Diffusive Nuclear Burning (DNB) in Neutron Star Envelopes

Phil Chang
Lars Bildsten

Chang & Bildsten 2003, ApJ, 585, 464
(CB03)

Outline of the talk

- Motivation & Observations of INS
- Diffusive Nuclear Burning
  - nuclear limited (CB03)
  - diffusion limited
- magnetic effects
- Application to 1E 1207

What makes up the envelope of a NS?

Candidates? not just Bush or Gore

- H (accretion from ISM; fall back)
- Fe (NS are remnants of collapsed Fe cores in type II SN)

Why do we care?

- Affects spectra of the thermal radiation from the surface (Romani 1987)
  - Fe is more bb-like
  - H/He is harder than bb at given T_{eff}
- Affects $T_{eff} - T_c$ relation (Potekhin, Chabrier, Yakovlev 97)
  - implications for NS cooling
- may give handle on $\frac{M}{R}$ and nuclear e.o.s.

Observations: what do they say?

- two ways of determining surface composition
  - A. atomic lines (1E1207-56)
    - susceptible to B-field GR / degeneracy
    - But sets of atomic lines might be free from this (Mori & Hailey 2003)
  - B. detailed modeling of spectra.
    - fits to detailed models should give surface composition
    - Hard - only H/He done in detail (Pavlov & Zavlin 2002 review)
    - End of day - fits to H/He and BB equally good in χ^2 sense
    - How do we fix this?

H/He gives harder spectra than BB

$\Rightarrow T_{color,H/He} > T_{color,BB}$

We also have

- distance (Parallax)

- measured luminosity

T_{eff}, L + d $\Rightarrow$ size of emitting surface

- Assume emitting area $\approx$ size of NS
- Assume $R_{NS} \approx 10$ km for $M = 1.4 M_\odot$

$\Rightarrow$ Gives a favored model.

Table 3. Surface temperatures of eight isolated middle-aged neutron stars inferred from observations.

Source	lg t [yr]	lg T_s^∞ [K]	Model[a]	Confid. level	References
RX J0822–43	3.57	$6.23^{+0.02}_{-0.02}$	H	95.5%	Zavlin et al. (1999)
1E 1207–52	3.85	$6.10^{+0.05}_{-0.06}$	H	90%	Zavlin et al. (1998)
RX J0002+62	3.95[b]	$6.03^{+0.03}_{-0.03}$	H	95.5%	Zavlin & Pavlov (1999)
PSR 0833–45 (Vela)	4.4[c]	$5.83^{+0.02}_{-0.02}$	H	68%	Pavlov et al. (2001)
PSR 0656+14	5.00	$5.96^{+0.02}_{-0.03}$	bb	90%	Possenti et al. (1996)
PSR 0633+1748 (Geminga)	5.53	$5.75^{+0.05}_{-0.08}$	bb	90%	Halpern & Wang (1997)
PSR 1055–52	5.73	$5.88^{+0.03}_{-0.04}$	bb	d)	Ögelman (1995)
RX J1856–3754	5.95	$5.72^{+0.05}_{-0.06}$	e)	d)	Pons et al. (2001)

H atmosphere

Fe atmosphere

a) Observations are interpreted either with a hydrogen atmosphere model (H), or with a black body spectrum (bb).

b) The mean age taken according to Craig et al. (1997).

c) According to Lyne et al. (1996).

d) Confidence level is uncertain.

e) Analytic fit with Si-ash atmosphere model of Pons et al. (2001).

- Possible evolution from light elements (H/He) to more BB elements (Fe?) Timescale $\sim 10^{4\text{-}5}$ yrs.
- Evolution via nuclear processes is hard on the surface

$T_{ph} \sim 10^6$ K

$\rho \sim 0.1 \frac{g}{cm^3}$

$\Rightarrow \tau_p \sim 10^{21}$ yrs via pp

Sun's core

$T \sim 2 \times 10^7$ K

$\rho \sim 100 \frac{g}{cm^2}$

$\Rightarrow \tau_p \sim 10^9$ yrs via pp

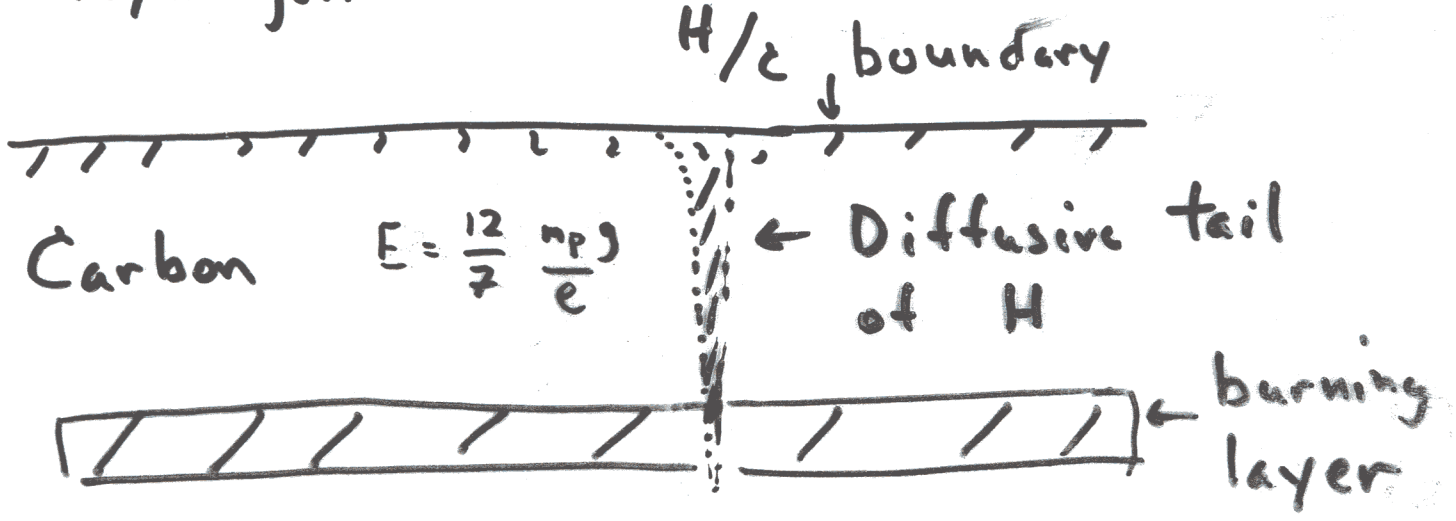
- But $T_c \approx 6\text{-}7 \times 10^7$ K for $T_{eff} \approx 10^6$ K

  10 m below photosphere

- Burning in the diffusive tail is important (Rosen 1968)

Simple picture (Fact: $E = \frac{A}{Z+1} \frac{m_p g}{e}$)

$$E = \frac{1}{2} \frac{m_p g}{e}$$



$^{12}C(p,\gamma)^{13}N$, $^{13}N(e^+,\nu_e)^{13}C \Rightarrow$ ^{13}C sinks ↓

Two limits of DNB

1) $t_{Diff} << t_{nuc}$ (nuclear limited DNB)
   - burns in diffusive equilibrium (D.E.)

2) $t_{Diff} \not< t_{nuc}$ (diffusion limited DNB)
   - burns out of D.E.

- Basic equations of structure (in D.E.)

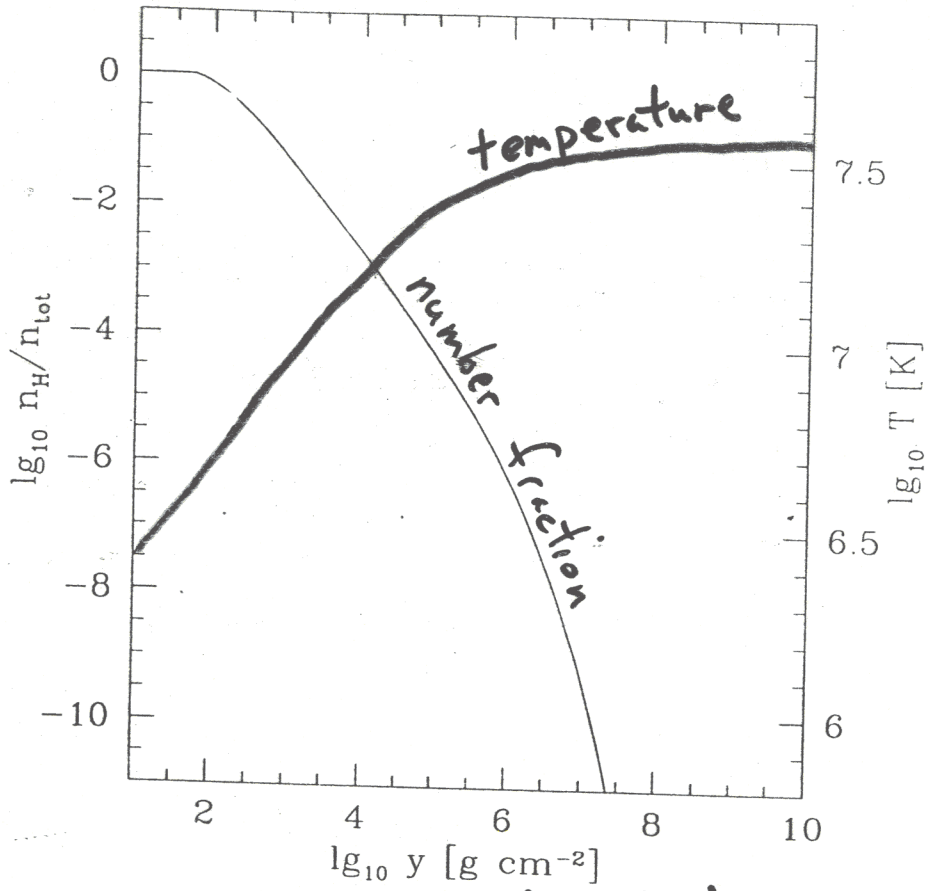
$$\frac{dP_i}{dr} = -(A_i m_p g - Z_i e E)\, n_i$$ (HB for ions & electrons)

$$\frac{dP_e}{dr} = -eE n_e$$ ← number density

$$n_e = \sum_i Z_i n_i$$ (charge neutrality)

$$\frac{dT}{dr} = -\frac{3\kappa\rho}{4ac}\frac{\sigma T_{eff}^4}{T^3}$$ (constant flux eq.)

- Solve for E, numerically integrate



H/C model

$y_H = 100 \frac{g}{cm^2}$

$T_e = 8 \times 10^5$ K

- introduces a new scale height
the ion scale height

- Equations of nuclear burning

  - local rate = $\frac{n_H}{\tau_{nuc}}$ ← local lifetime of proton against nuclear reactions

  possible reactions

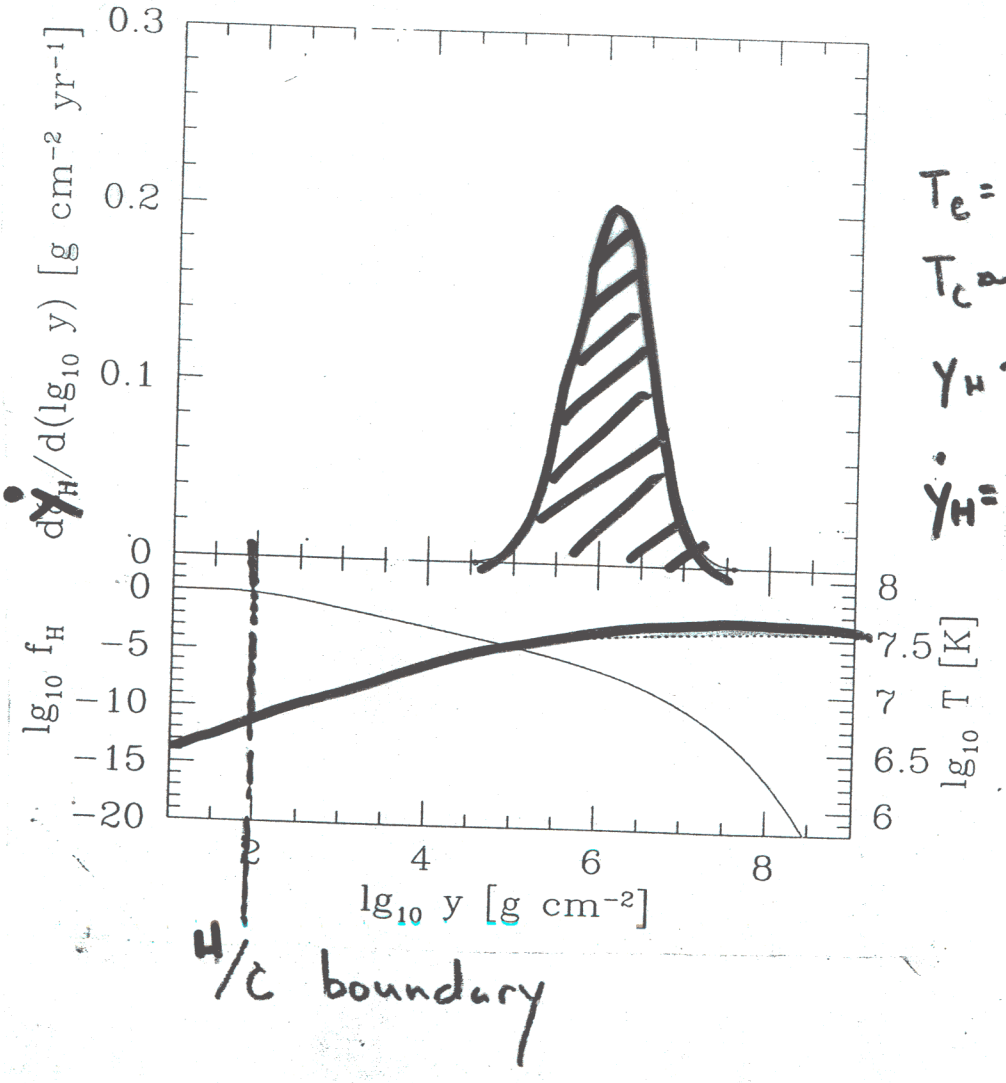
  $p(p, e^+, \nu_e)\,^2D$ - pp reaction ← slow.

  $p(^{12}C, \gamma)\,^{13}N$ - p-capture

  - Integrated burning rate

  $\frac{\gamma_H}{\tau_{nuc}} \equiv \dot{\gamma}_H = m_p \int \frac{n_H}{\tau_{nuc}} dz$

  ← column lifetime

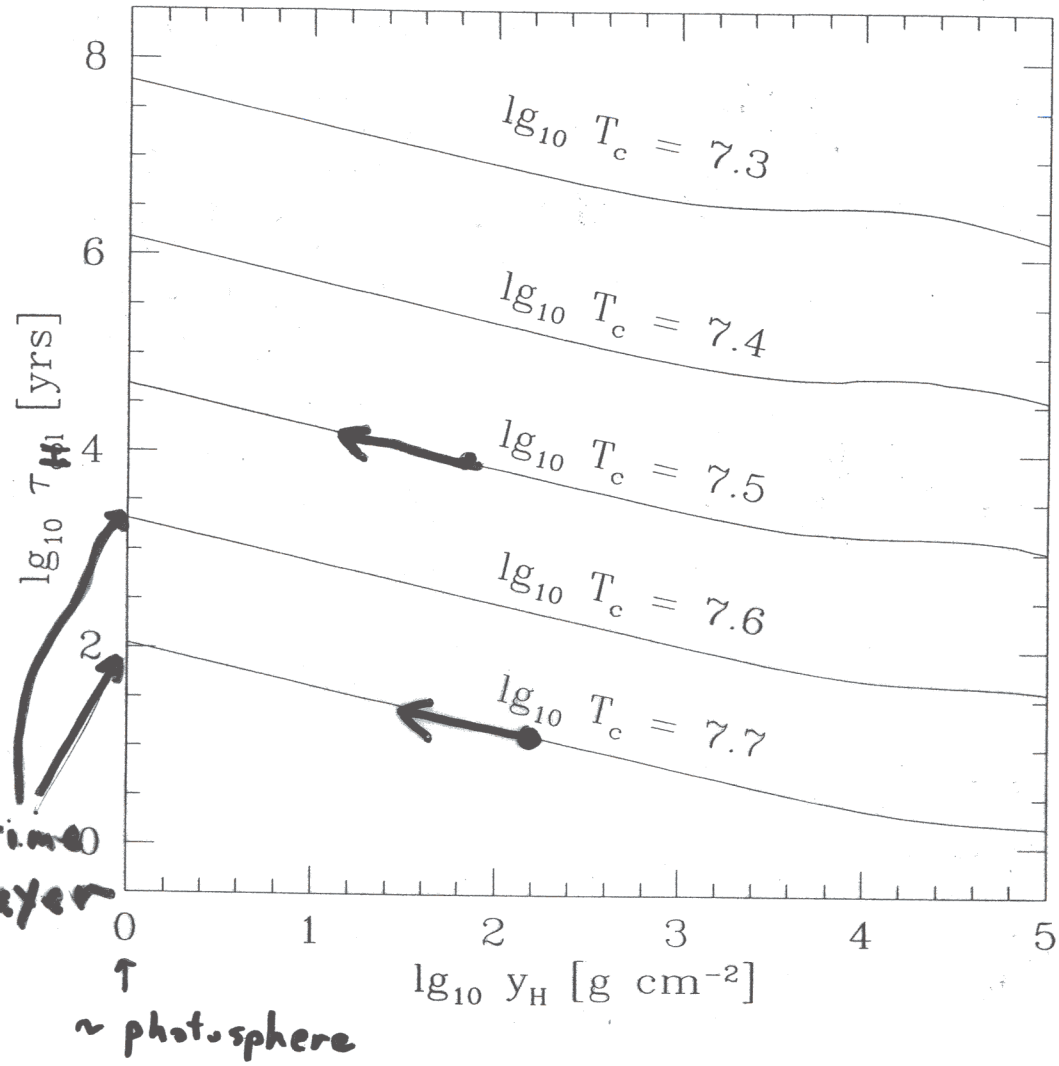


$T_e = 8 \times 10^5$ K

$T_c \approx 4 \times 10^7$ K

$\gamma_H \sim 100 \frac{g}{cm^2}$

$\dot{\gamma}_H = 0.24\ g\,cm^{-2}\,yr^{-1}$



total lifetime of H layer

↑ ~ photosphere

- Arrows indicate the effect of Burning
- total lifetime of the H layer is thus set by τ_{cool} at the photosphere.

What about when D.E. breaks down?

Timescale for diffusion is

$$\tau_{diff} = \frac{\ell^2}{D}$$

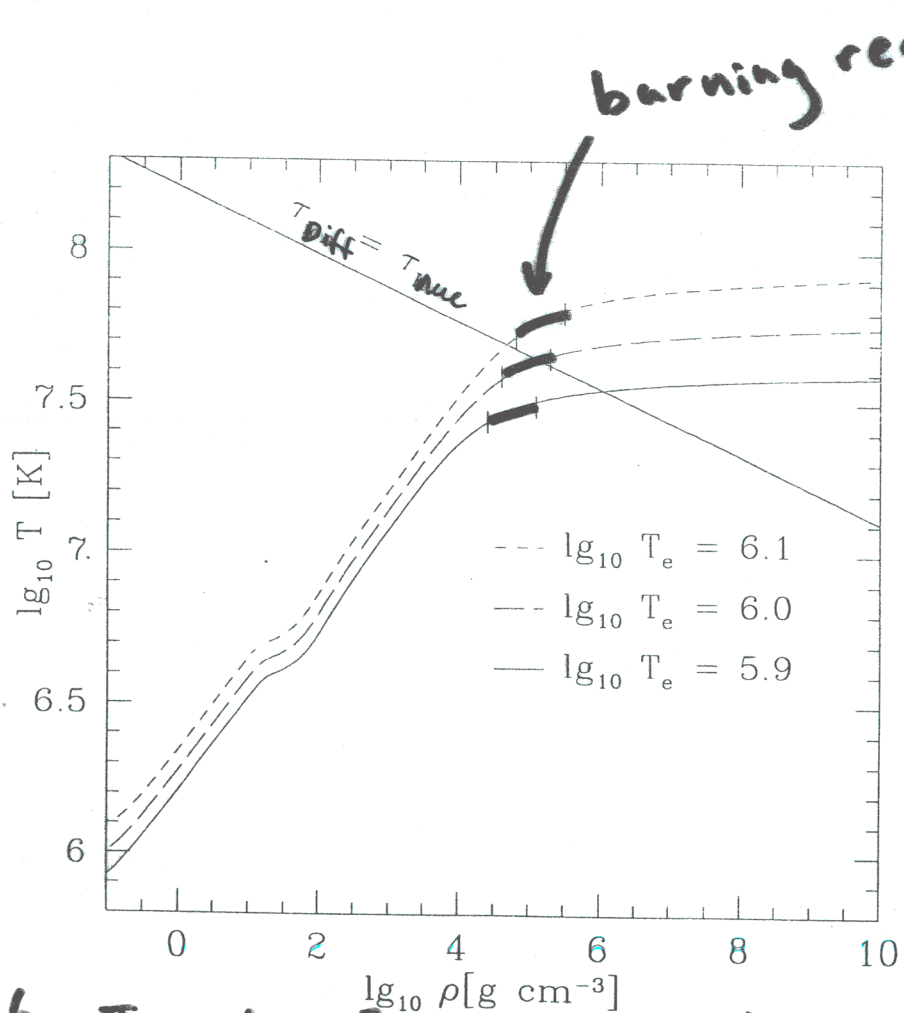
ℓ^2 ← ion scale height

D ← diff. coefficient

so we can say when

$$\tau_{Diff} \approx \tau_{nuc}$$

D.E. is violated.



$\Rightarrow T_{eff} \approx 10^6$, $T_c \approx 6 \times 10^7$ is where D.E. is violated.

Equations of structure for Diffusive equilibrium

- constant flux $\frac{dT}{dr} = -\frac{3\kappa\rho}{4ac}\frac{\sigma T_{eff}^4}{T^3}$
- H.B. for electrons $\frac{dP_e}{dr} = -eE n_e$
- H.B. for carbon $\frac{dP_e}{dr} = -(12 m_p g - 6eE) n_c$
- H.B. for Hydrogen $\frac{dP_H}{dr} = -(m_p g - eE) n_H$

number density

When we are not in diffusive equilibrium, presuming H is a trace element.

- H.B. for H

$$\frac{dP_H}{dr} = -(m_p g - eE - \underbrace{\tau_{ip} v_H n_c}_{\text{drag force}}) n_H$$

- Drag force is small (usually) but when it gets large ($\tau_{ip} v_H n_c \frac{n_H}{n_H} \sim m_p g$) it cuts off n_H rapidly

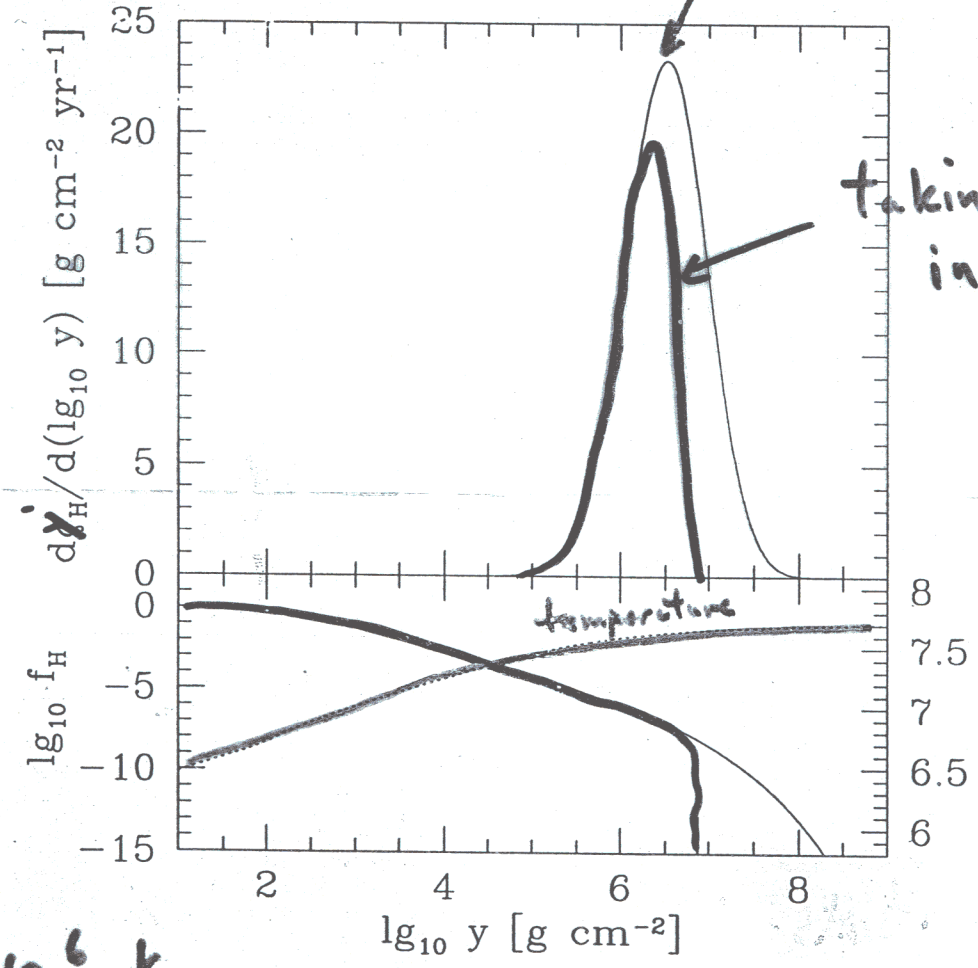
Local rate of nuc. burning = $\frac{n_H}{\tau_{nuc}}$

↑ lifetime of proton for capture

$$\frac{y_H}{\tau_H} \equiv \dot{y}_H = m_p \int \frac{n_H}{\tau_{nuc}} dz$$

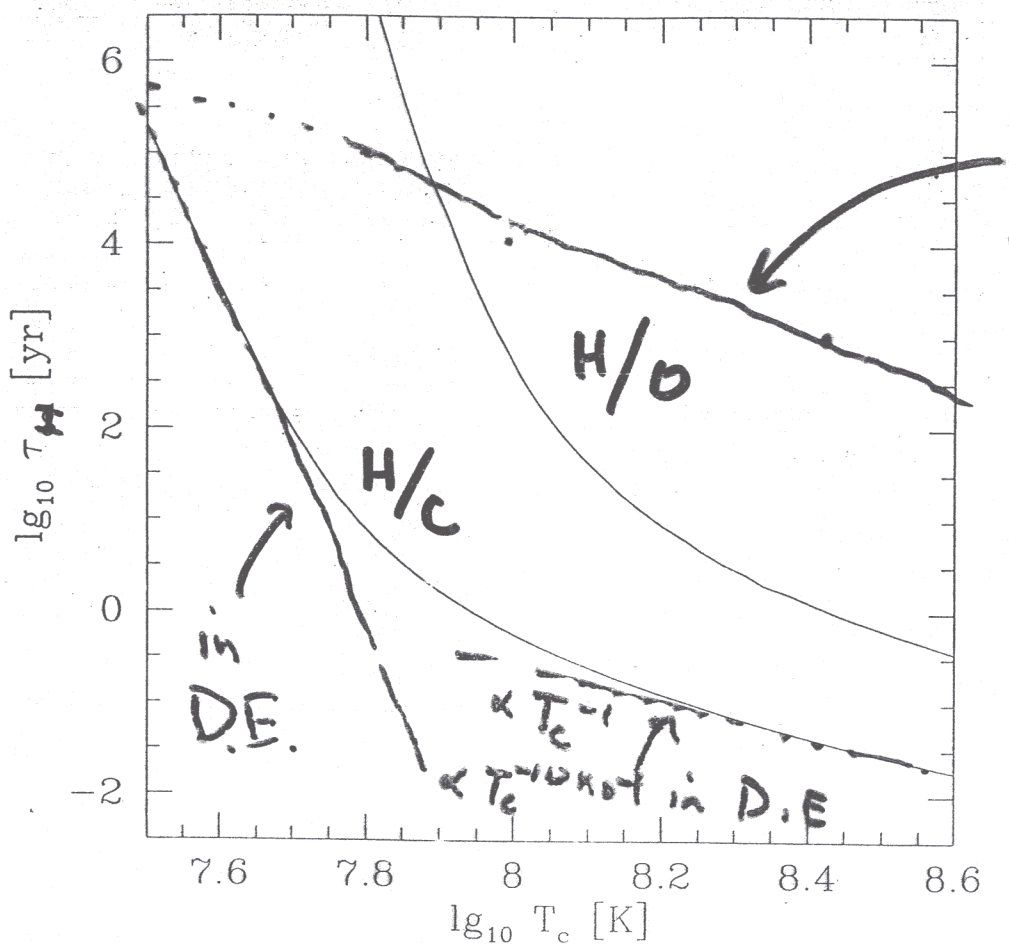
presuming diff. equilibrium

taking diff. into account



$T_{eff} = 10^6$ K

$y_H = 100 \frac{g}{cm^2}$



Two limits

$\tau_{Diff} \ll \tau_{nuc} \Rightarrow \tau_H \propto T_c^{-9.7}$

- exponent set by nuclear reactions

$\tau_{Diff} \gg \tau_{nuc} \Rightarrow \tau_H \propto T_c^{-1}$

- set by dependence of D on T

Magnetic Fields $10^9\ G < B < 10^{13}\ G$

$r_g \approx a_0$ ions still ideal

2 main effects

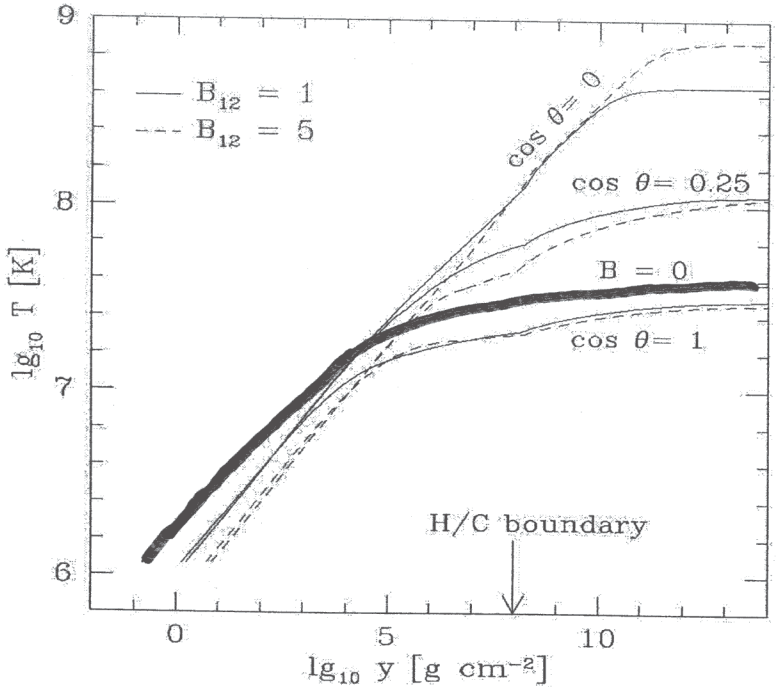
A. electron EOS (Lai 2001)

- For $kT < E_F < \hbar\omega_B$

  ⇒ 1-d Fermi Gas $P \propto \rho^3$ not $\rho^{5/3}$

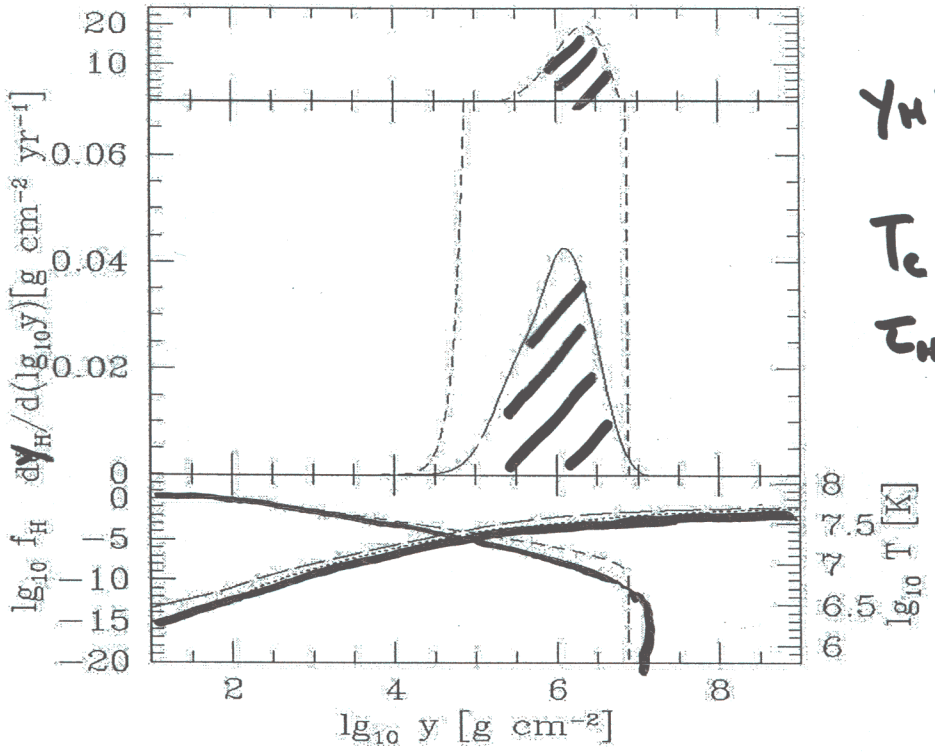
B. Opacity (Silant'ev & Yakovlev 80; Yakovlev 84)

- Strong B field reduces phase space e's can scatter into
- depends on both B-field strength & orientation



$T_{eff} = 10^6$ K for all models

- B fields create tremendous variation in DNB due to T variations



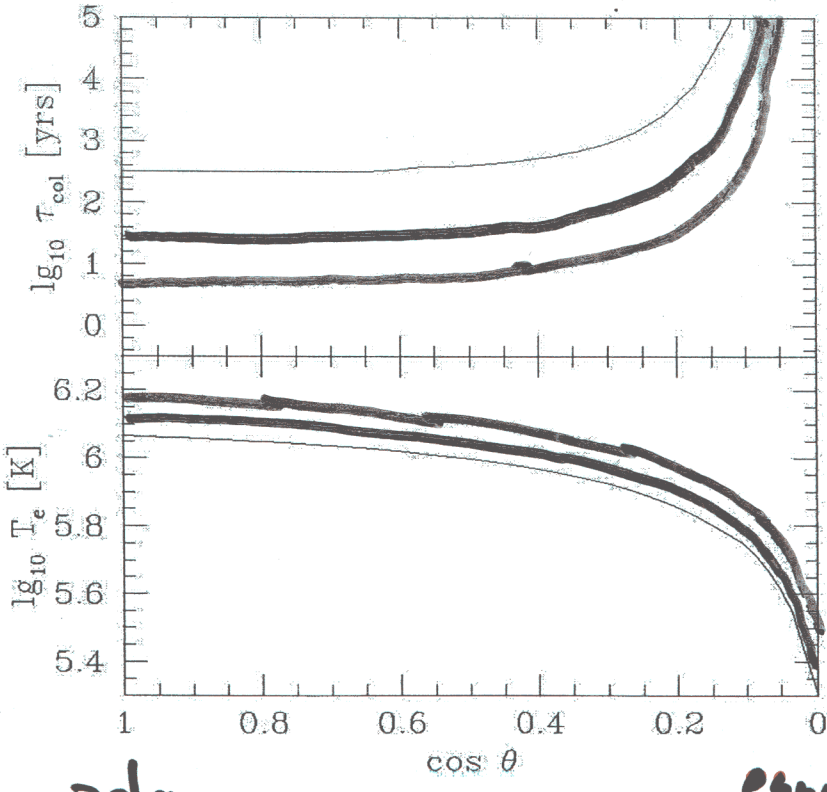
$y_H = 100 \frac{g}{cm^2}$

$T_c = 5.6 \times 10^7$ K

$\tau_H = 2000$ yrs for $B_{12} = 1$

$\tau_H \approx 6$ yrs for $B = 0$

- DNB is latitude dependent.



$T_c = 6 \times 10^7$ K

$T_c = 8 \times 10^7$ K

$T_c = 10^8$ K

$y_H = 100$ gcm^{-2}

$B_{12} = 1$ at poles for dipole geo.

Characteristics of 1E1207-56

- lines at 0.7 and 1.4 keV
- marginal detection at 2 keV

Interpretation

A. NOT electron cyclotron lines

$\Rightarrow B = 6 \times 10^{10} (1+z)$ G

B from P/$\dot{P}$ measurements (Zavlin 2000; Pavlov et al 2002)

$\Rightarrow B \approx 3 \times 10^{12}$ G

B. NOT ion cyclotron lines

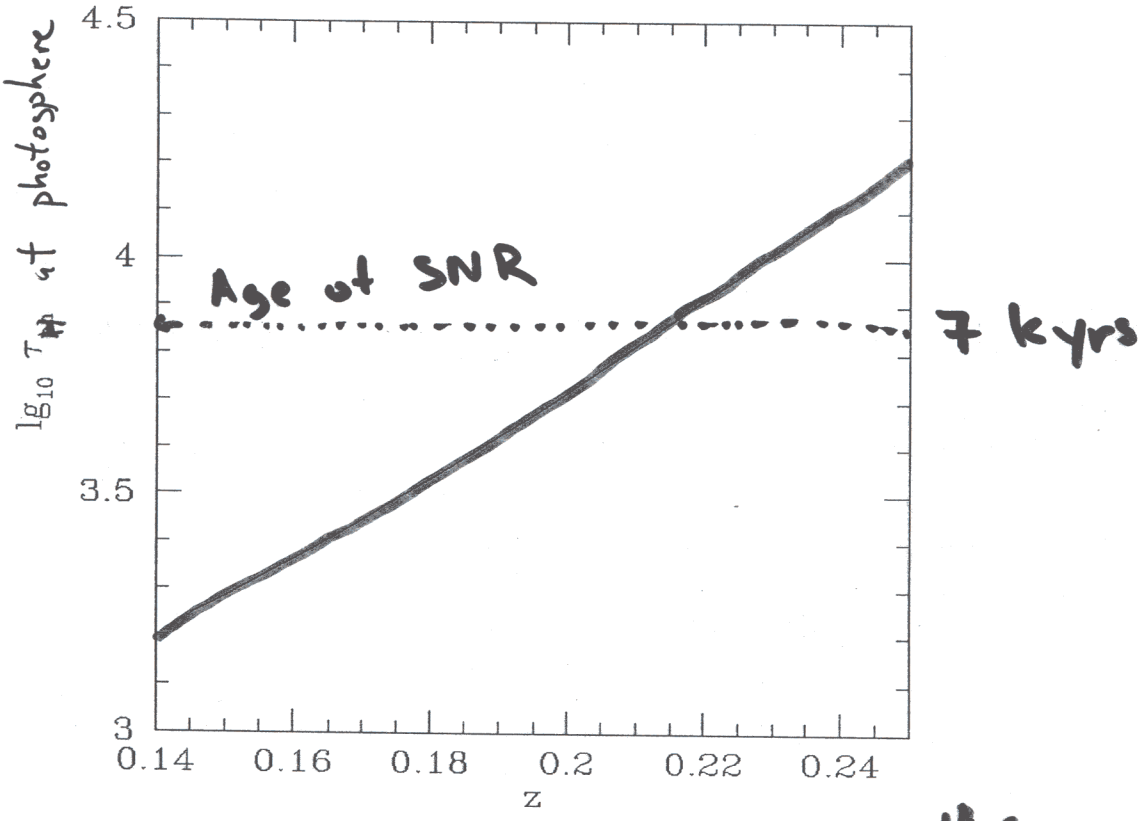
$\Rightarrow B > 10^{14}$ G

C. Atomic lines

- Sanwal et al (2002) $\Rightarrow$ He lines at 10^{14} G
  - off centered dipole
- Hailey & Mori (2002; 2003)
  $\Rightarrow$ O or Ne lines at
  $B \approx 10^{12}$ G

But whatever these lines are they are not H. i.e. no pair of H lines would match observations

H/O model for 1E1207



$Z = 0.14 - 0.25$ $B = 6.2 - 8 \times 10^{13}$ G
from Kaye Mori's talk.

$T_{eff} = 1.1 \times 10^6$ K (H-atmosphere fit
from Merenghetti et.al. 2002)

- For large range of parameters it is easy to consume all H in 7 kyrs

Conclusions

- Observations of INS suggest
  H → (something else) in $10^{4\text{-}5}$ yrs
  maybe due to some strange microphysics
- DNB can account for this evolution
  - vulnerable to accretion
  - T_c sensitive
  - what about He?
- DNB can explain O-lines on 1E1207
  - needs contrived H/O model

More Questions

- He and DNB
  - nonideal effects (Coulomb physics, thermal corrections)
- Applications to
  LMXBs
  MSPs