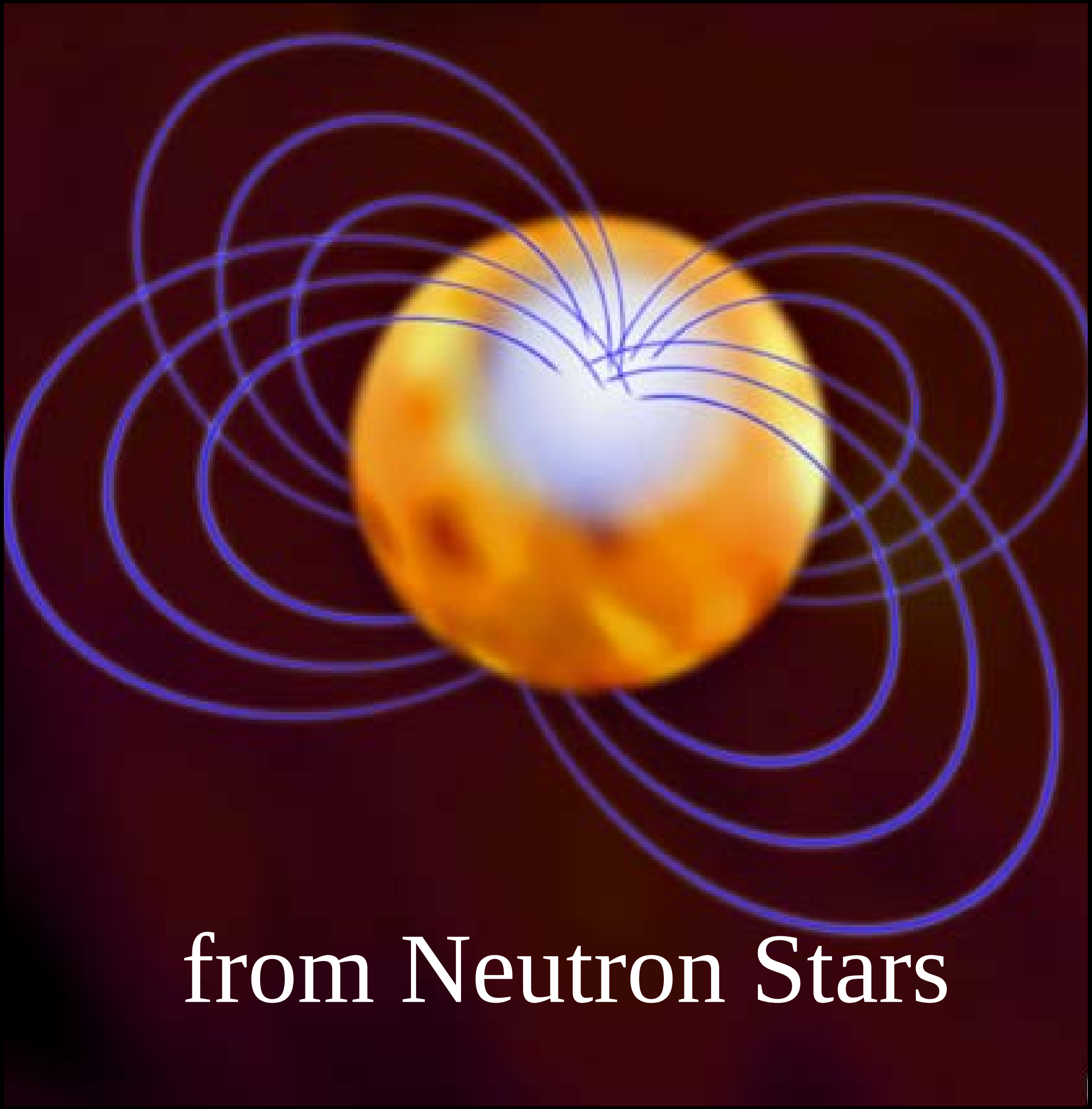
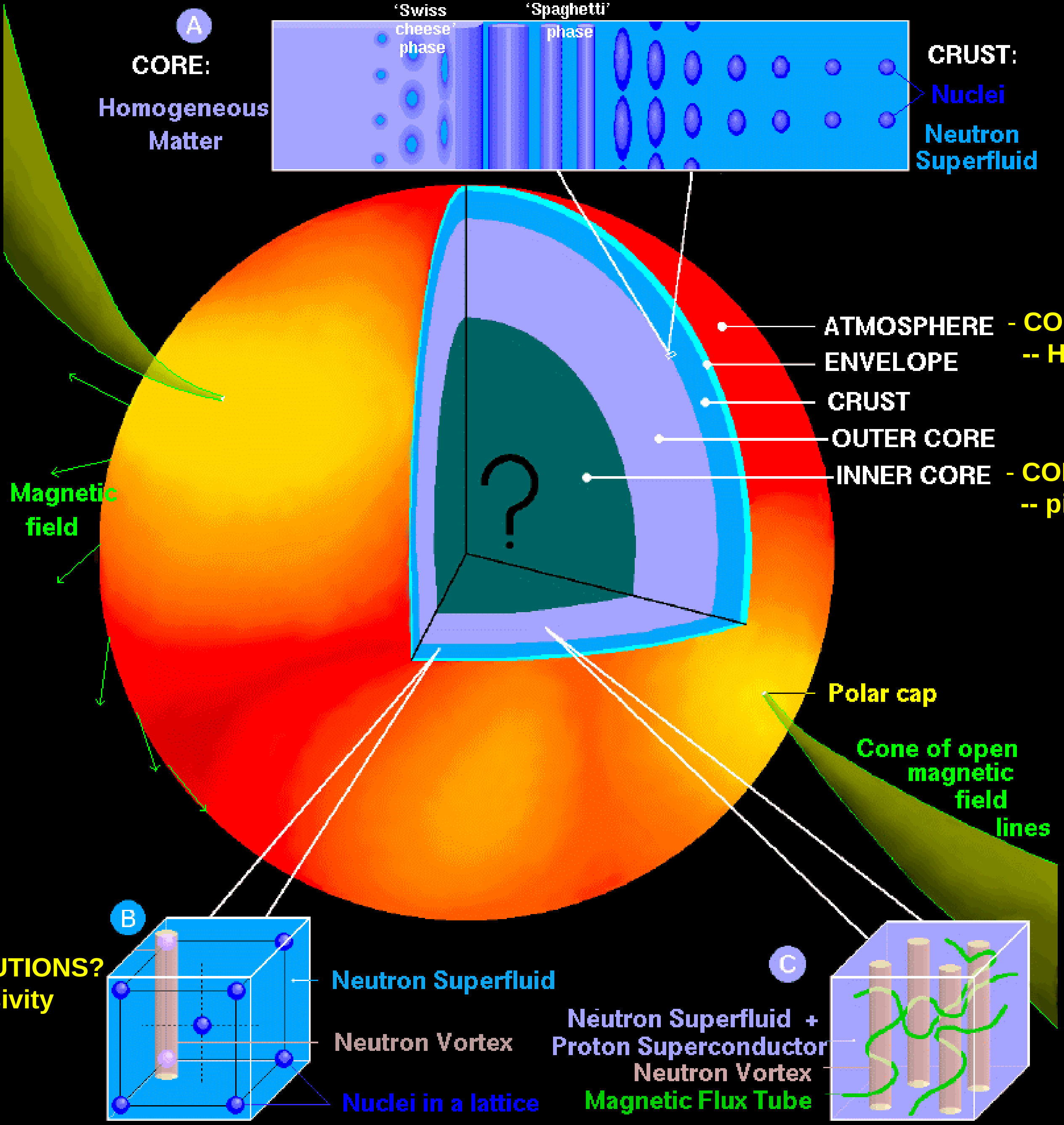
Surface Emission



from Neutron Stars

A NEUTRON STAR: SURFACE and INTERIOR



- COMPOSITION?
-- H, He, Fe?

- COMPOSITION?
-- pions, kaons, quarks?

- HOW STRONG?
-- affects opacity
-- cyclotron features?

- SUPERFLUID CONTRIBUTIONS?
-- strongly affect ν emissivity

-PULSAR WIND?
-- that nasty nonthermal emission

Neutron Star Cooling: An Introduction

- **NS Structure is modeled like any star:**
  - hydrostatic equilibrium
  - energy balance between production & radiation
  - energy transport

- **Auxiliary equations relating these are:**
  - equation of state, describing pressure conditions
  - opacity equation, regulating energy transport
  - ν emission equation, yielding energy input

Why is this Complicated?

- **Composition is not well known**
  - details of strong interactions at ultrahigh densities are uncertain

    ∴ variety of EOS models exist

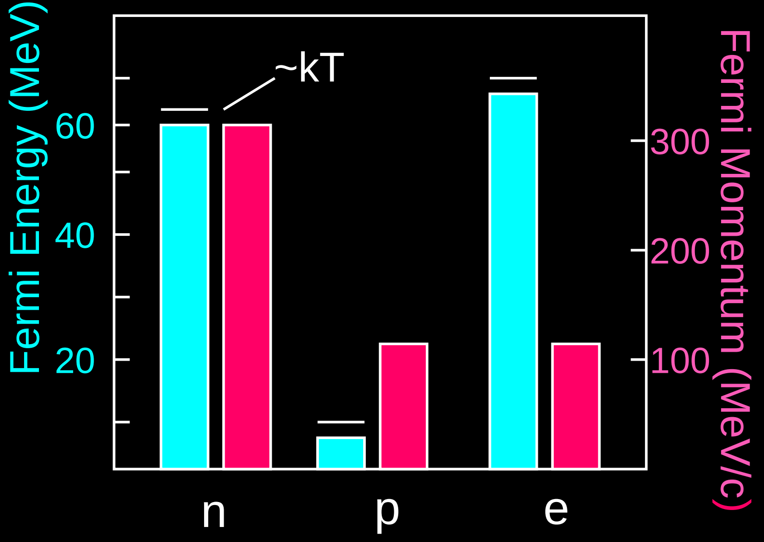
- **Superfluid state is not well constrained**
  - critical temperature and energy gap for proton and neutron superfluid states not well known
  - strongly affects emissivity, as thermal properties change dramatically under superfluid conditions

    ∴ variety of superfluid models exist

- **ν emissivity depends critically on presence/absence of pions/kaons/etc**
  - “standard” emissivity is from modified URCA process and ν bremsstrahlung
  - pion-induced β-decay proceeds at a much higher rate; presence or absence of pions is thus crucial to cooling rate (and same is true of kaons and quarks)

    ∴ “standard” and “exotic” cooling models exist

How Does the Neutron Star Interior Cool?



Urca process:

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

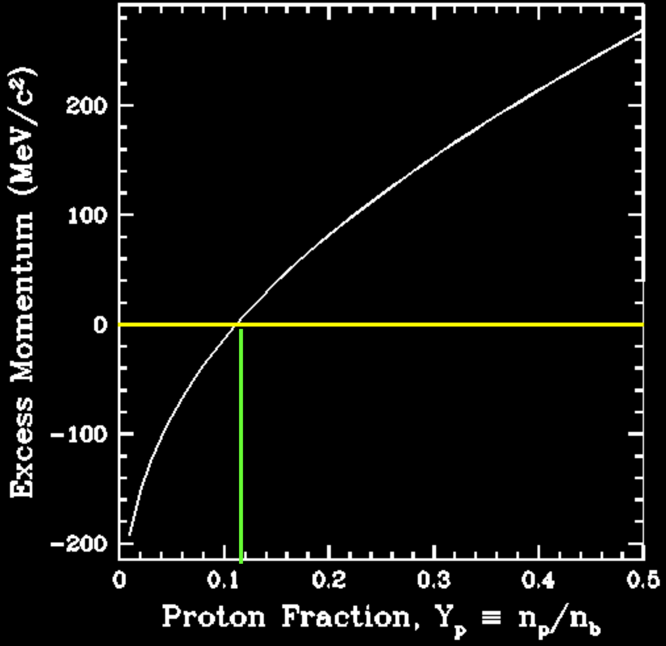
$$p + e^- \rightarrow n + \upsilon_e$$

$$\rho_{\mathrm{b}} \approx 2.8 \times 10^{14}\ \mathrm{g\ cm^{-3}}$$

$$\mathrm{Y_p} = n_p / n_b \approx 0.05?$$

$$E_F = \frac{h^2}{8m}\left(\frac{3n}{\pi}\right)^{2/3}$$

$$p_F = \sqrt{2mE_F}$$



- **Charge neutrality requires:**

$$n_e = n_p \Rightarrow p_F(e) = p_F(p)$$

- **NS matter is highly degenerate**

$$T < 10^9\,\mathrm{K};\ kT < 0.01\,\mathrm{MeV} << E_F$$

$$\therefore E - E_F \sim kT \text{ for all particles}$$

- **Momentum conservation requires**

$$p_p + p_e \geq p_n$$

- **We thus require**

$$\chi = \sqrt{2m_p E_F(p)} + \sqrt{2m_e E_F(e)} - \sqrt{2m_n E_F(n)} \geq 0$$

- momentum can only be conserved for Urca reactions if proton fraction is >0.12
- for lower values, need bystander particle to conserve momentum

Cooling Curves: Standard vs. Exotic Cooling

- Urca reactions:

$$n \rightarrow p + e^{-} + \bar{\nu}_e \quad (\beta\text{-decay})$$

$$p + e^{-} \rightarrow n + \upsilon_e \quad (\text{inv. } \beta\text{-decay})$$

- cannot conserve energy <u>and</u> momentum in highly degenerate NS core
- MUrca adds bystander:

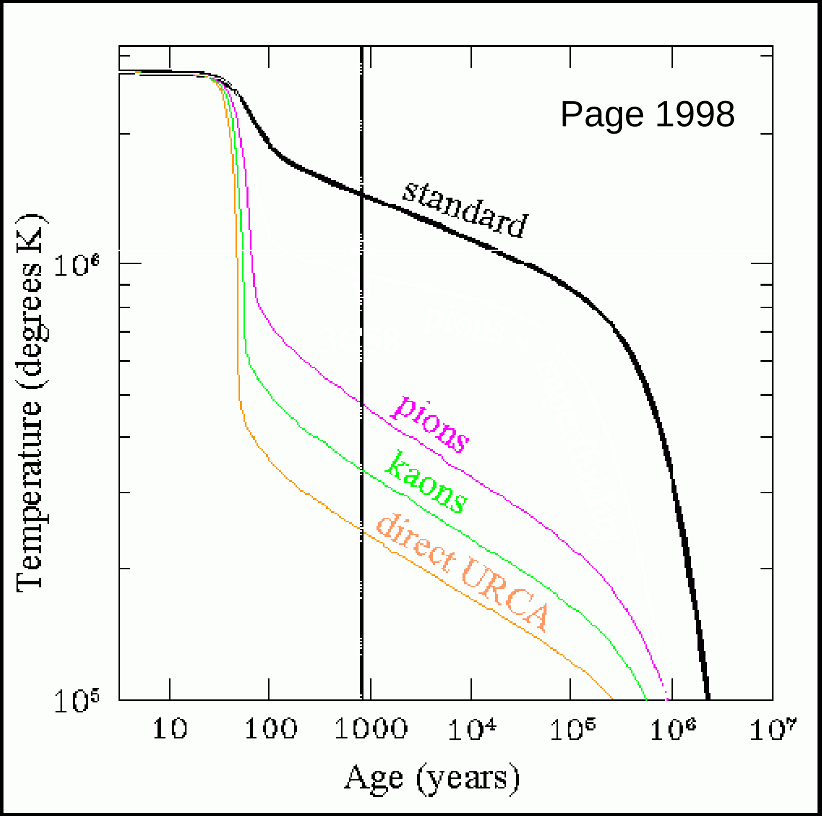
$$n + n \rightarrow n + p + e^{-} + \bar{\nu}_e$$

$$n + p + e^{-} \rightarrow n + n + \upsilon_e$$

- lower reaction rate

"Standard" cooling dominated by Modified Urca in core

$$L_{\nu}^{MUrca} = 5.3\times 10^{39} \frac{M}{M_{\Theta}} \left(\frac{\rho_{nuc}}{\rho}\right)^{1/3} T_9^8$$



- In some equations of state, proton fraction in core is high enough for direct Urca cooling
  - cooling rate is increased even above pions, etc.
  - unclear if this occurs before presence of exotic particles
- Superfluidity strongly affects ν rate
  - rapid cooling is delayed
  - details poorly understood/ heavily model dependent

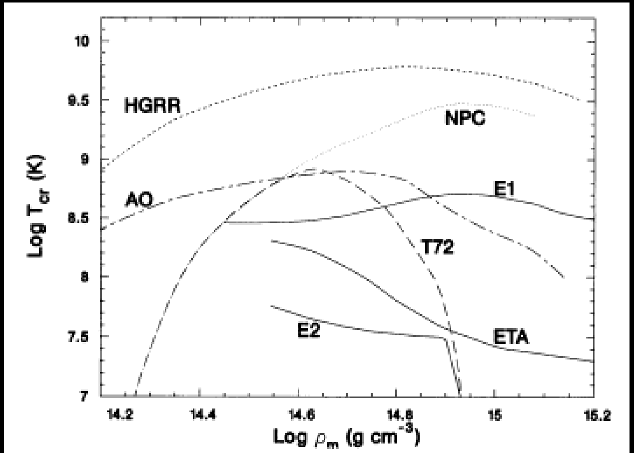
- Pion cooling
  - if pion condensates exist in core, ν rate is enhanced

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

$$n + e^{-} \rightarrow n + \pi^{-} + \upsilon_e$$

$$L_{\nu}^{\pi} = 1.4\times 10^{46} \frac{M}{M_{\Theta}} \theta^2 \left(\frac{\rho_{nuc}}{\rho}\right) T_9^6$$

- Kaon condensates or free quarks also enhance ν rate
  - degree to which exotic particles exist in core depends on EOS
  - EOS is not well known because many-body modeling of strong interactions at ultrahigh densities isn't well understood

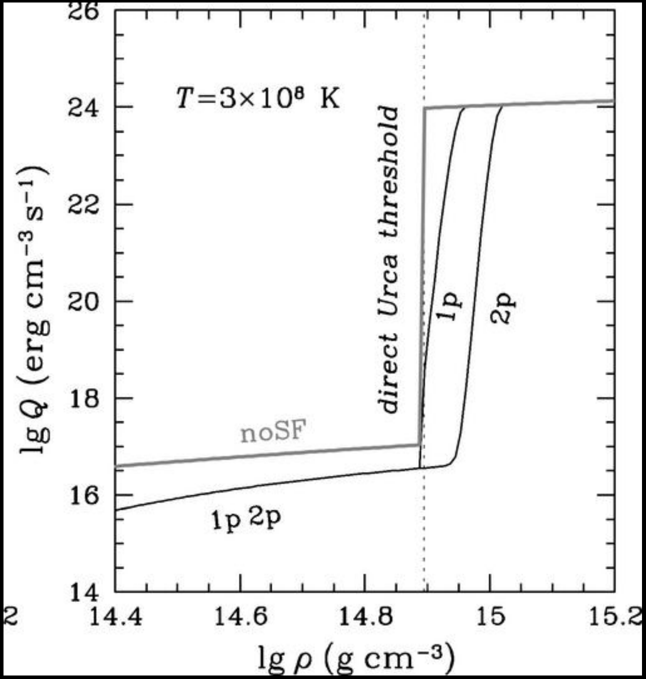


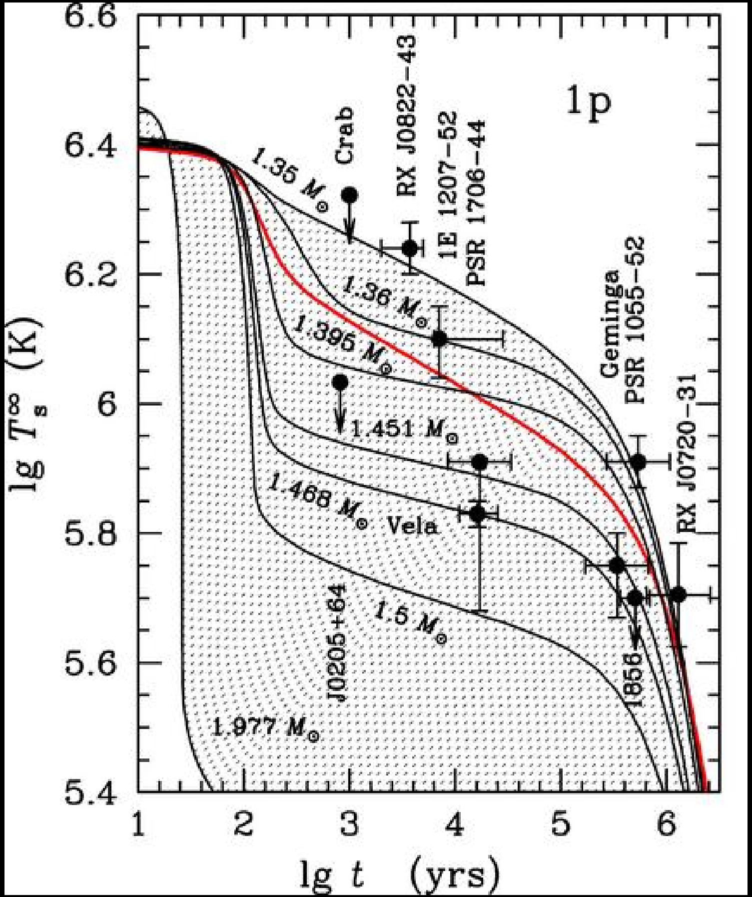
NS Cooling (cont.)

- For sufficiently high densities, direct Urca cooling proceeds
  - for a given equation of state, this corresponds to the possibility of dUrca onset for more massive stars

- Superfluidity moderates rapid cooling
  - different models for energy gap yield different cooling paths

Yakovlev & Pethick 2004





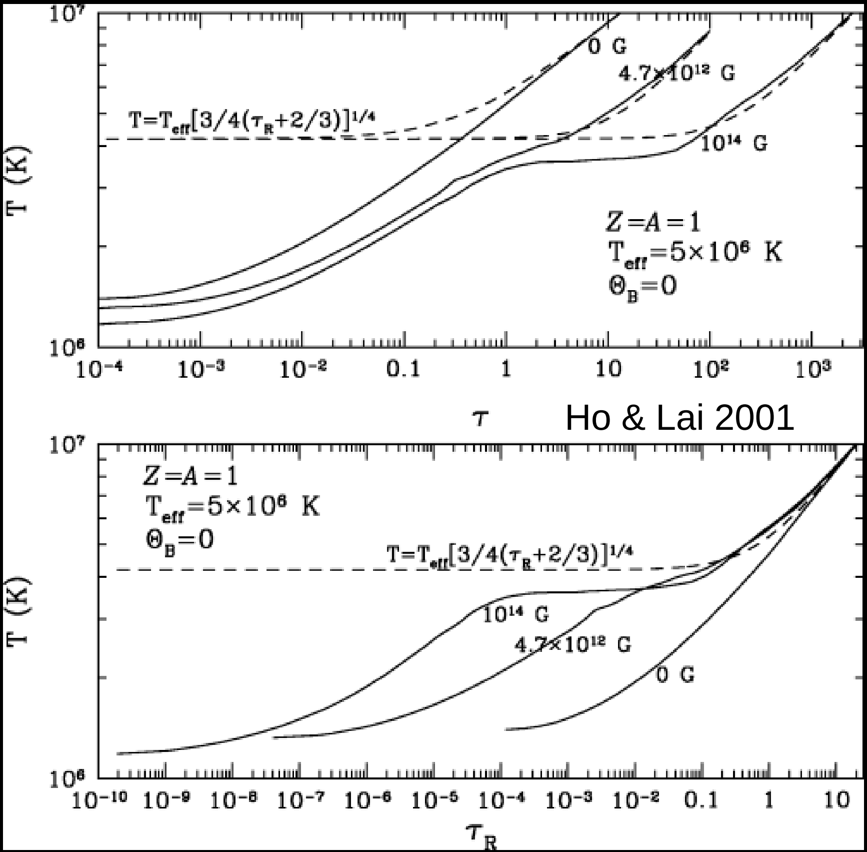
- X-ray observations of young neutron stars provide constraints on cooling models
  - current observations can all be explained within context of above cooling scenarios
  - dUrca (or other) rapid cooling appears required for several young NSs, possibly indicating a distribution in NS masses

NS Atmospheres

- The emission from a NS surface is significantly modified by the presence of an atmosphere
  - atmosphere is highly compressed; scale height is ~0.1-10 cm, density is of order 0.1-1000 gm/cc; not an ideal gas!

- Any small amount of accretion from fallback or ISM is sufficient to form an optically thick atmosphere
  - composition and stratification depends on equation of state; upper layer most likely H, but burning could yield He
  - without accretion, expect mostly Fe

- Opacity is a function of temperature, density, and composition
  - emission from different optical depths sample different temperatures
  - result is a spectrum that deviates from a blackbody, with emission extending beyond Wien tail
  - line features result, particularly for heavy element atmospheres (e.g. Fe)



Ho & Lai 2001

Temperature vs opacity depth for scattering (upper) and absorption (lower)

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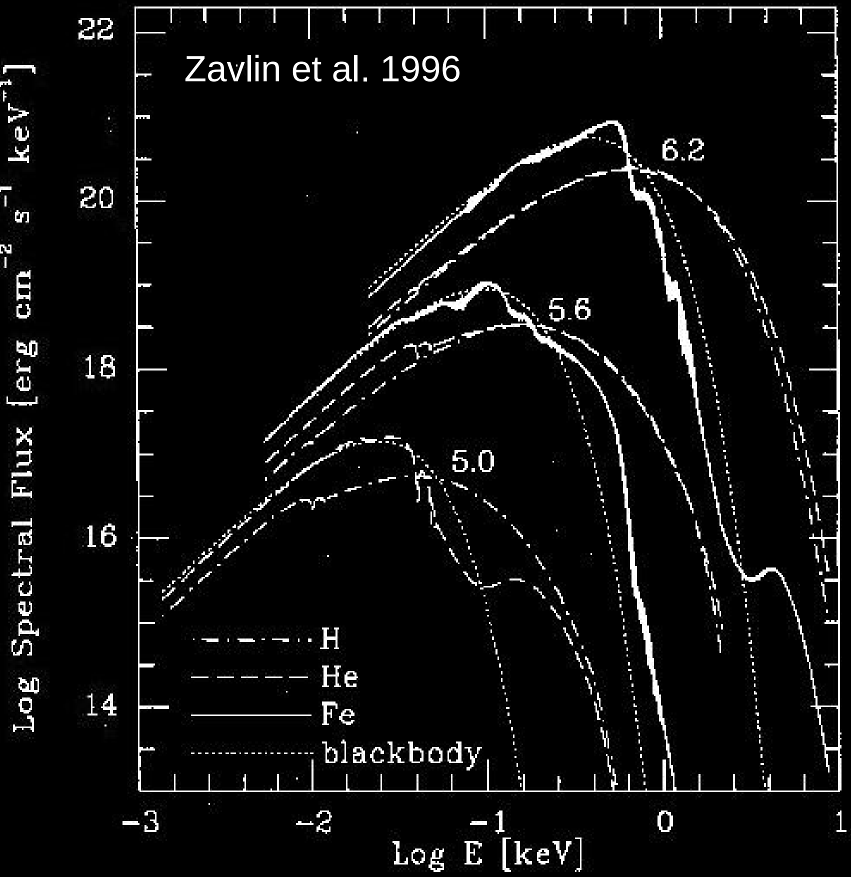
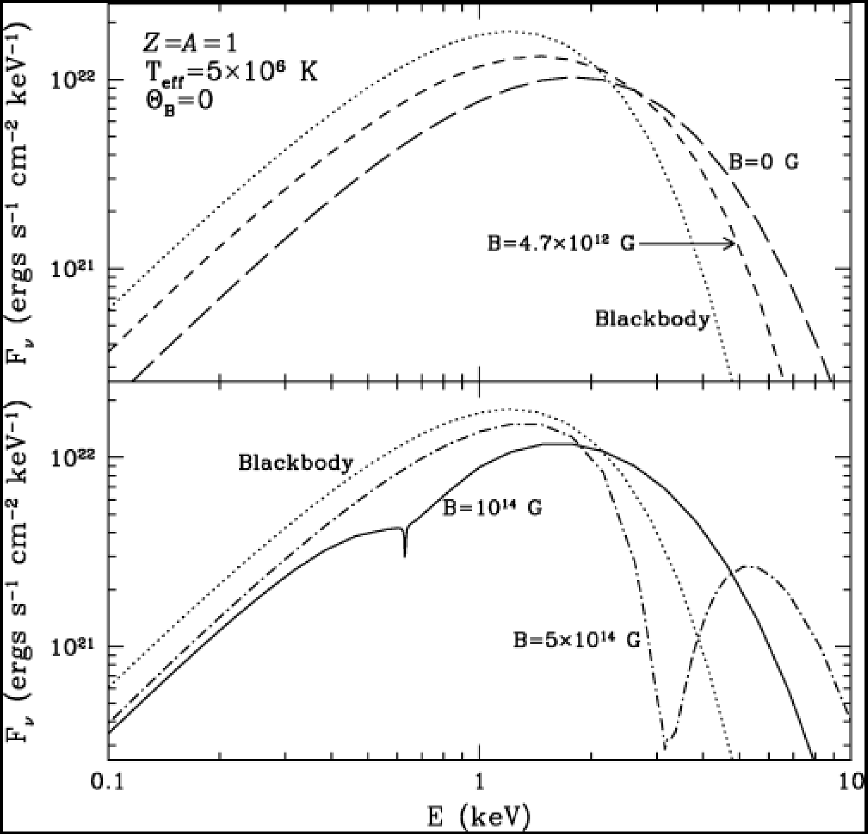

Zavlin et al. 1996

NS Atmospheres (cont.)

- When B > 10^9 G, properties of atoms are completely different from B = 0 case
  - cyclotron radius is

$$r_c = \left(\frac{\hbar c}{cB}\right)^{1/2} = 2.6 \times 10^{-10} B_{12}^{-1/2}\ \mathrm{cm}$$

  - for large B, this is smaller than Bohr radius of atom
  - Coulomb force is more effective in binding electrons along B field, and atoms attain a cylindrical structure
  - for B = 10^{12} G, ionization potential for H atom is 160 eV (compare with 13.6 eV for B = 0)



- Motion is quantized to Landau levels with

$$E_{ce} = \frac{\hbar e B}{m_e c} = 11.6 B_{12}\ \mathrm{keV} \qquad E_{pe} = \frac{\hbar e B}{m_p c} = 0.63 B_{14}\ \mathrm{keV}$$

  - cyclotron absorption features result
  - can get multiple harmonics
  - opacity increases near (not just at) ω_c → broader lines
  - range of B-field strength on surface also contributes to broadening

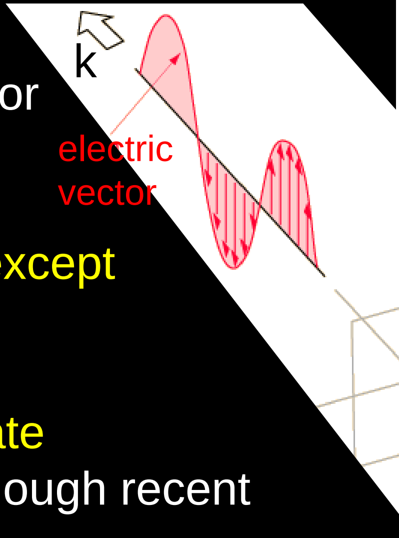
NS Atmospheres (cont.)

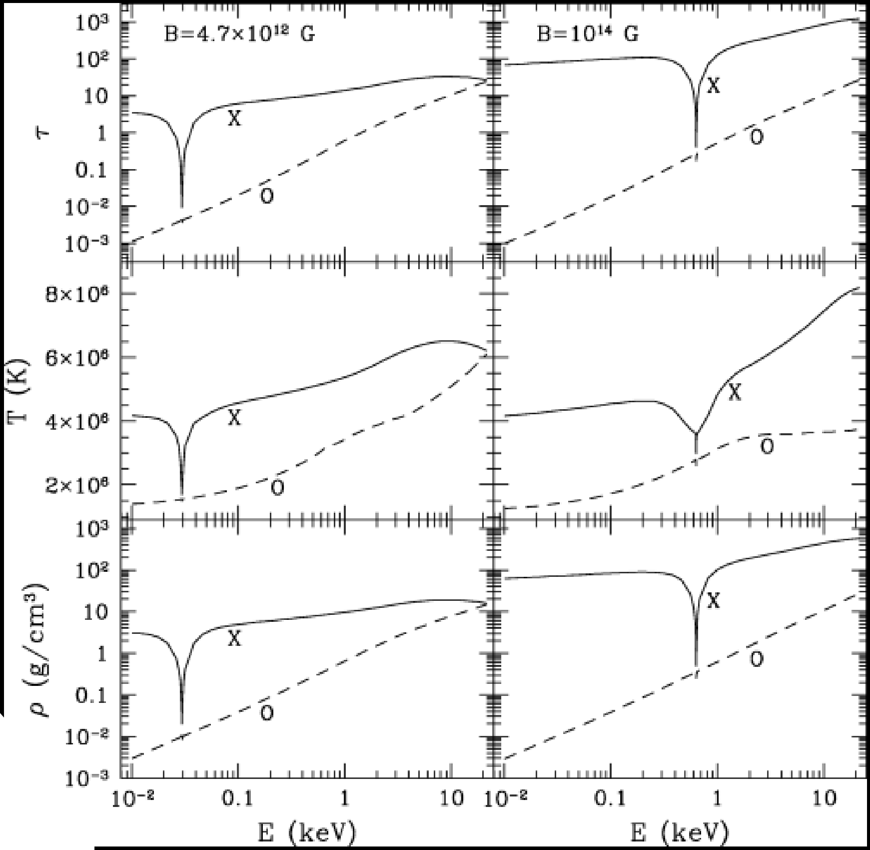
- Polarization effects in magnetized plasma modify the resultant spectrum. Two modes:
  - ordinary (O) mode: photon electric field vector in **k**-**B** plane
  - extraordinary (X) mode: photon electric field vector perpendicular to **k**-**B** plane

- Opacity is higher for O-mode (since electrons/ions can absorb easily along B)
  - X-mode samples higher temperatures and dominates spectrum (thus emission is polarized)
  - cyclotron absorption is significant for X-mode (and thus overall)

- He atmospheres very similar to H, except for position of cyclotron resonances

- Ionization balance difficult to calculate
  - full ionization typically assumed, though recent work done on partial ionization





Optical depth, temperature, and density at point from which photons of a given energy originate (Ho & Lai 2001).

NS Atmospheres (cont.)

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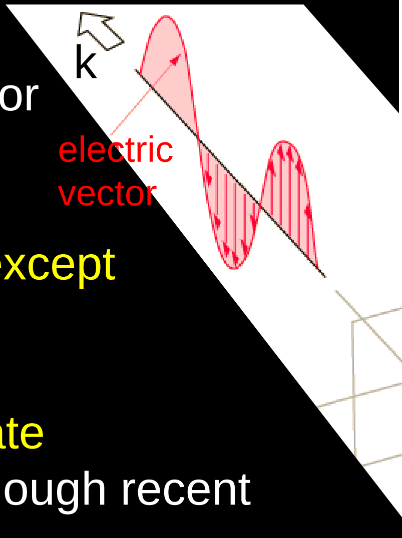

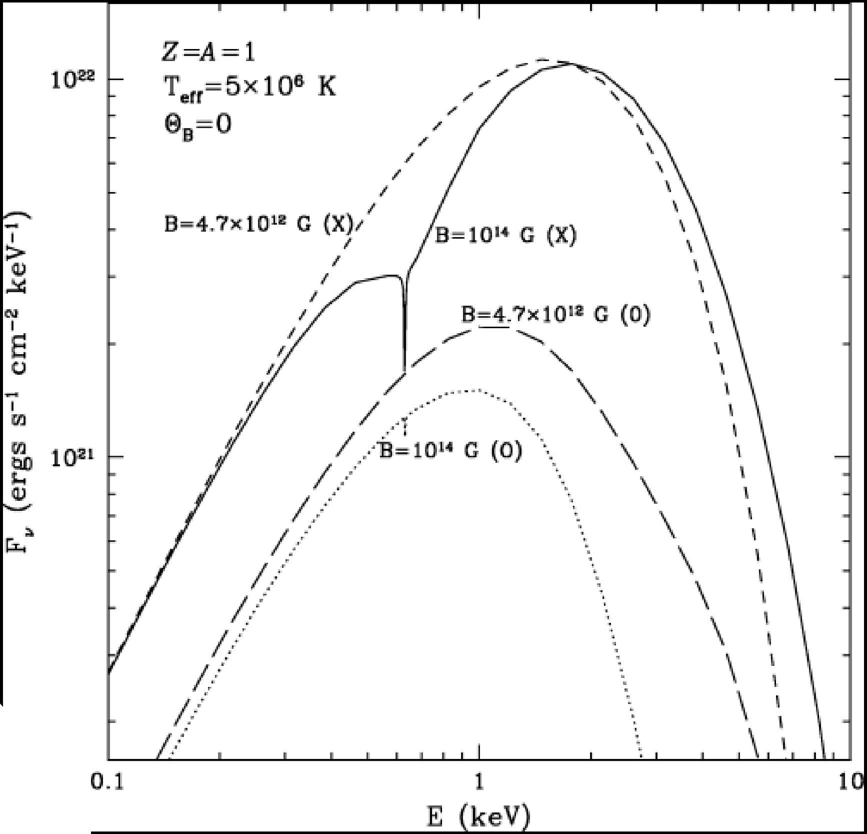

Hydrogen model for magnetic atmosphere. (Ho & Lai 2001).

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NS Atmospheres (cont.)

- Vacuum polarization effects modify atmosphere spectrum for very large fields
  - polarization of atmosphere due to virtual e^+e^- pairs becomes significant above quantum critical field

$$B > B_Q = \frac{m_e^2 c^3}{e\hbar} = 4.4 \times 10^{13}\ \mathrm{G}$$

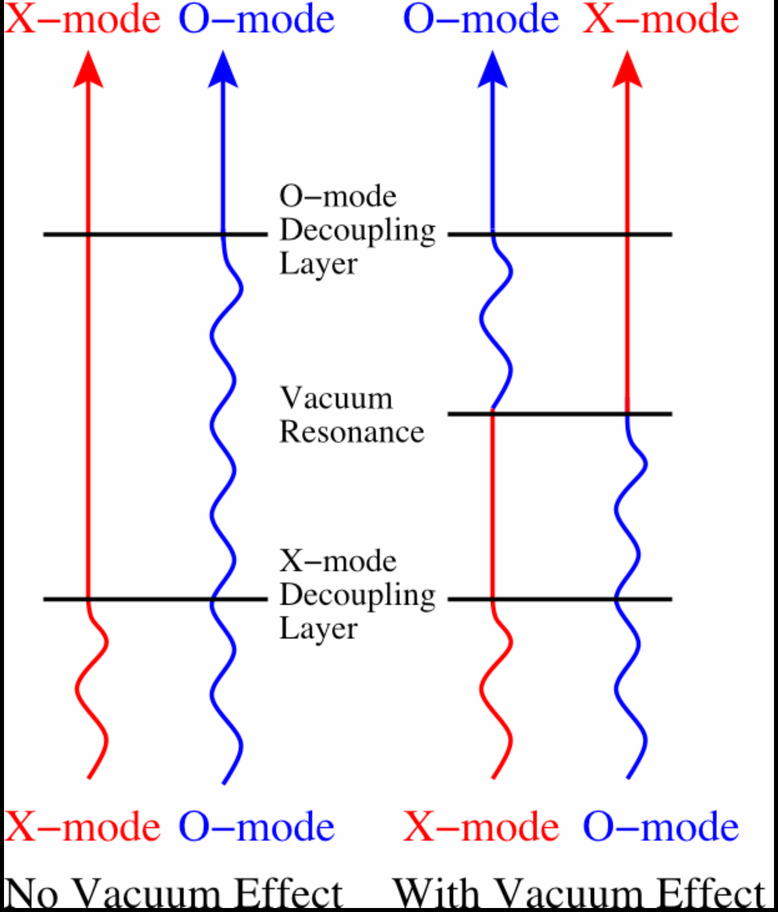
  - dielectric properties of medium are modified; scattering and absorption opacities are affected
  - where effects of plasma and vacuum on the linear polarization cancel, a resonance occurs:

$$E_v \approx \left(\frac{Z\rho}{A}\right)^{1/2} B_{14}^{-1}\ \mathrm{keV}$$

  - results in broad depression because of large density range in atmosphere

- Mode conversion can occur as photon traverses resonant density
  - converts one polarization mode to another (analogous to MSW effect for neutrino oscillations)
  - since the two modes have very different opacities, this conversion strongly affects spectrum

from W. Ho



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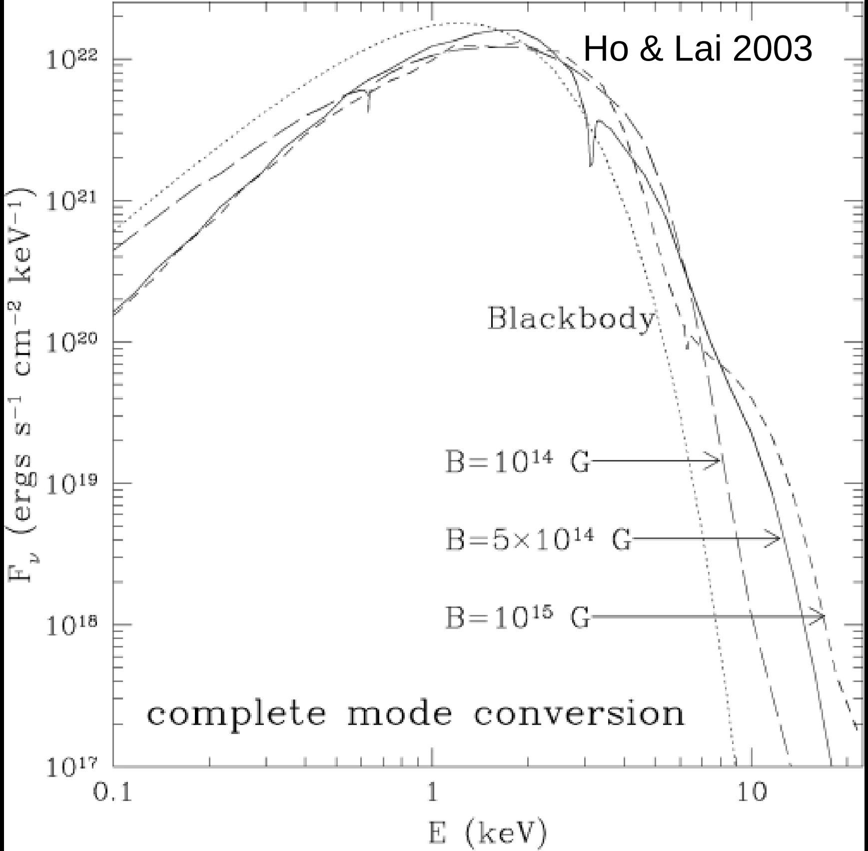

Ho & Lai 2003

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Neutron Star Emission: Gravitational Effects

- Layering of atmosphere
  - EOS determines density/temperature distribution (as discussed above)
- Gravitational redshift: $$\frac{\lambda}{\lambda_0} = \sqrt{1 - \frac{2GM}{c^2 R}}$$
  - affects inferred temperature and luminosity
  - for discrete lines, redshift gives M/R (line detection thus important!)
  - total flux gives R (for known distance and measured temperature)

$$R_\infty = R\left[1 - \frac{2GM}{c^2 R}\right]^{-1/2}$$

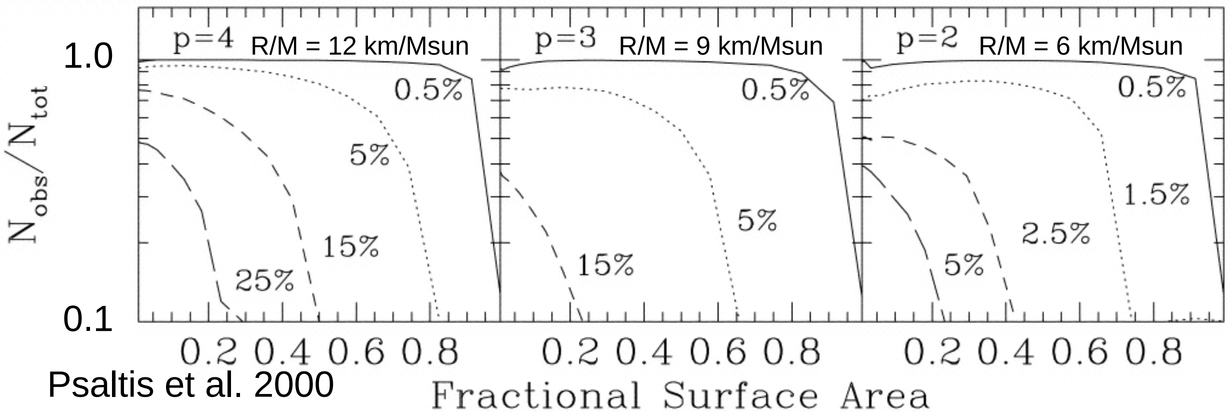
  - thus, can get M (assuming R represents total surface)

$$T_s^\infty = T_s\sqrt{1 - \frac{2GM}{c^2 R}}$$

$$L_\gamma^\infty = L_\gamma\left[1 - \frac{2GM}{c^2 R}\right]$$

$$R_\infty^2 = \frac{L_\gamma^\infty}{4\pi\sigma(T_s^\infty)^4}$$

- Pulsed fraction
  - pulsed thermal emission results from compact emission regions on surface
  - smaller region produces larger PF
  - however, gravitational bending of light smears out the contrast
  - can get very small PF even for very small emitting regions



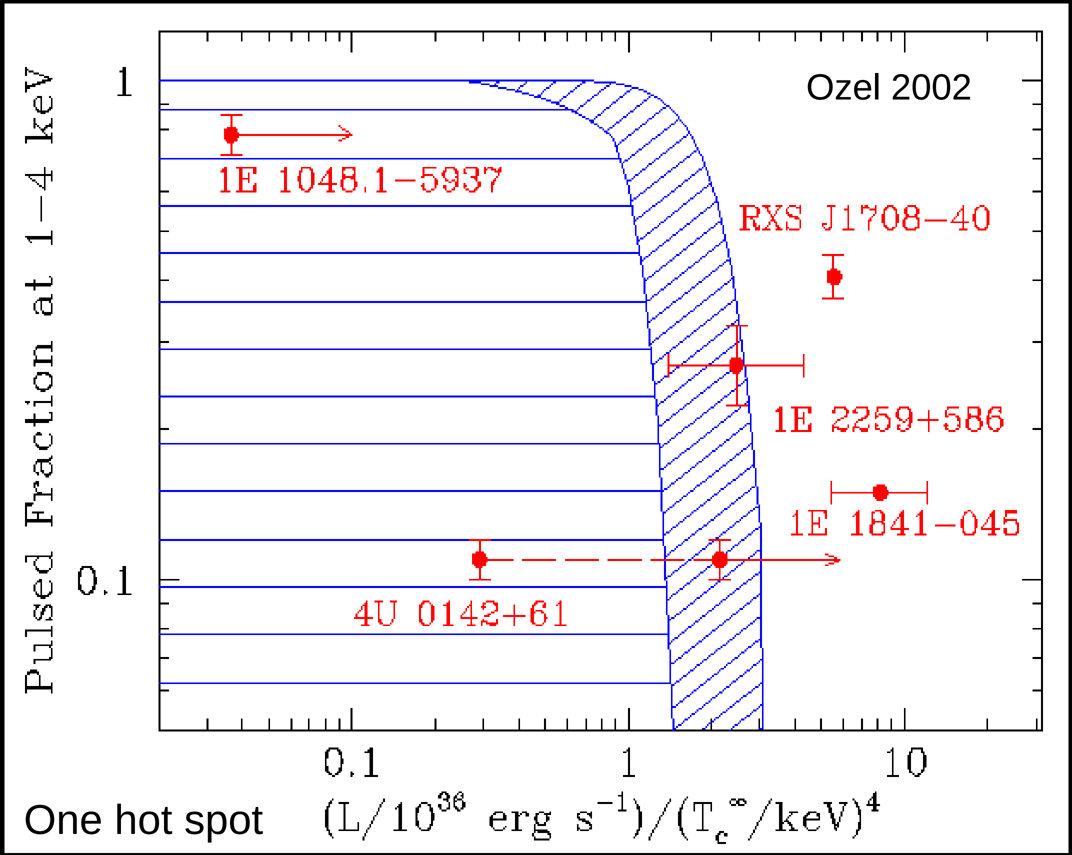
Psaltis et al. 2000

Pulse Profile and Emission Geometry

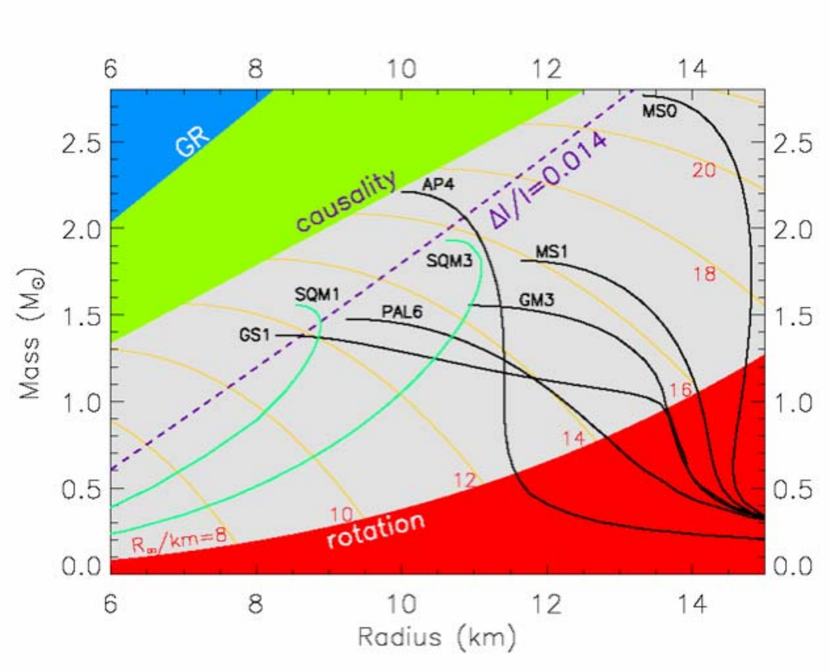
- GR effects dramatically affect observable modulation
  - large emitting regions or *M/R* ratios yield low pulsed fractions

- Size of emitting region limits the blackbody-like flux
  - tradeoff off between pulsed fraction and L_x
  - observed flux

- For AXPs, some appear to have emitting areas too large to explain observed pulsed fractions
  - indicative of incorrect atmosphere yielding luminosity that is too high?



Mass-Radius Constraints From NS EOS Models



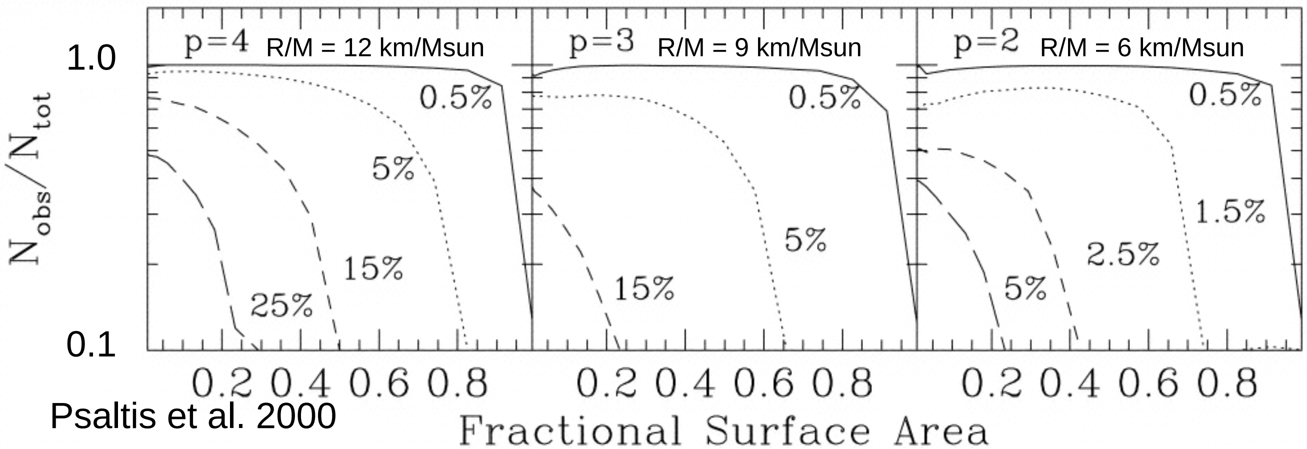
RX J1856.5-3754 is a nearby isolated neutron star first identified in observations with the ROSAT observatory. It is sufficiently nearby that HST observations yield a parallax distance, d = 120 pc. Its X-ray spectrum is well-fit by a blackbody model with a temperature of $T_\infty = 7.5 \times 10^5$ K The associated bolometric flux is $F_\gamma^\infty = 2.5 \times 10^{-11}$ ergs s^{-1} .

What is the observed radius of the emitting region? Compare this with predictions of NS radii from equation-of-state calculations (Figure 1). What can be concluded about the nature of RX J1856.5-3754?

If the observed blackbody emission is the result of a small emission region on the NS surface, one might expect pulsations as the star rotates. Gravitational light bending reduces the expected pulsed fraction. Unfavorable viewing geometry can also reduce or eliminate pulsations (Figure 2).

Timing measurements for RX J1856.5-3754 yield no evidence for pulsations, with an upper limit of 5% on the pulsed fraction. Can the pulsed fraction limit be reconciled with the observed blackbody spectrum while still being consistent with the sources being a neutron star?

See Ransom et al. 2002, 570, L75; Walter 2004, J. Phys. G: Nucl. Part. Phys. 30 S461



Psaltis et al. 2000

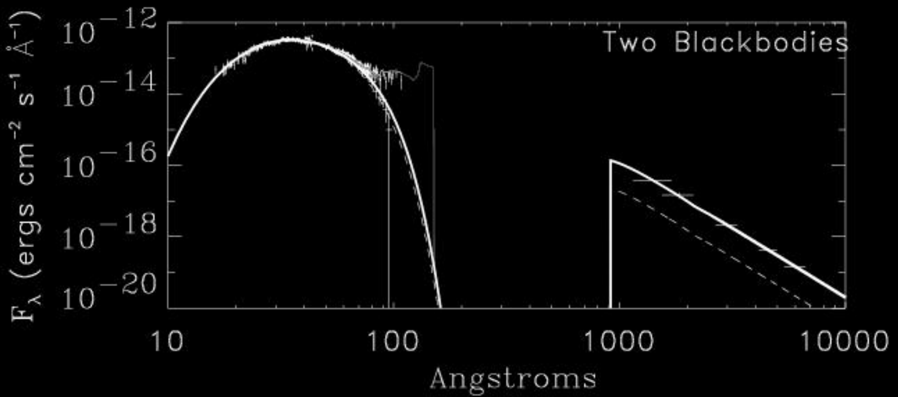
RX J185635-3754: An Old Isolated NS(?)

- Distance known well from parallax
  - d = 117 +- 12 pc (Walter & Lattimer 2002)

- X-ray emission consistent with blackbody
  - no lines seen despite 450 ks Chandra LETG observation; rules out heavy element atmosphere
  - kT = 63 eV; R = 4.3 km at d = 117 pc
  - this is too small for a neutron star! (quark star??!!)

- X-ray BB spectrum under-predicts optical/UV flux
  - model with two BBs needed; 27 eV and 64 eV
  - then $R_\infty = 17 \pm 1.9$ km
  - but smaller size still needed for X-rays; hot spot
  - no quark star needed…

- No pulsations observed
  - pulsed fraction < 5%; how can this be?
  - GR bending (hard to reconcile with optical radius)



- Recent atmosphere model holds promise (Ho et al. 2006)
  - emission from partially-ionized H yields reasonable NS size and log B ~ 12.6
  - but, need very thin atmosphere so that not optically thick at all temp; how does this arise???