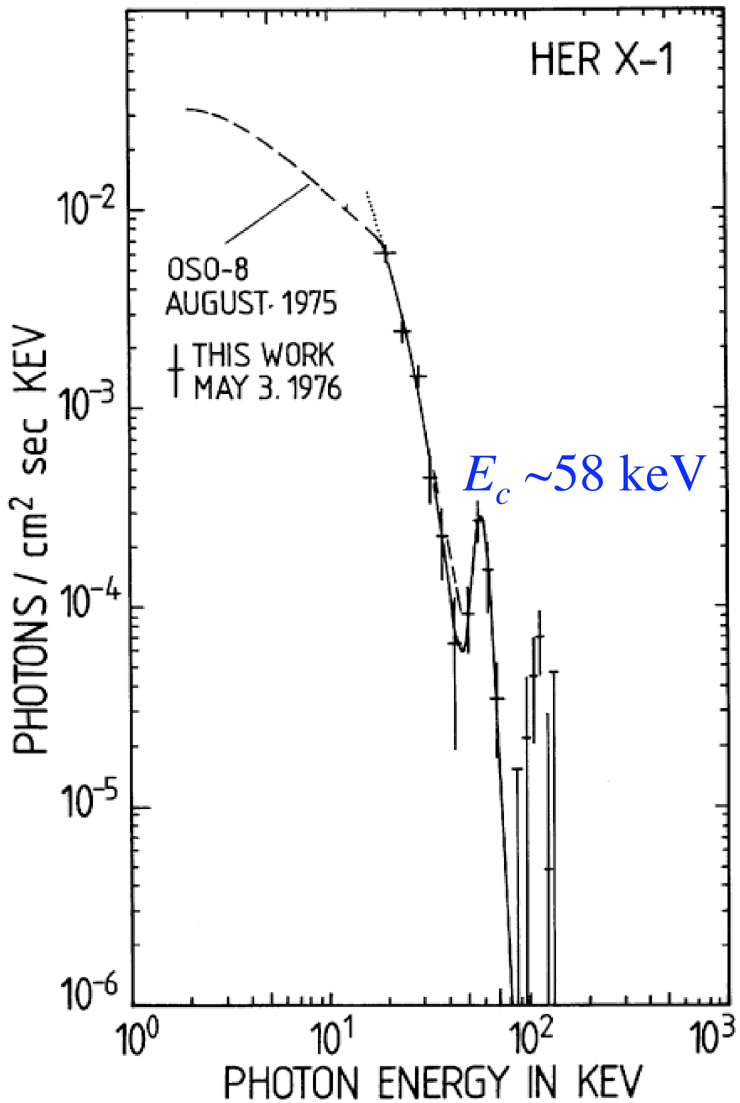
thermal and/or

non-thermal



Isolated Neutron Stars,
V.M Kaspi, M.S.E. Roberts & A.K. Harding
astro-ph/0402136

Discovery of a cyclotron line in Her X-1



$$E_c = \hbar \frac{eB}{m_e c} = 11.2\ B_{12}\ \text{keV}$$

Was interpreted as an emission line.

Present interpretation favors an absorption line at ~ 40 keV

Evidence for strong cyclotron line emission in the hard X-ray spectrum of Hercules X-1
Truemper, J.; Pietsch, W.; Reppin, C.; Voges, W.; Staubert, R.; Kendziorra, E.
1978ApJ 219, L105

Cyclotron lines in accreting X-ray pulsars

TABLE 1. List of pulsars with securely detected cyclotron lines. The discovery instrument is listed along with the discovery reference and whether the line has been observed with *RXTE*.

Source	Energy (keV)	Discovery Instrument	*RXTE*?
4U 0115+63†	12	*HEAO-1*	Y
4U 1907+09†‡	18	*Ginga*	Y
4U 1538−52‡	20	*Ginga*	Y
Vela X−1†‡	25	HEXE	Y
V 0332+53	27	*Ginga*	N
Cep X−4	28	*Ginga*	Y
Cen X−3‡	28.5	*RXTE/BSAX*	Y
X Per	29	*RXTE*	Y
XTE J1946+274	36	*RXTE/BSAX*	Y
MX0656−072	36	*RXTE*	Y
4U 1626−67	37	*RXTE/BSAX*	Y
GX 301−2‡	37	*Ginga*	Y
Her X−1‡	41	Balloon	Y
A 0535+26	50?, 110	HEXE	N

† objects with $>$ 1 harmonic observed

‡ high inclination system

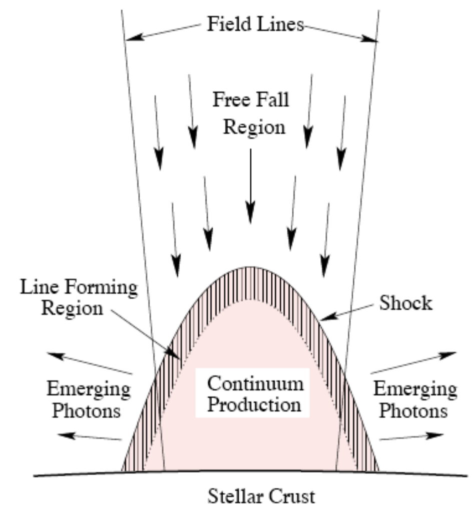
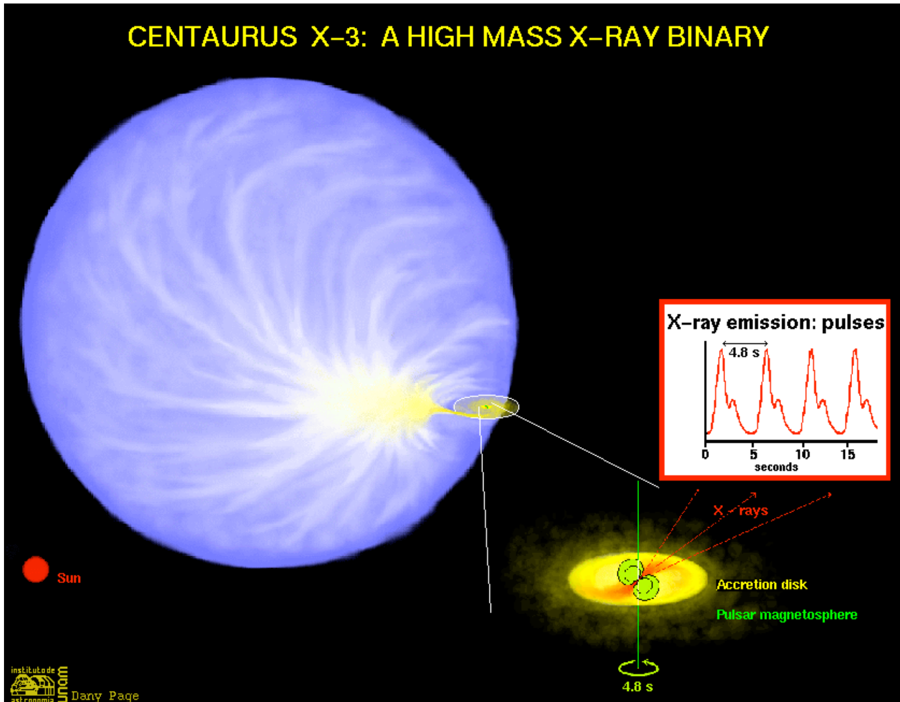


FIGURE 1. Schematic diagram of the "accretion mound" showing the line-forming region as a discrete layer covering the continuum production zone.

Timing and Spectroscopy of Accreting X-ray Pulsars: the State of Cyclotron Line Studies
Heindl, W. A et al. (2004) AIP, .714 p. 323 [astro-ph/0403197]

Neutron stars in X-ray binaries



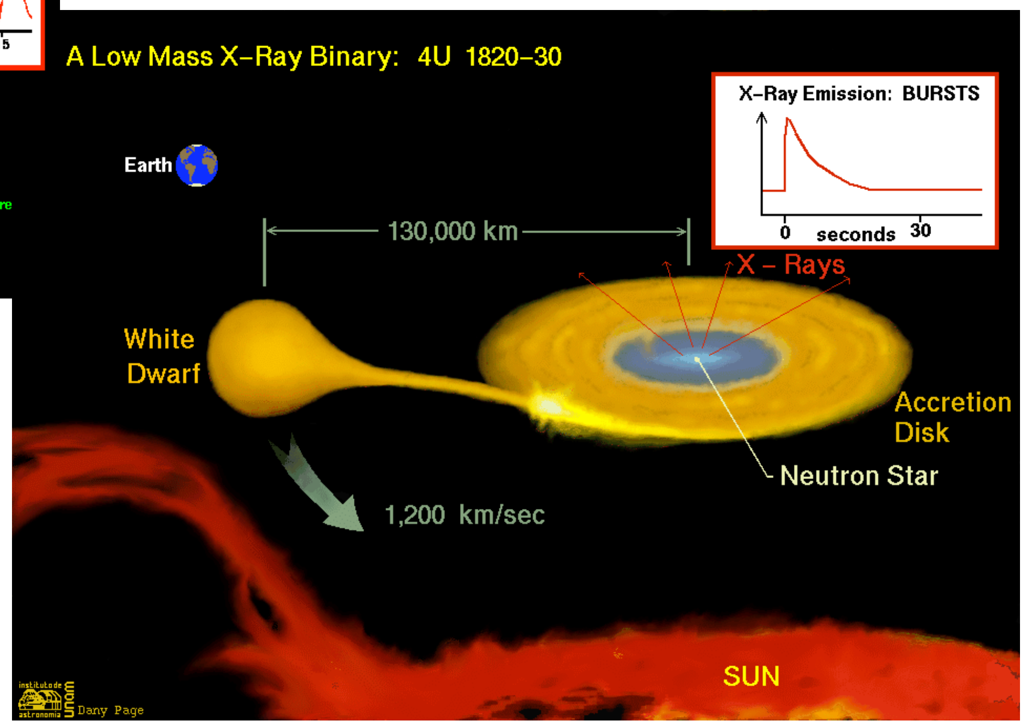
← High mass companion:

- short lived (~10^6 yrs)
- little mass accretion (~0.01 M_0)

Low mass companion →

long lived (~10^9 yrs)

large mass accretion (~0.5 M_0)



<u>Neutron</u> stars do not exist !

Do blackholes exist ?

Simple question because blackhole are simple objects

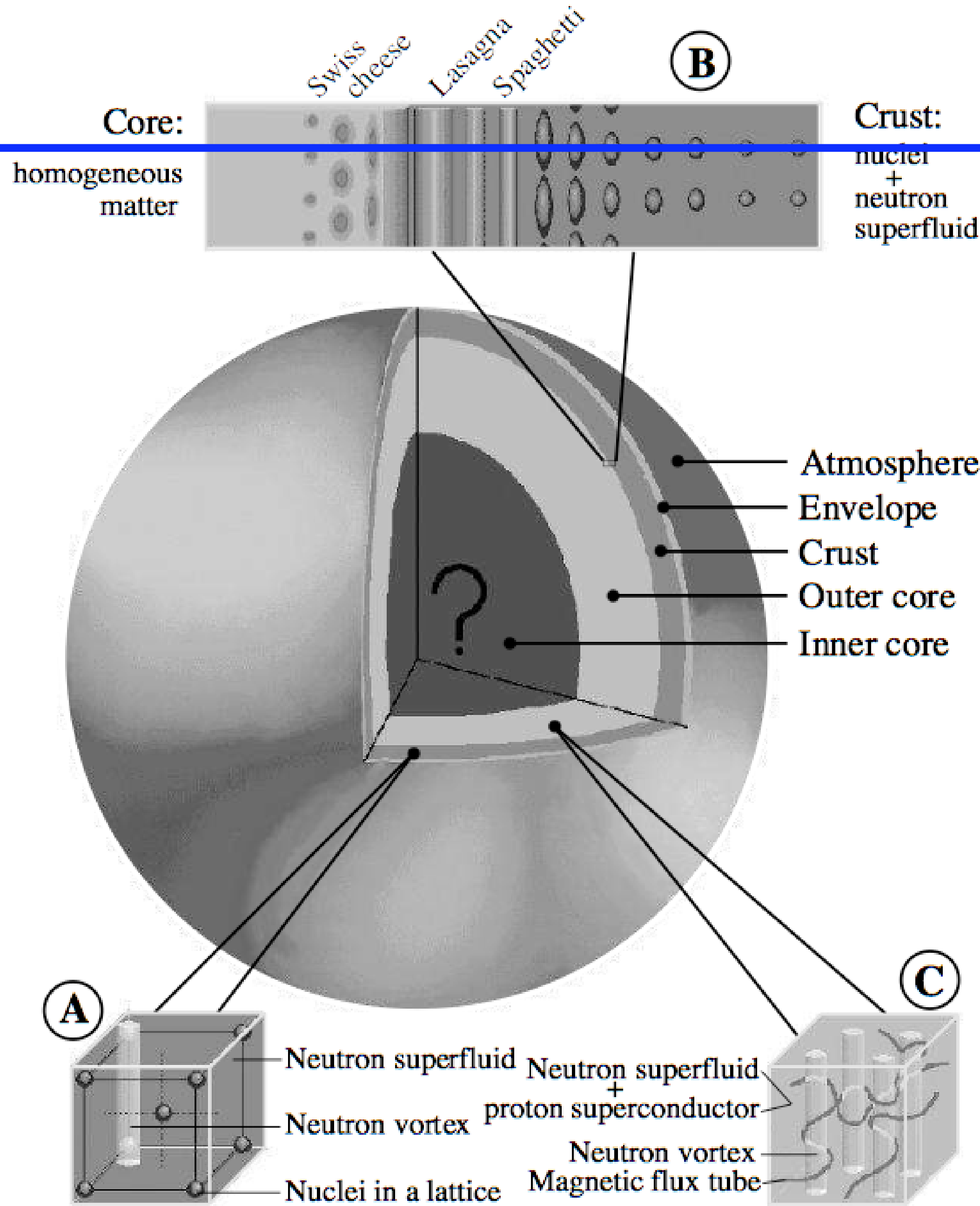
Do "neutron" stars exist ?

No doubt that compact (or whatever name you choose) stars exist.

<u>Neutron</u> stars, as originally conceived by Landau, Baade & Zwicky, Oppenheimer & Volkoff **do not** exist:

having a one solar mass ball of neutrons, the neutrons will immediately start to decay into protons

$$n \rightarrow p + e^- + \bar{\nu}_e$$



Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page, D., & Reddy, S. 2006, Annu. Rev. Nucl. Part. Sci., 56, p. 327

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Building models of dense matter

Simplest case of n-p-e-μ matter:

- Bayon number density: $n_B = n_p + n_n$
- Charge neutrality: $n_p = n_e + n_\mu$
- Chemical equilibrium: $\mu_n = \mu_p + \mu_e$ & $\mu_e = \mu_\mu$

$$\mu_e = p_F(e)c \qquad \mu_\mu = \sqrt{m_\mu^2 c^4 + p_F^2(\mu)c^2}$$

$$\mu_p = m_p c^2 + \frac{p_F^2(p)}{2m_p} + V_p \qquad \mu_n = m_n c^2 + \frac{p_F^2(n)}{2m_n} + V_n$$

$\Rightarrow$ strong model dependence on how V_n and V_p are calculated

Walecka type model of dense matter

The model proposes that in dense matter, nucleons interact with effective short-range forces. The Lagrangian is given by

$$\begin{aligned}\mathcal{L}_N &= \bar{\Psi}_N(i\gamma^\mu\partial_\mu - m_N^* - g_{\omega N}\gamma^\mu V_\mu - g_{\rho N}\gamma^\mu\vec{\tau}_N \times \vec{R}_\mu)\Psi_N \\ &+ \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - U(\sigma) - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} \\ &+ \frac{1}{2}m_\omega^2 V_\mu V^\mu - \frac{1}{4}\vec{R}_{\mu\nu}\times\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{R}_\mu \times \vec{R}^\mu, \qquad 7.\end{aligned}$$

where $m_N^* = m_N - g_{\sigma N}\sigma$ is the nucleon effective mass, which is reduced in comparison to the free nucleon mass m_N owing to the scalar field σ, taken to have $m_\sigma = 600$ MeV. The vector fields corresponding to the isoscalar omega and isovector rho mesons are given by $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ and $\vec{R}_{\mu\nu} = \partial_\mu\vec{R}_\nu - \partial_\nu\vec{R}_\mu$, respectively. The exchange of these mesons mimics the short-range forces between nucleons. In addition to the coupling between nucleons and mesons, a self-interaction between scalar mesons given by

$$U(\sigma) = \frac{b}{3}m_N(g_{\sigma N}\sigma)^3 + \frac{c}{4}(g_{\sigma N}\sigma)^4, \qquad 8.$$

Walecka type model of dense matter

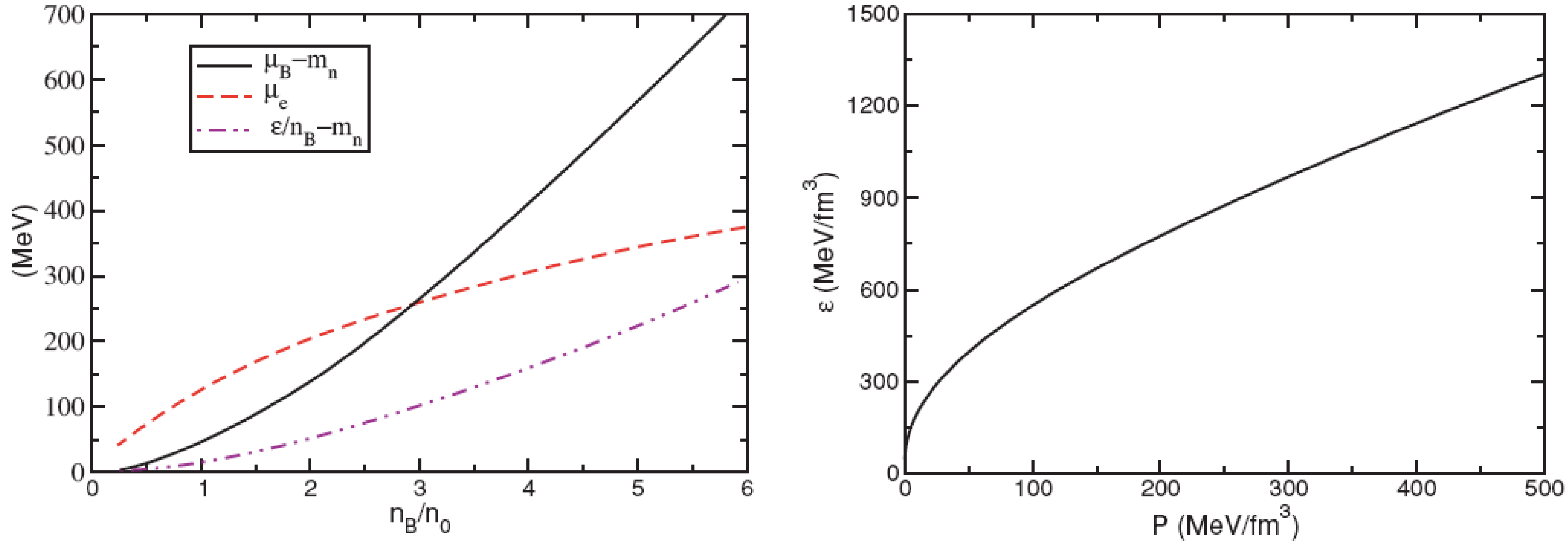


Figure 9 The nuclear equation of state. (*Left*) The density dependence of the baryon chemical potential, the electron chemical potential, and the energy per baryon. (*Right*) The relation between energy density and pressure.

$\mu_B \equiv \mu_n = m_n$ + hundreds of MeVs: rapidly reaches Λ and Σ masses !

Hyperons in dense matter

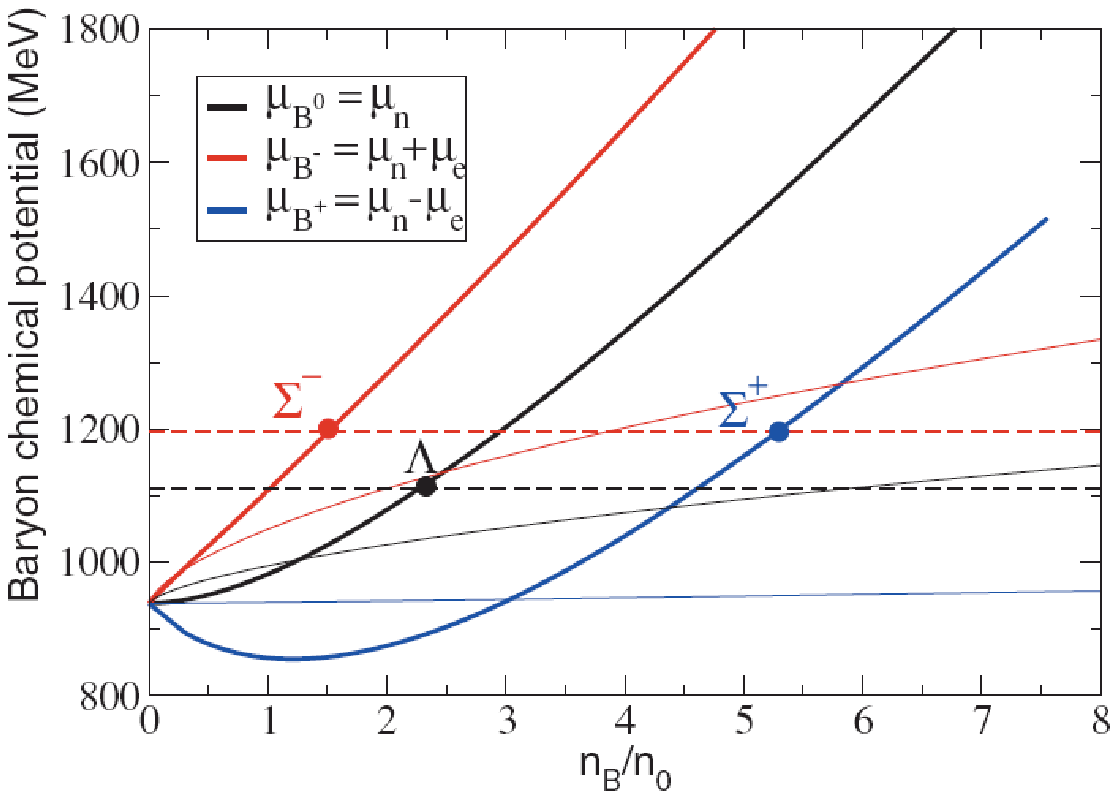
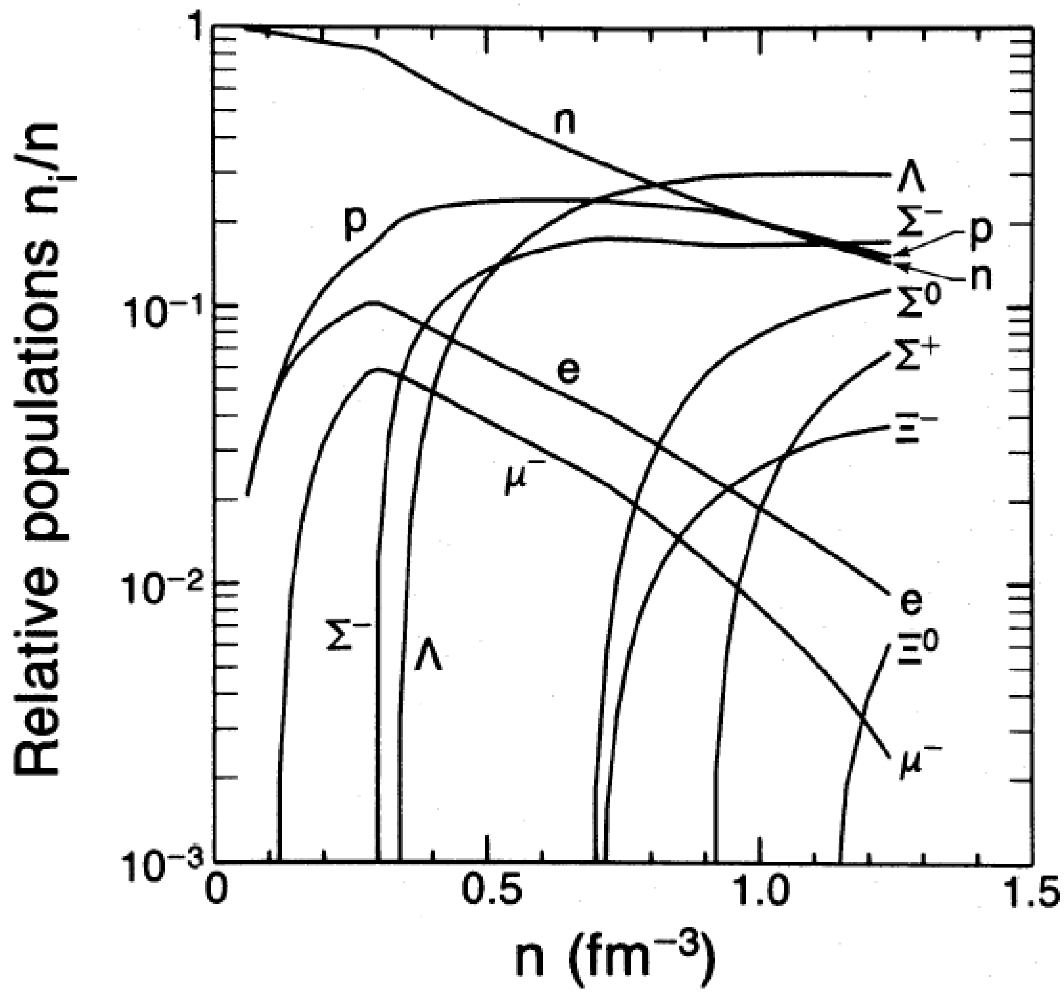


Figure 10 Baryon chemical potentials in dense stellar matter.

Thick lines: Walecka type model

Thin lines: free gases

An example of hyperonic matter



Neutron stars are giant hypernuclei ?, N.K. Glendenning, ApJ 293, 470 (1985)

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How to find "exotic" matter: neutrino cooling

SOME CORE NEUTRINO EMISSION PROCESSES AND THEIR EMISSIVITIES

Process Name	Process	Emissivity Q_ν[a] (ergs s^{-1} cm^{-3})	Emissivity References
Modified Urca	$\begin{cases} n + n' \to n' + p + e^- + \overline{\nu}_e \\ n' + p + e^- \to n' + n + \nu_e \end{cases}$	$\sim 10^{20} T_9^8$	Friman & Maxwell 1979
Kaon condensate	$\begin{cases} n + K^- \to n + e^- + \overline{\nu}_e \\ n + e^- \to n + K^- + \nu_e \end{cases}$	$\sim 10^{24} T_9^6$	Brown et al. 1988
Pion condensate	$\begin{cases} n + \pi^- \to n + e^- + \overline{\nu}_e \\ n + e^- \to n + \pi^- + \nu_e \end{cases}$	$\sim 10^{26} T_9^6$	Maxwell et al. 1977
Direct Urca	$\begin{cases} n \to p + e^- + \overline{\nu}_e \\ p + e^- \to n + \nu_e \end{cases}$	$\sim 10^{27} T_9^6$	Lattimer et al. 1991
Quark Urca	$\begin{cases} d \to u + e^- + \overline{\nu}_e \\ u + e^- \to d + \nu_e \end{cases}$	$\sim 10^{26} \alpha_c T_9^6$	Iwamoto 1980

[a] T_9 is the temperature in units of 10^9 K.

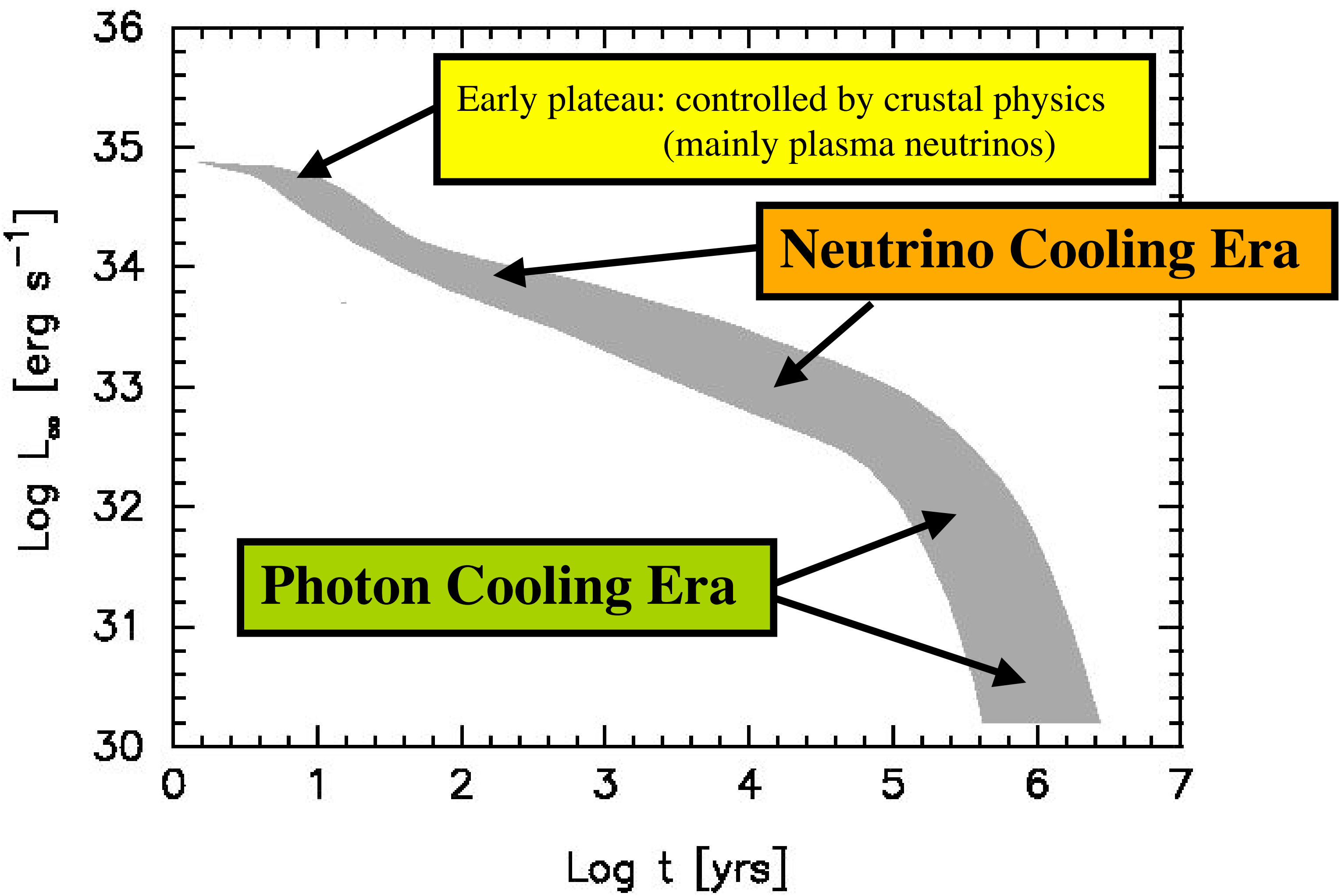
How to find "exotic" matter: neutrino cooling

SOME CORE NEUTRINO EMISSION PROCESSES AND THEIR EMISSIVITIES

Process Name	Process	Emissivity Q_ν[a] (ergs s^{-1} cm^{-3})	Emissivity References
Modified Urca	$\begin{cases} n + n' \to n' + p + e^- + \overline{\nu}_e \\ n' + p + e^- \to n' + n + \nu_e \end{cases}$	$\sim 10^{20} T_9^8$	SLOW
Kaon condensate	$\begin{cases} n + K^- \to n + e^- + \overline{\nu}_e \\ n + e^- \to n + K^- + \nu_e \end{cases}$	$\sim 10^{24} T_9^6$	FAST
Pion condensate	$\begin{cases} n + \pi^- \to n + e^- + \overline{\nu}_e \\ n + e^- \to n + \pi^- + \nu_e \end{cases}$	$\sim 10^{26} T_9^6$	
Direct Urca	$\begin{cases} n \to p + e^- + \overline{\nu}_e \\ p + e^- \to n + \nu_e \end{cases}$	$\sim 10^{27} T_9^6$	
Quark Urca	$\begin{cases} d \to u + e^- + \overline{\nu}_e \\ u + e^- \to d + \nu_e \end{cases}$	$\sim 10^{26} \alpha_c T_9^6$	

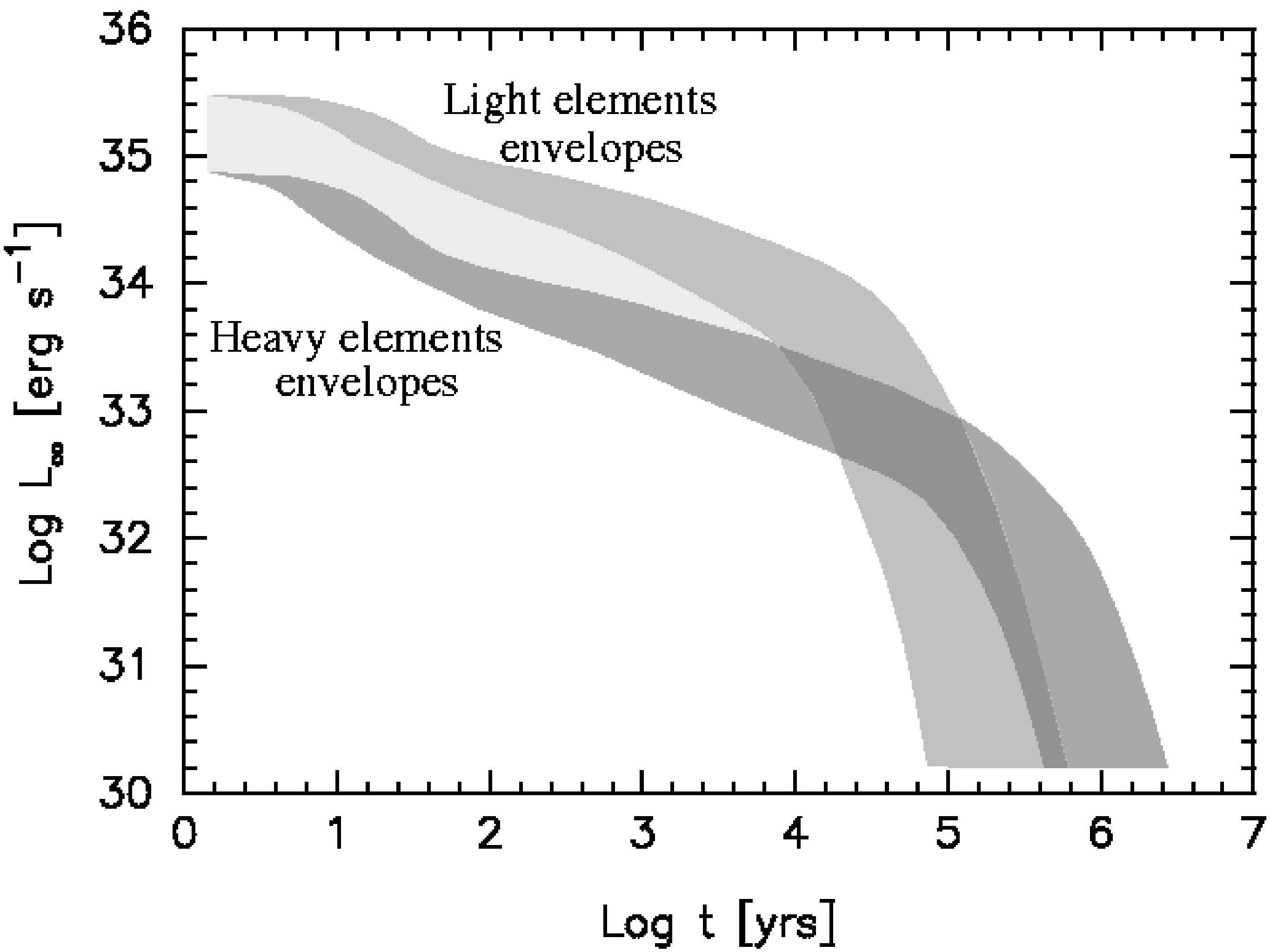
[a] T_9 is the temperature in units of 10^9 K.

Minimal cooling of neutron stars



Minimal Cooling of Neutron Stars: A New Paradigm
D. Page, J.M. Lattimer, M. Prakash & A.W. Steiner, 2004, ApJS 155, p. 623

Minimal cooling of neutron stars



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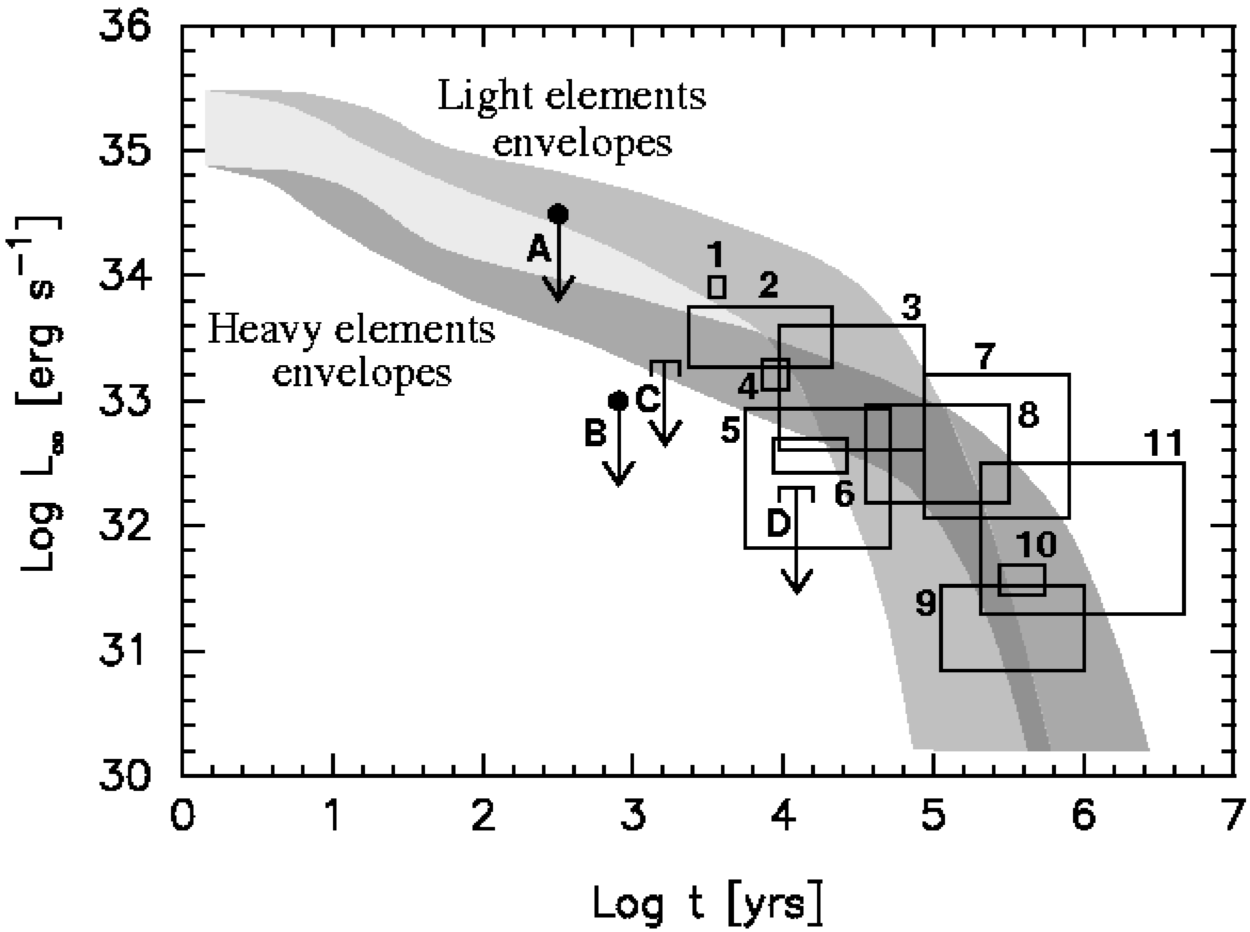
D. Page, J.M. Lattimer, M. Prakash & A.W. Steiner, 2004, ApJS 155, p. 623

Minimal cooling: comparison with data



Mag H fits:

1) RX J0822-4247 (in Puppis A)

2) 1E 1207.4-5209 (in PKS 1209-52)

3) PSR 0538+2817

4) RX J0002+6246 (in CTB 1)

5) PSR 1706-44

6) PSR 0933-45 (in Vela)

BB fits:

7) PSR 1055-52

8) PSR 0656+14

9) PSR 0633+1748 "Geminga"

10) RX J1856.5-3754

11) RX J0720.4-3125

Upper limits:

A) CXO J232327.8+584842 (in Cas A)

B) PSR J0205+6449 (in 3C58)

C) PSR J1124-5916 (in G292.0+1.8)

D) RX J0007.0+7302 (in CTA 1)

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D. Page, J.M. Lattimer, M. Prakash & A.W. Steiner, 2004, ApJS 155, p. 623

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How to find "exotic" matter: stellar radii

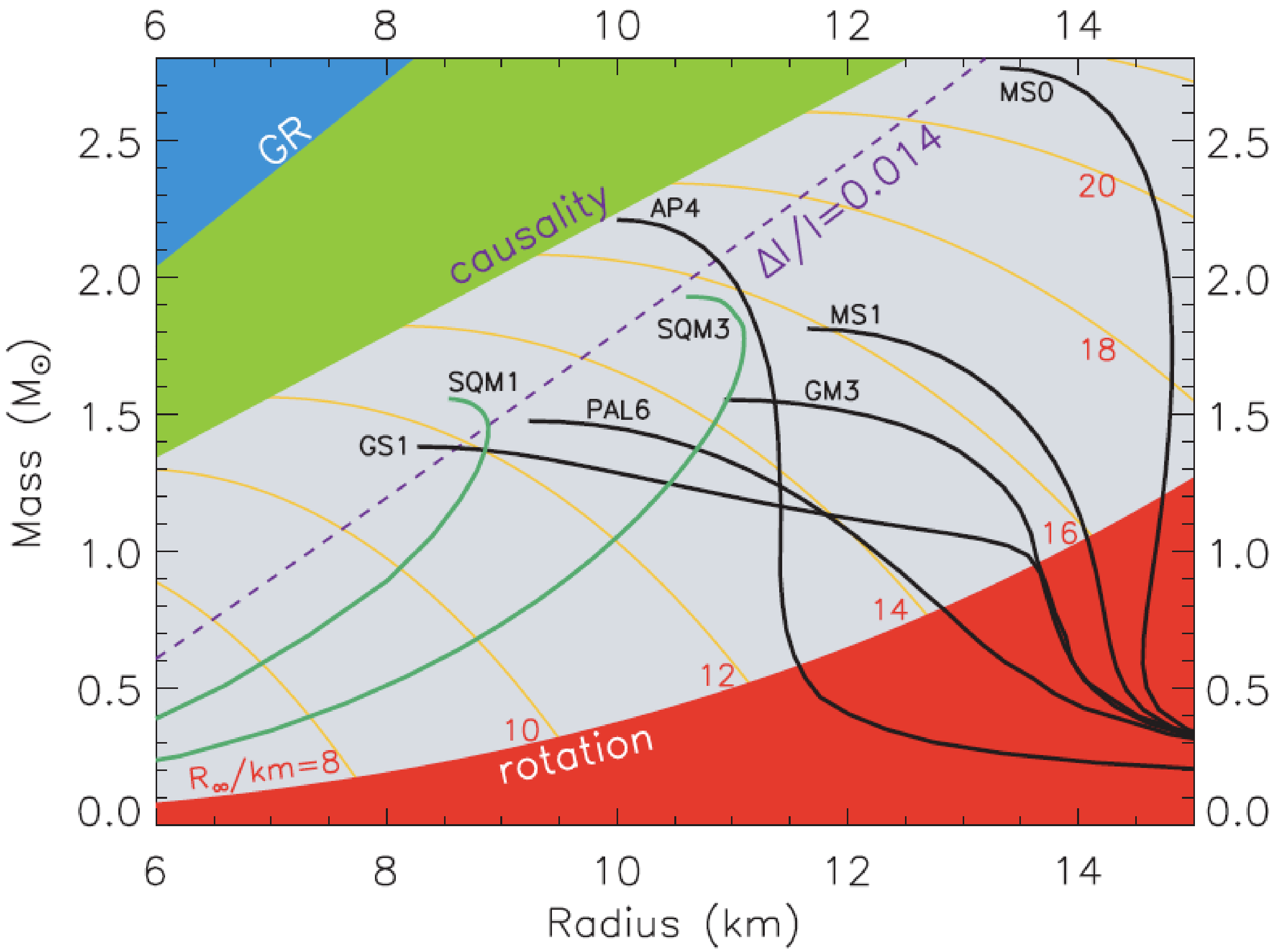
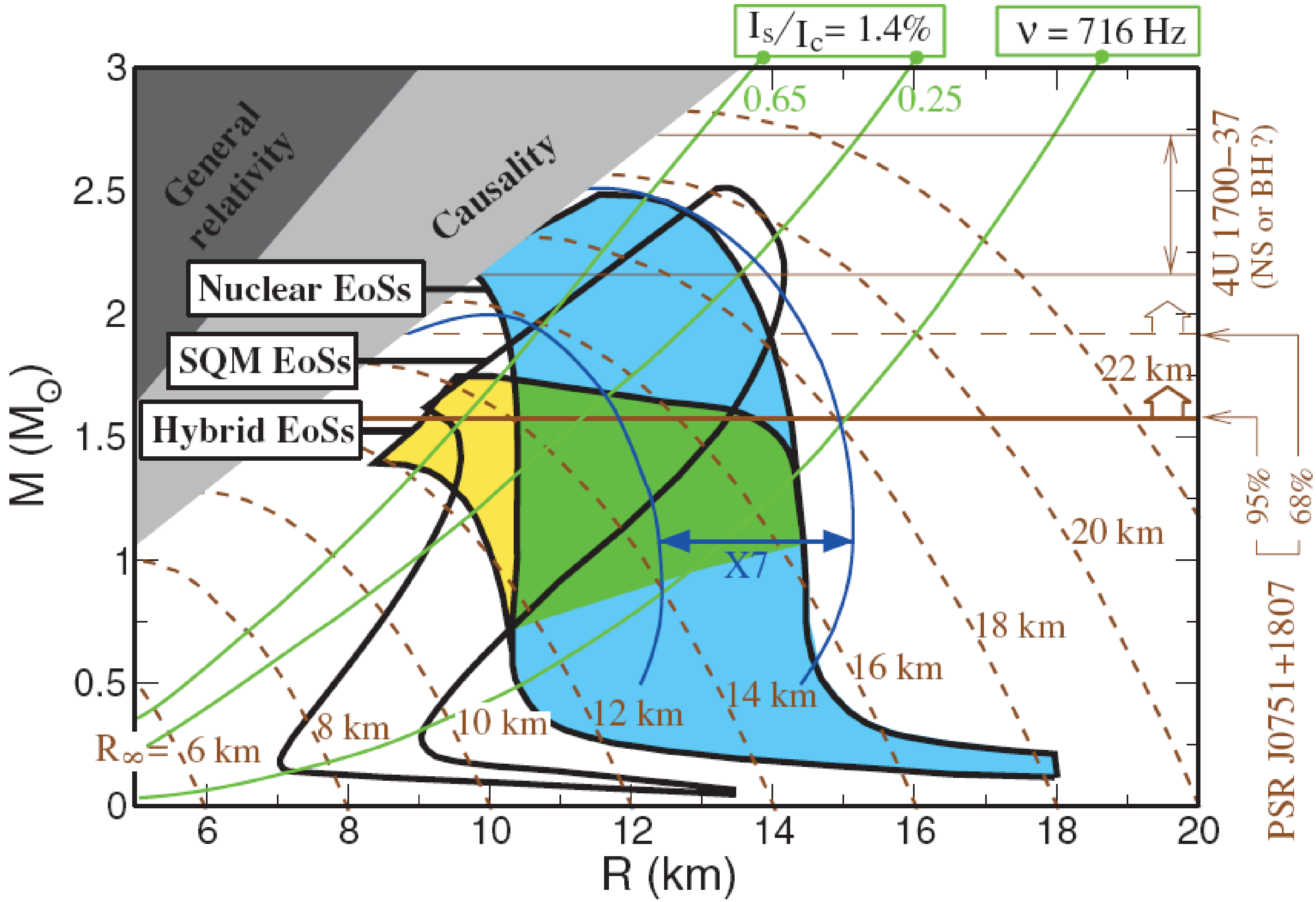


Fig. 2. Mass-radius diagram for neutron stars. Black (green) curves are for normal matter (SQM) equations of state [for definitions of the labels, see (*27*)]. Regions excluded by general relativity (GR), causality, and rotation constraints are indicated. Contours of radiation radii R_∞ are given by the orange curves. The dashed line labeled $\Delta I/I = 0.014$ is a radius limit estimated from Vela pulsar glitches (*27*).

The Physics of Neutron Stars, Lattimer, J. M.; Prakash, M. 2004,Science 304, p. 536

How to find "exotic" matter: stellar radii

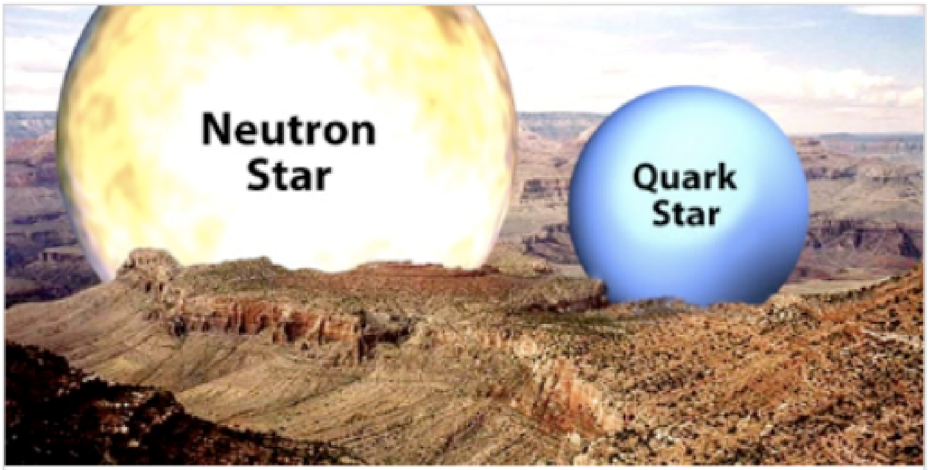


Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page, D., & Reddy, S. 2006, Annu. Rev. Nucl. Part. Sci., 56, p. 327

Measuring the radius of an isolated neutron star

Quark-Matter Stars Said Found

By Jack Lucentini



The sizes of a neutron star and a quark star compared to the Grand Canyon. The smallest, most massive, most compressed neutron star possible is about 17 kilometers in diameter. A quark star can be smaller than 11 kilometers diameter. The canyon is 29 kilometers from rim to rim. In reality this scene couldn't exist; the entire Earth would collapse almost instantly to a thin layer coating the surface of either superdense star. Illustration by D. Berry / Chandra X-ray Center.

April 11, 2002 | Astronomers say they have likely found a bizarre new type of superdense star made of a weird form of matter like nothing else in the universe.

$$L_\gamma = 4\pi R^2 \sigma_{SB}\, T^4$$

$$\Rightarrow F_{rec} = \left(\frac{R}{D}\right)^2 \sigma_{SB}\, T^4$$

F_{rec} observed "directly"

T "measured" from the shape of the spectrum

D measured (HST parallaxe)

==> R "measured"

RX J1856.5-3754:

Drake *et al.* (2002) found

R = 4-6 km ==> Quark Star !

"Better" spectral models +

new parallaxe distance

==> R = 24 km !?!?!

"Anti Quark Star" ?

Thermal spectra and interstellar absorption

$$F_{\mathrm{Obs}}(E) = e^{-N_H \sigma_{eff}(E)} F(E)$$

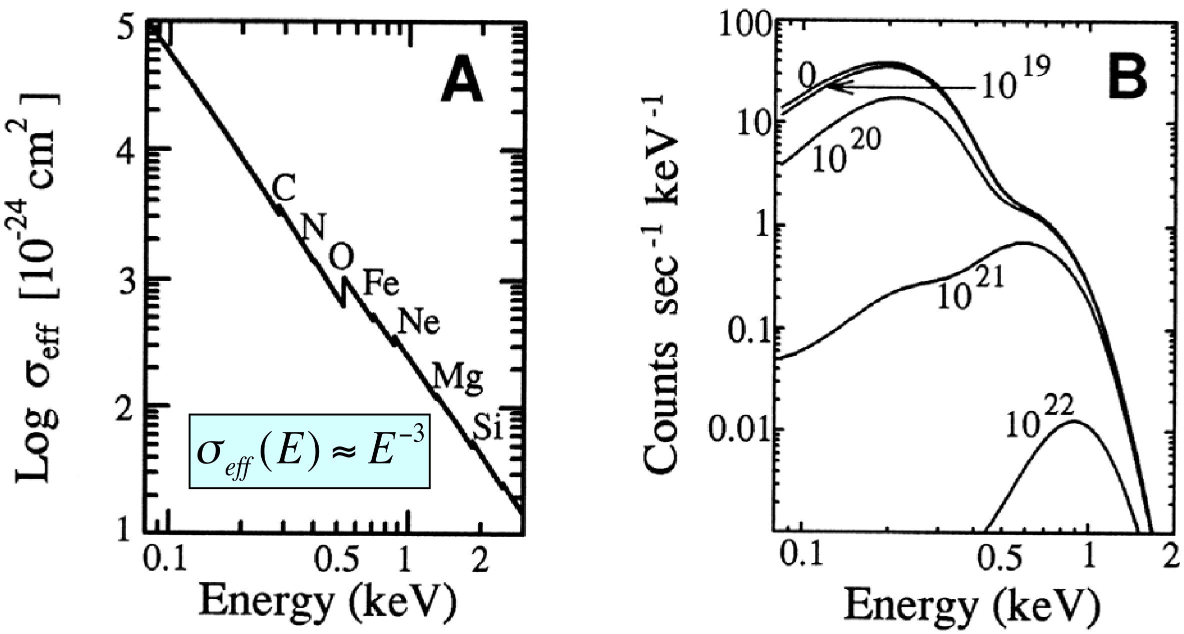


Fig. 1. **A**: Effective cross section for interstellar absorption, taking into account a standard chemical composition of the interstellar medium. Absorption edges from metals are indicated. (From Morrison & McCammon, 1983).
B: Blackbody spectrum (R_∞ = 13 km, M = 1.4 $M_\odot$ neutron star at 500 pc with T_e^∞ = 10^6 K) and interstellar absorption with various values of N_H as indicated. These spectra take into account the *ROSAT* PSPC response.

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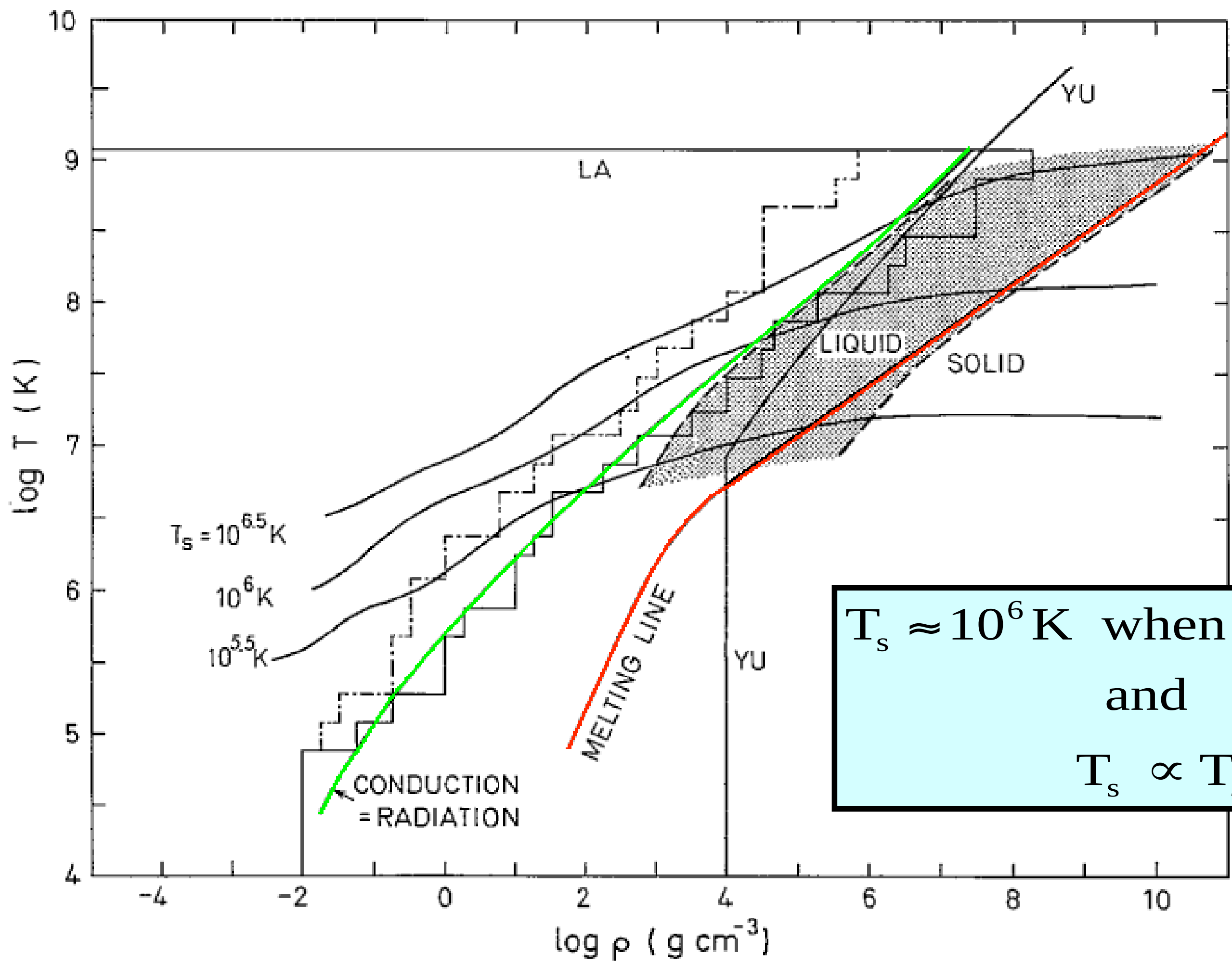
Temperature drop in the neutron star envelope



$$T_s \approx 10^6\,\mathrm{K} \quad \text{when } T_b \approx 10^8\,\mathrm{K}$$

and

$$T_s \propto T_b^{1/2}$$

Gudmundsson, Pethick & Epstein, Ap. J. 259 (1982), L19 and Ap. J. 272 (1983) 286

Anisotropic heat transport with magnetic fields

Electron thermal conductivity

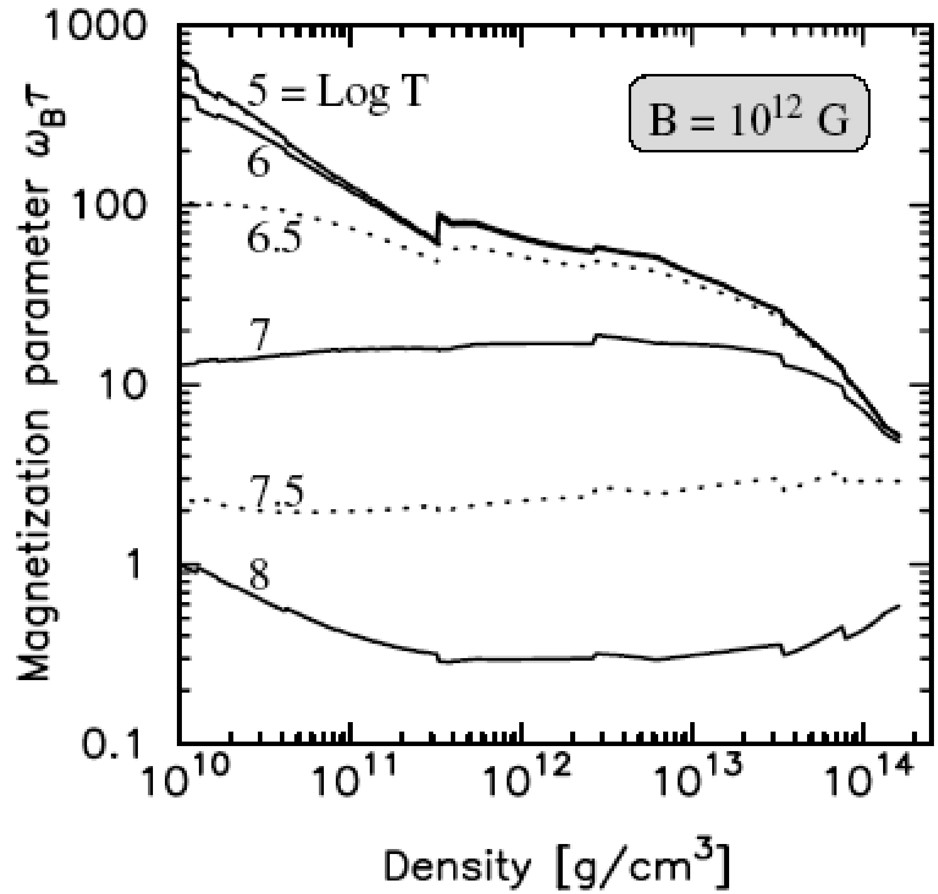
$$\overset{\leftrightarrow}{\kappa} = \begin{pmatrix} \kappa_{\parallel} & 0 & 0 \\ 0 & \kappa_{\perp} & \kappa_{\wedge} \\ 0 & -\kappa_{\wedge} & \kappa_{\perp} \end{pmatrix}$$

$$\kappa_{\parallel} = \kappa_0$$

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

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

$$\omega_B = \frac{eB}{m^* c}$$ electron gyrofrequency



Anisotropic heat transport in a magnetized envelope

$$\kappa(\Theta_B) = \kappa_{\parallel} \cdot \cos^2\Theta_B + \kappa_{\perp} \cdot \sin^2\Theta_B \qquad \Theta_B = \text{angle}(\mathbf{B},\mathbf{r})$$

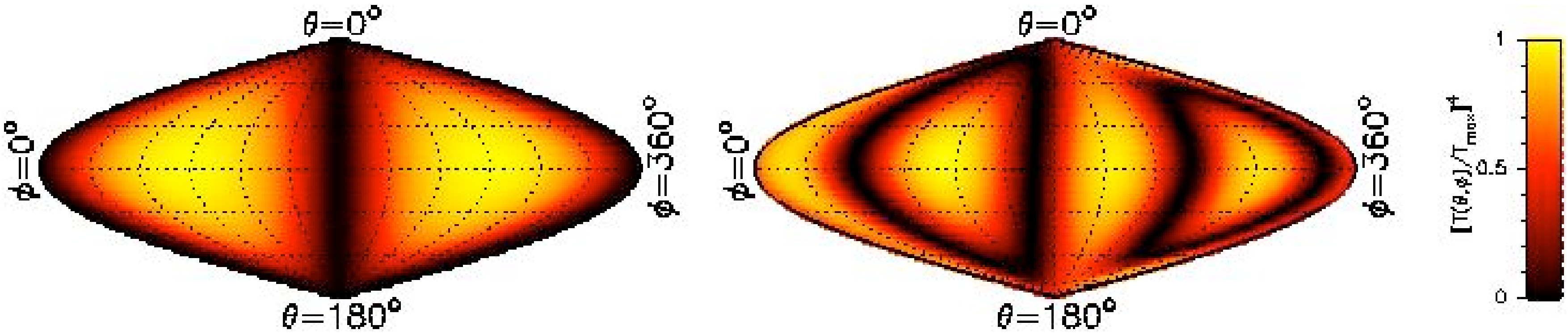
Considering the effect of the magnetic field only in the envelope:

$$T_s^4(\Theta_B) = T_s^4(\Theta_B = 0)\cos^2\Theta_B + T_s^4(\Theta_B = 90)\sin^2\Theta_B$$

Greenstein & Hartke, 1983

Best present version: Potekhin & Yakovlev, 2001

Purely Dipolar Field   Dipole + Quadrupole Field



D. Page "*Surface temperature distribution in magnetized neutron stars. I. dipolar fields*", 1995

D. Page & A. Sarmiento,"*Surface temperature distribution in magnetized neutron stars. II*" 1996

Anisotropic heat transport in a magnetized crust

Need to model B in the crust ⇔ Choose currents locations

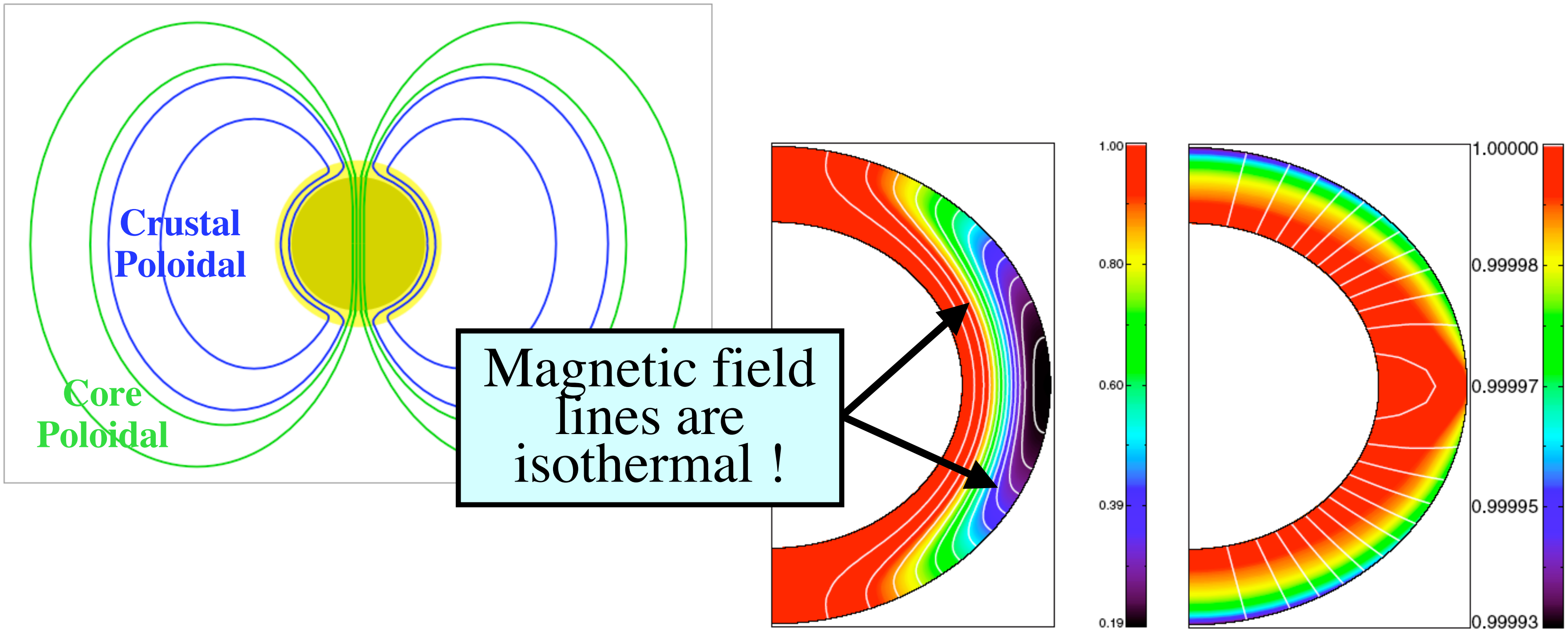
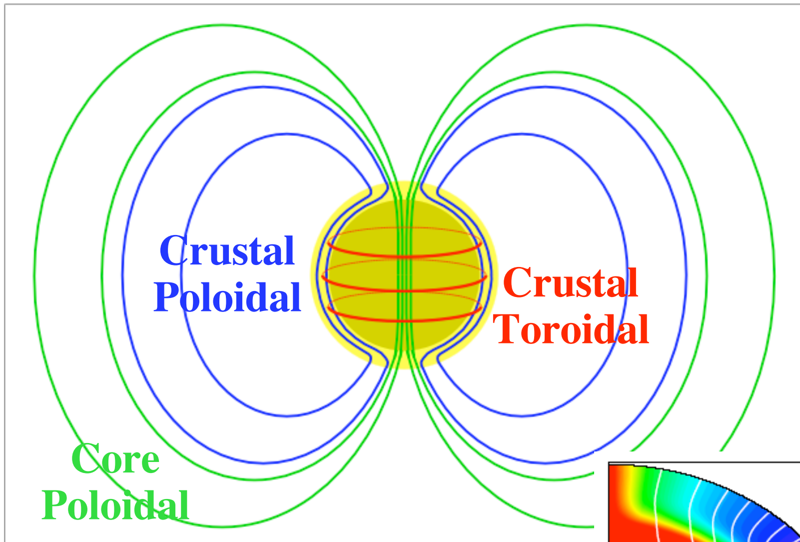
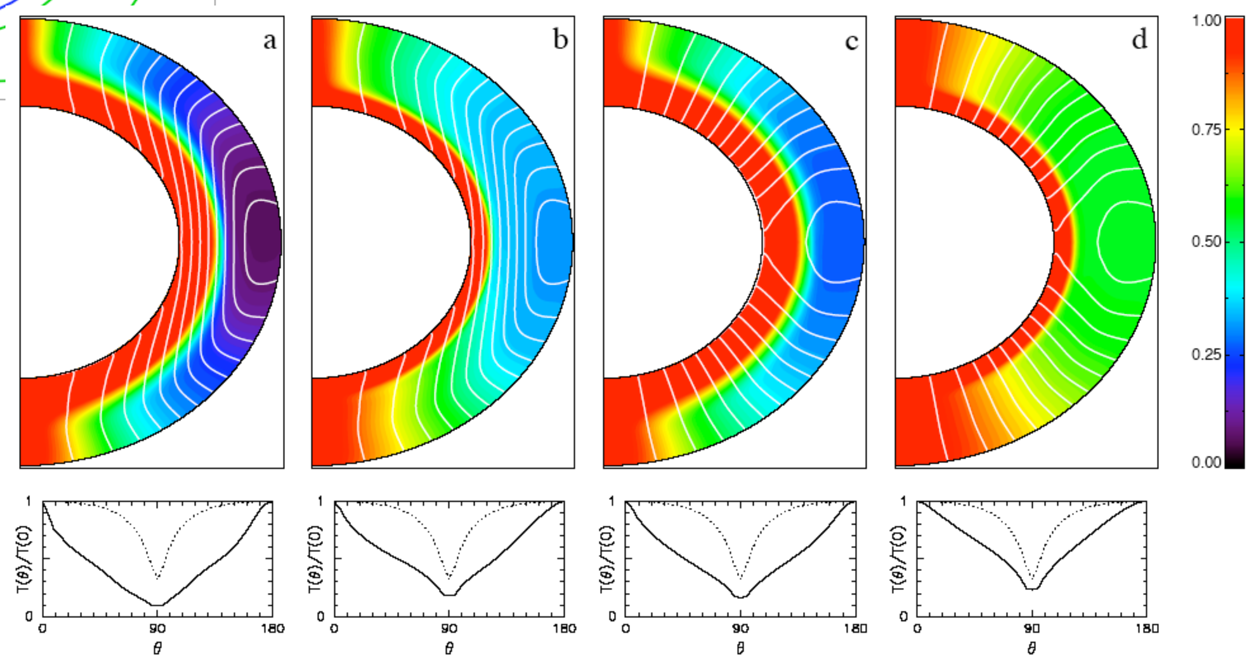


Fig. 7. Representation of both field lines and temperature distribution in the crust whose radial scale ($r(\rho_n) \leq r \leq r(\rho_b)$) is stretched by a factor of 5, assuming $B_0 = 3 \times 10^{12}$ G and $T_{\rm core} = 10^6$ K. Left panel corresponds to a crustal field, right panel to a star-centered core field. Bars show the temperature scales in units of $T_{\rm core}$.

Geppert, Kueker & Page, 2004

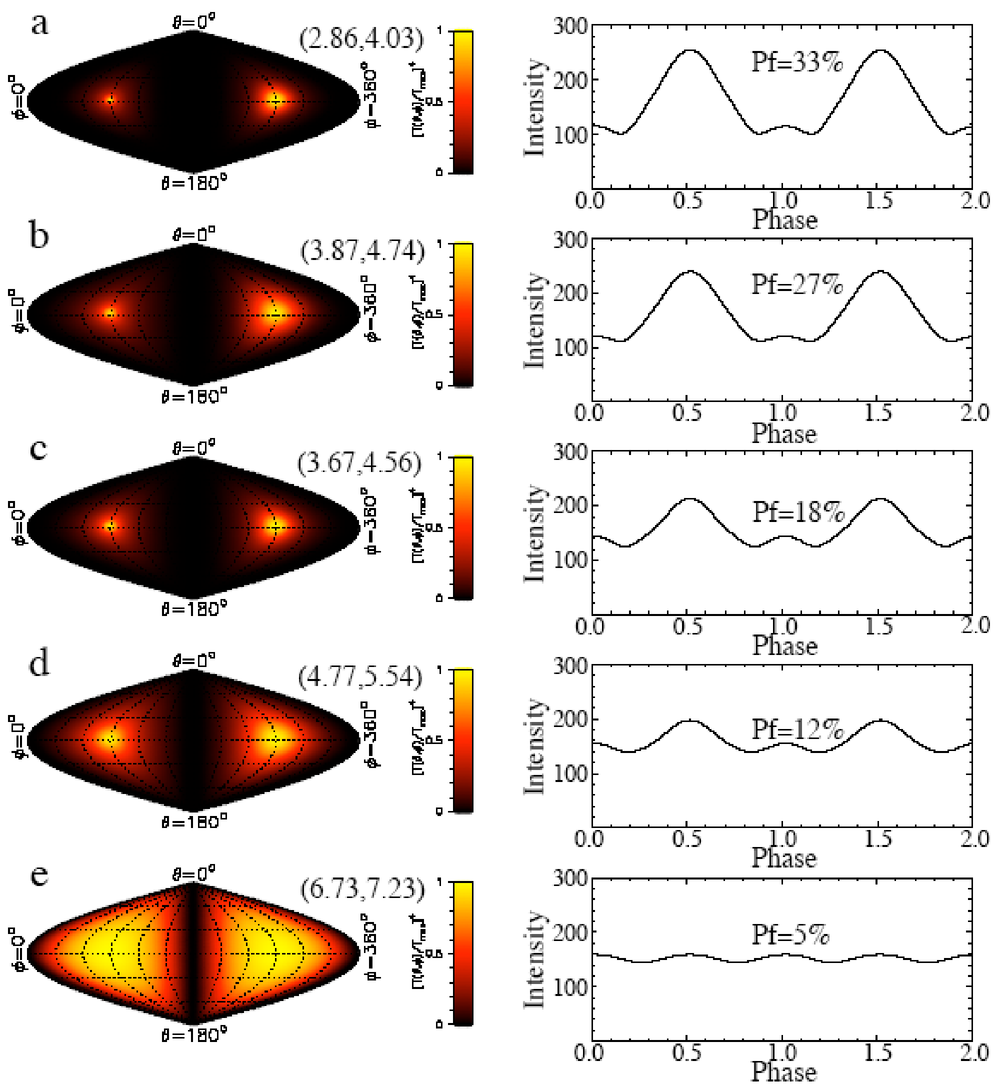
Anisotropic heat transport in a magnetized crust





Geppert, Kueker & Page, 2006

Surface tempertures, pulse profiles, BB spectra



Fit of RX J1856.5-3754
optical and X-ray spectrum

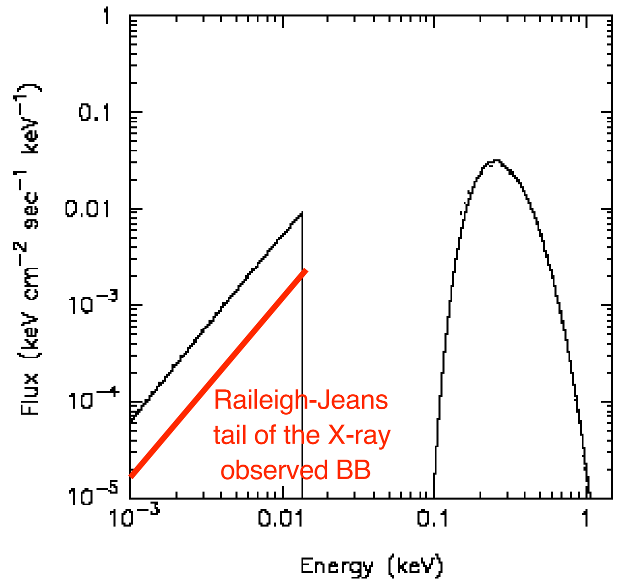


Fig. 10. Fit of the spectrum of RX J1856.5-3754. Dotted lines show the two blackbodies fit to the data from Trümper *et al.* (2004). The continuous line show our results: the star has a radius R = 14.4 km and R_∞ = 17.06 km for a 1.4 $M_\odot$, at a distance of 122 pcs ($N_H = 1.6 \times 10^{20}$ cm^{-2} 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 $T_{\rm eff}^\infty = 4.62 \times 10^5$ K and $T_{\rm max}^\infty = 8.54 \times 10^5$ K

Geppert, Kueker & Page, 2006

CONCLUSIONS

we need to understand the thermal emission from the surface of a neutron star in order to have a chance to understand what is happening inside a "neutron" star.

$\Rightarrow$ we need to understand the structure of matter in strong magnetic fields.


"That's all Folks!"