Magnetic Neutron Star Surfaces: Physics and Applications

Dong Lai
Cornell University

INT, 6/25/2007

Neutron Star Surface & Crust: Standard Lore & Issues

- Atmosphere/ocean
- Outer crust
- Inner crust (above n drip)

$$\Gamma = \frac{(Ze)^2}{r_i kT} > 175$$

Issues:

- Composition: Assume fully catalyzed matter --> Fe, Ni, etc.

  Can this be realized? “Not clear” in outer layer (Shirakawa ‘07 PhD Thesis)

  Accretion (inc. surface burning/weak interaction) changes compositon (e.g. Haensel & Zdunik 1990; Schatz et al.1999; Chang et al.2005)
- Assume “Pure” Lattice (one kind of nucleus at a given density)

  Jones (1999,2004):Thermodynamical fluctuations at freezing leads to impure solid; important for B field dissipation and heat conduction in crust
- Inner Crust: n superfluidity, vortex/lattice pinning/interactions (affect glitches? Precession?), nuclear pasta? etc

Effects of Magnetic Field

- Energy (transverse) energy quantized (Landau levels):

$$\hbar\omega_c = \hbar\frac{eB}{m_e c} = 11.6 B_{12}\ \mathrm{keV}$$

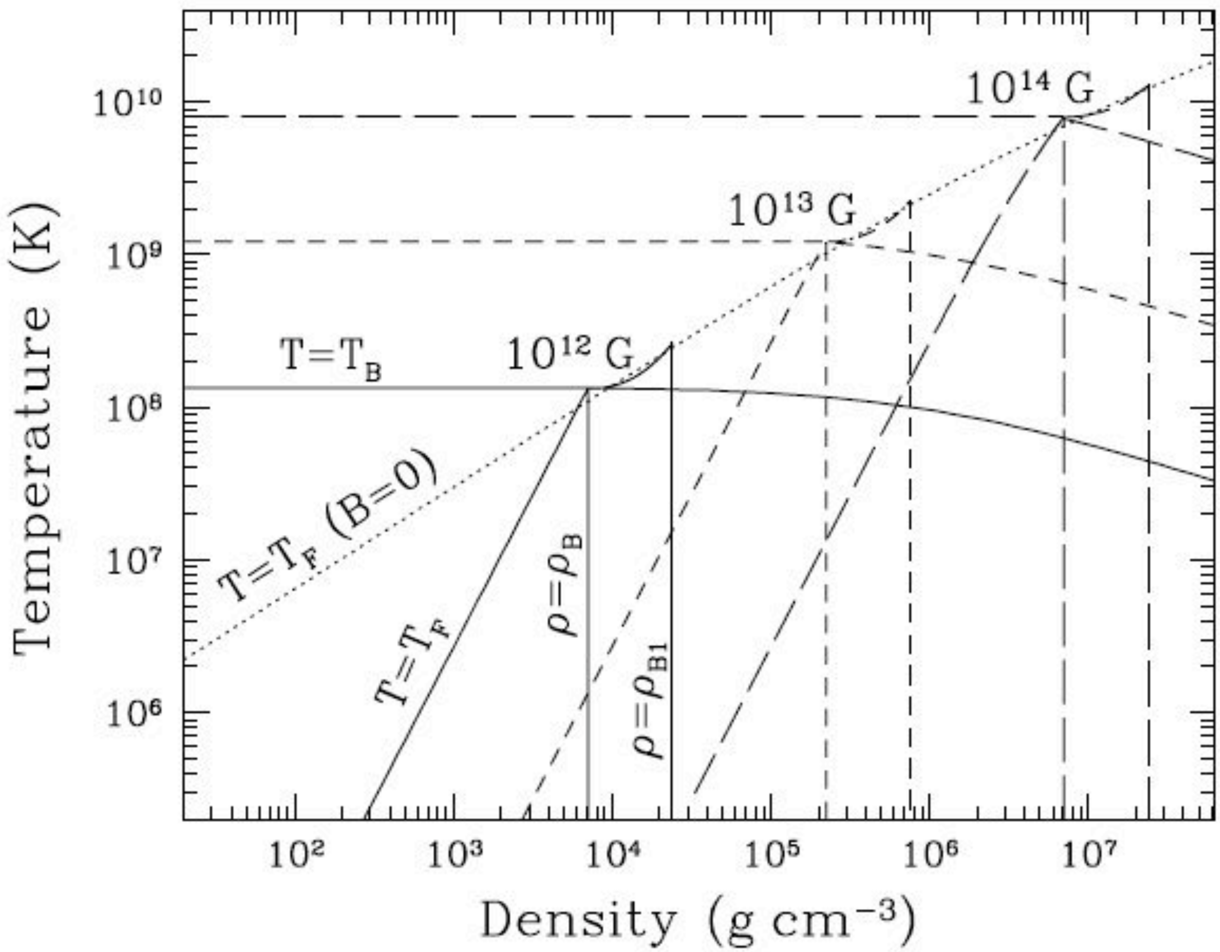
- Effects of Landau quantization on electron gas:

$$T_B = \frac{\hbar\omega_c}{k} = 1.34\times 10^{8} B_{12}\ \mathrm{K}$$

$$E_{\mathrm{Fermi}} = \hbar\omega_c \Longrightarrow \rho_B = 7000\, Y_e^{-1} B_{12}^{3/2}\ \mathrm{g\ cm^{-3}}$$

For $T \lesssim T_B$ and $\rho \lesssim \rho_B$ affects thermodynamical quantities

EOS (pressure, beta-equilibrium etc)
Rates (electron capture etc)
Electric & thermal conductivities, magnetizations, screening length, etc



Temperature (K)
Density (g cm⁻³)
10¹⁴ G
10¹³ G
10¹² G
T=T_B
T=T_F (B=0)
T=T_F
ρ=ρ_B
ρ=ρ_B1

Effects of Magnetic Field

- Energy (transverse) energy quantized (Landau levels):

$$\hbar\omega_c = \hbar \frac{eB}{m_e c} = 11.6 B_{12} \text{ keV}$$

- Effects of Landau quantization on electron gas:

$$T_B = \frac{\hbar\omega_c}{k} = 1.34 \times 10^8 B_{12} \text{ K}$$

$$E_{\text{Fermi}} = \hbar\omega_c \Longrightarrow \rho_B = 7000\, Y_e^{-1} B_{12}^{3/2} \text{ g cm}^{-3}$$

For $T \lesssim T_B$ and $\rho \lesssim \rho_B$ affects thermodynamical quantities

EOS (pressure, beta-equilibrium etc)
Rates (electron capture etc)
Electric & thermal conductivities, magnetizations, screening length, etc

npe gas

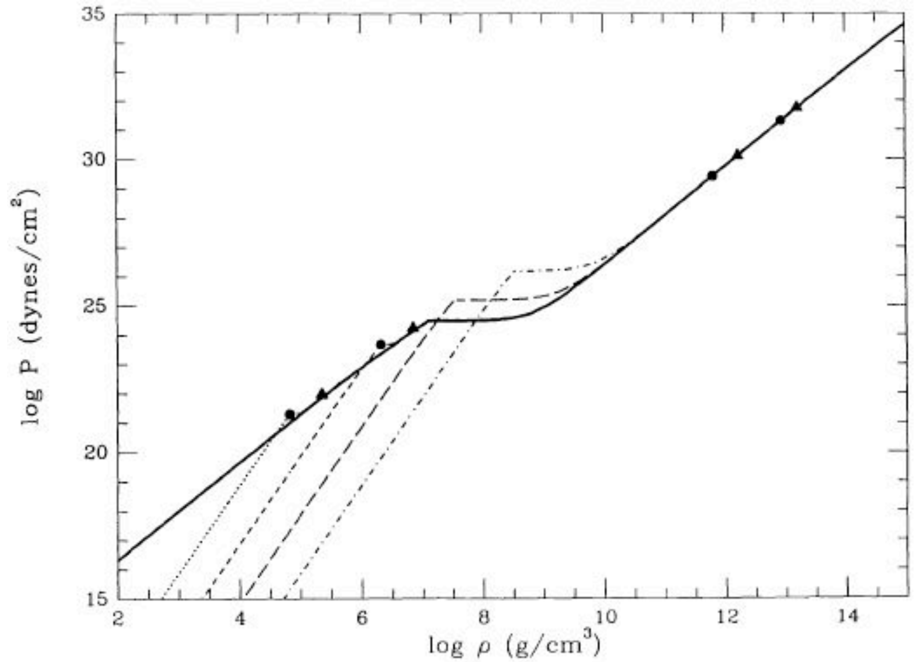
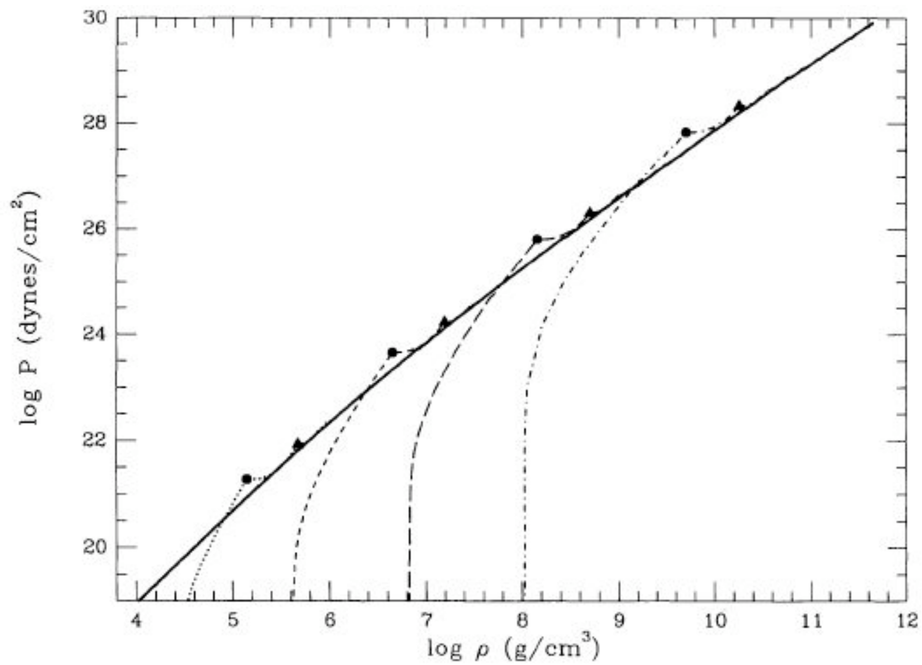
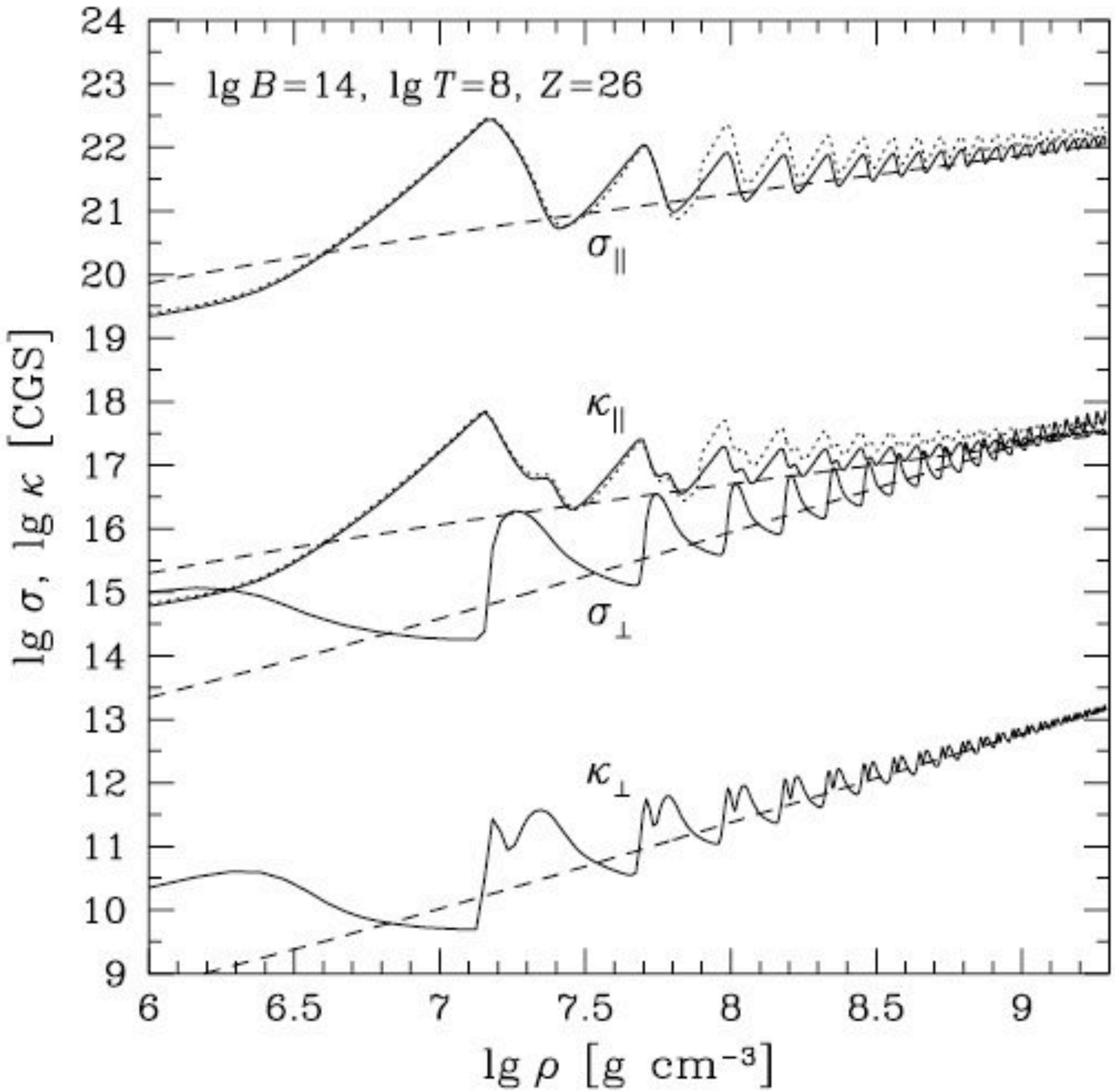


FIG. 1.—P vs. ρ for the cold homogeneous *npe* equilibrium system in a uniform magnetic field. Different curves represent different field strengths: $B = 0$ (*solid*), $B = 0.1B_c$ (*dot*), $B = B_c$ (*short dash*), $B = 10B_c$ (*long dash*), $B = 100B_c$ (*dot-dash*). The filled circles (triangles) indicate the densities at which electrons just begin to fill the first (second) Landau level for the four $B \neq 0$ cases.

BPS EOS





de Haas-van Alphen oscillations

Potekhin 1999

Magnetic fields affect the transport properties

(even for nonquantizing fields, $\rho \gtrsim \rho_B$)

gyrofrequency $\omega_c^* = \dfrac{eB}{m_e^* c} \gg$ elecron collision frequency τ_0^{-1}

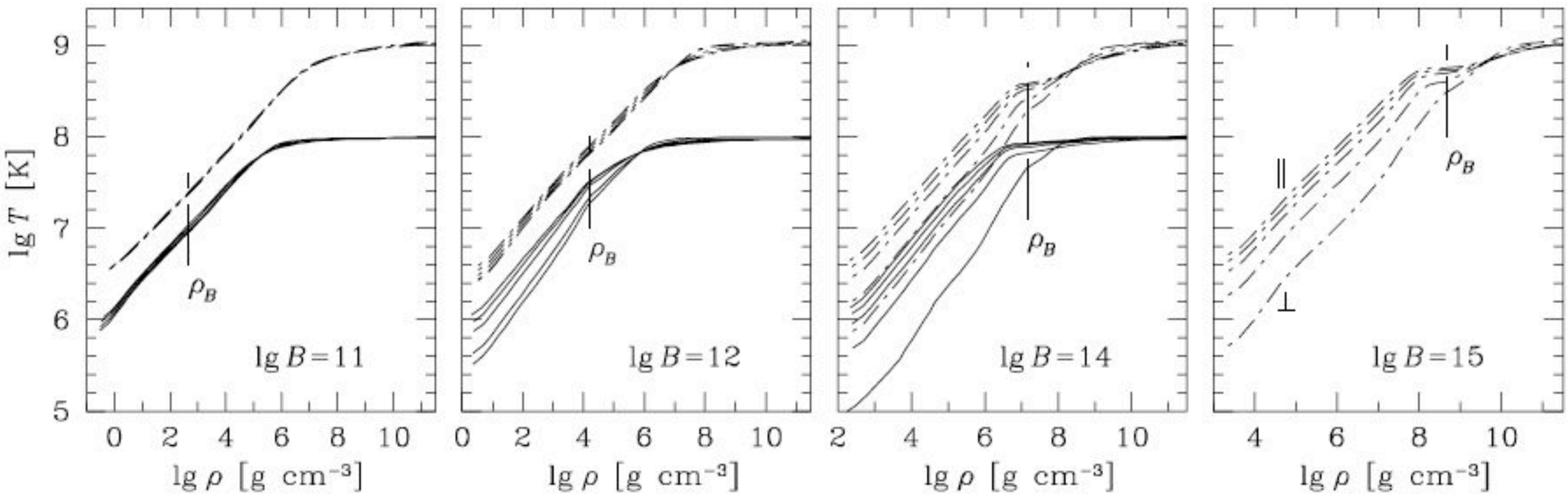
transverse conductivity suppressed by a factor of $(\omega_c^* \tau_0)^{-2}$

Affect thermal structure of NS envelope and cooling

(e.g. Hernquist, van Riper, Page, Heyl & Hernquist, Potekhin &Yakovlev etc.)

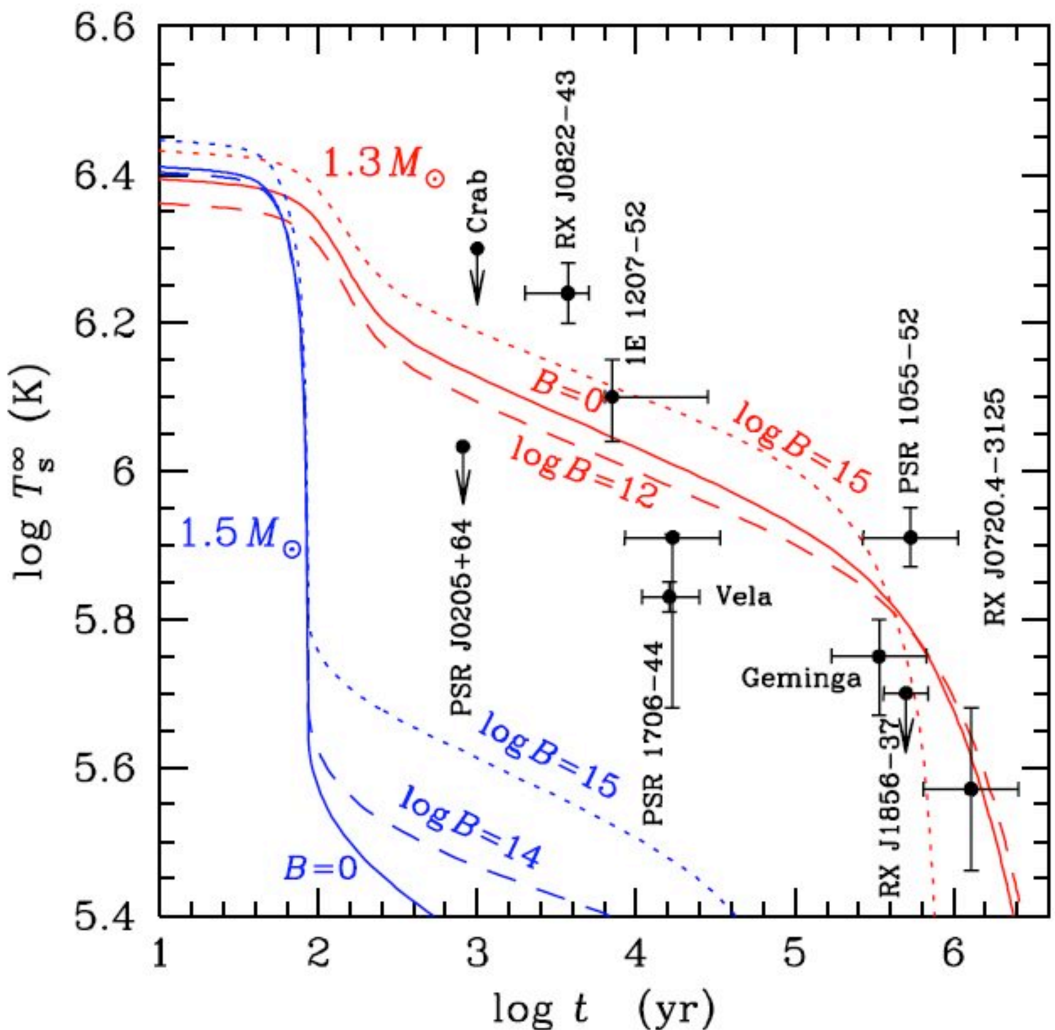
Nonuniform surface T due to anisotropic heat transport

- Region where B perpendicular to r: heat flux is reduced
- Region where B parallel to r: heat flux remains or increases (due to quantization)



Potekhin & Yakovlev 2001

Effect on (Passive) Cooling



Chabrier et al. 2006

Outermost layers

- Important because:
  - --mediates emergent radiation from surface to observer
  - --boundary condition for magnetosphere model
- Composition unknown a priori
  - --hint from observations?
- Depending on B, T and composition, may be
  - --gaseous and nondegenerate, nonideal, partially ionized atmospheres: e's, ions, atoms, molecules (small chains)
  - --condensed state (zero-pressure solid)

Bound states (atoms, molecules, condensed matter) in Strong Magnetic Fields:

Critical Field:

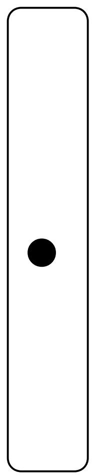
$$\hbar\omega_{ce} = \hbar\frac{eB}{m_e c} = \frac{e^2}{a_0} \quad \Longrightarrow \quad B = B_0 = 2.35 \times 10^9 \text{ G}$$

Strong field: $B \gg B_0$

Property of matter is very different from zero-field

Atoms and Molecules

Strong B field significantly increases the binding energy of atoms



For $b = \dfrac{B}{B_0} \gg 1, \quad B_0 = 2.35 \times 10^9 \text{ G}$

$$|E| \propto (\ln b)^2$$

E.g. $|E| = 160 \text{ eV}$ at 10^{12}G

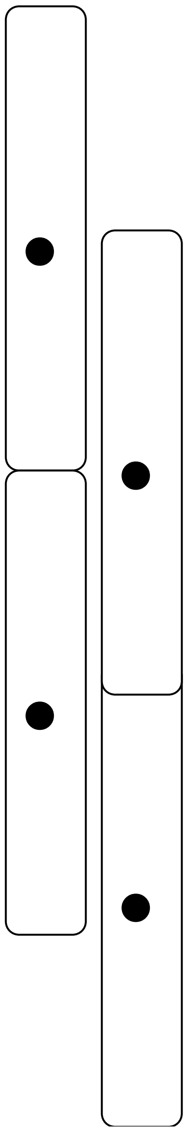
$|E| = 540 \text{ eV}$ at 10^{14}G

Atoms combine to form molecular chains:

E.g. H_2, H_3, H_4, …

Condensed Matter

Chain-chain interactions lead to formation of 3D condensed matter



Binding energy per cell $|E| \propto Z^{9/5} B^{2/5}$

Zero-pressure density

$$\simeq 10^3 A Z^{3/5} B_{12}^{6/5} \text{ g cm}^{-3}$$

Cohesive energy of condensed matter

- Strong B field increases the binding energy of atoms and condensed matter

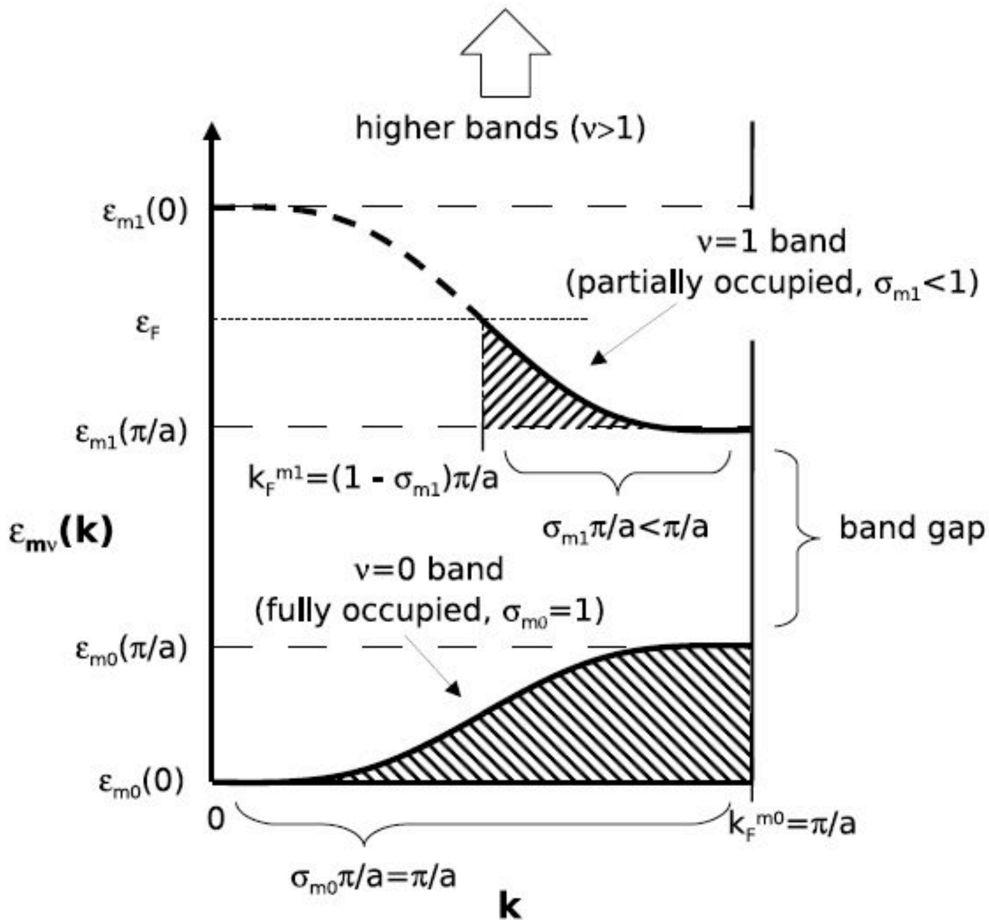
  Energy of atom: ~ $(\ln b)^2$
  Energy of zero-pressure solid: ~ $b^{0.4}$

==> Expect condensed surface to have large cohesive energy

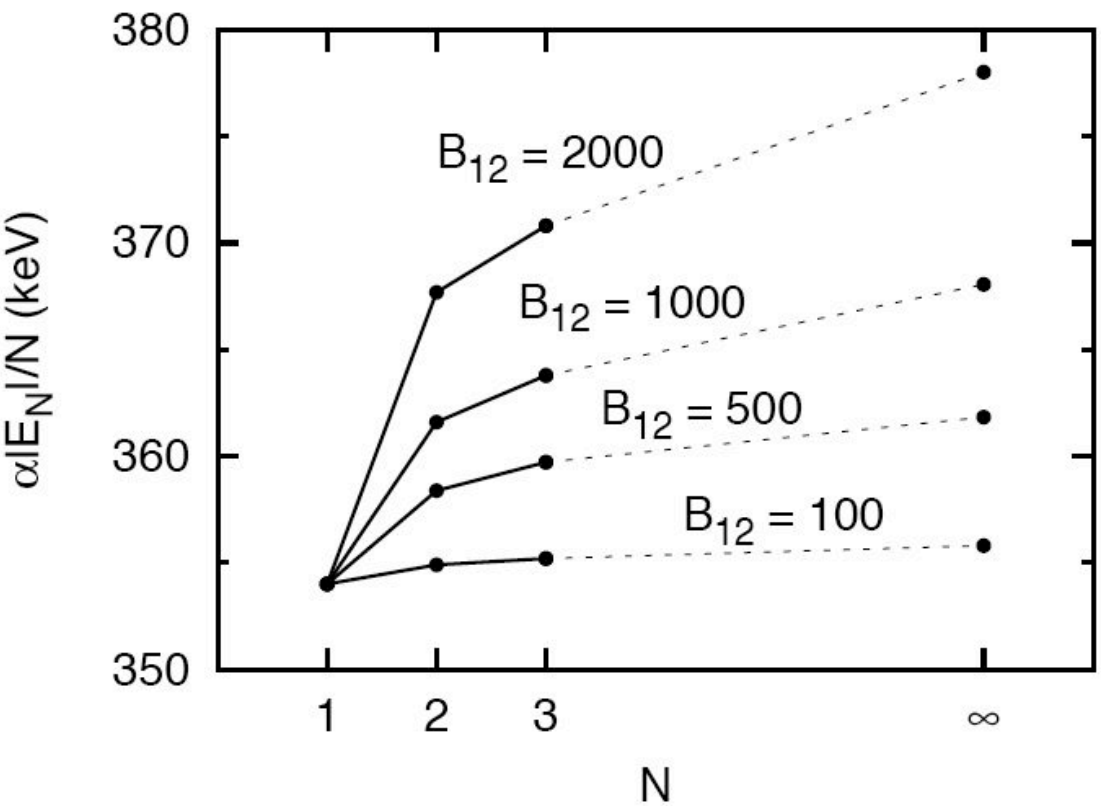
- Calculations in 1980s (Jones, Neuhauser et al.) showed that
  C, Fe solids are unbound (or weakly bound) at 10^{12}G;
  some conflicting results.

New calculations (Zach Medin & DL 2006a,b)

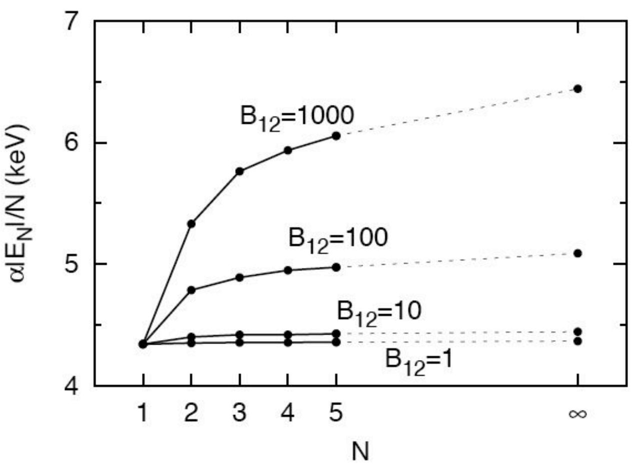
- Density functional theory
- Accurate exchange-correlation energy
- Improved treatment of band structure
- Extend to ~10^{15}G



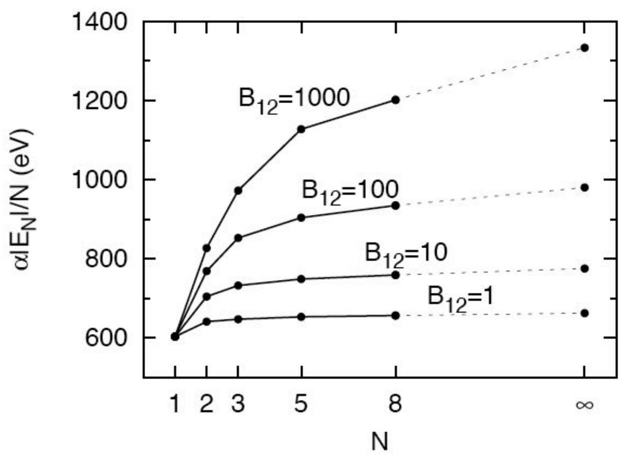
Medin & DL 2006



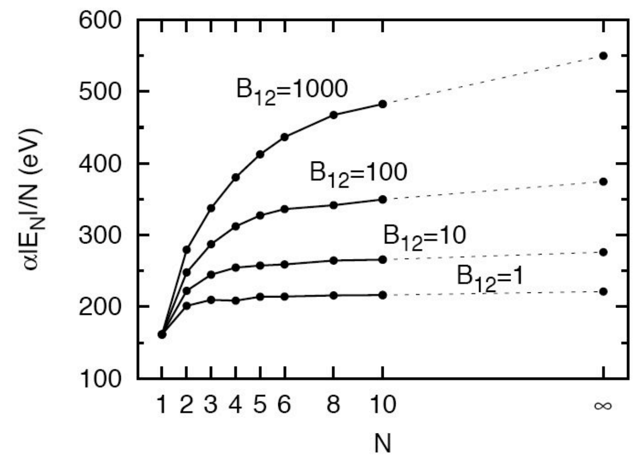
Fe_N



C_N

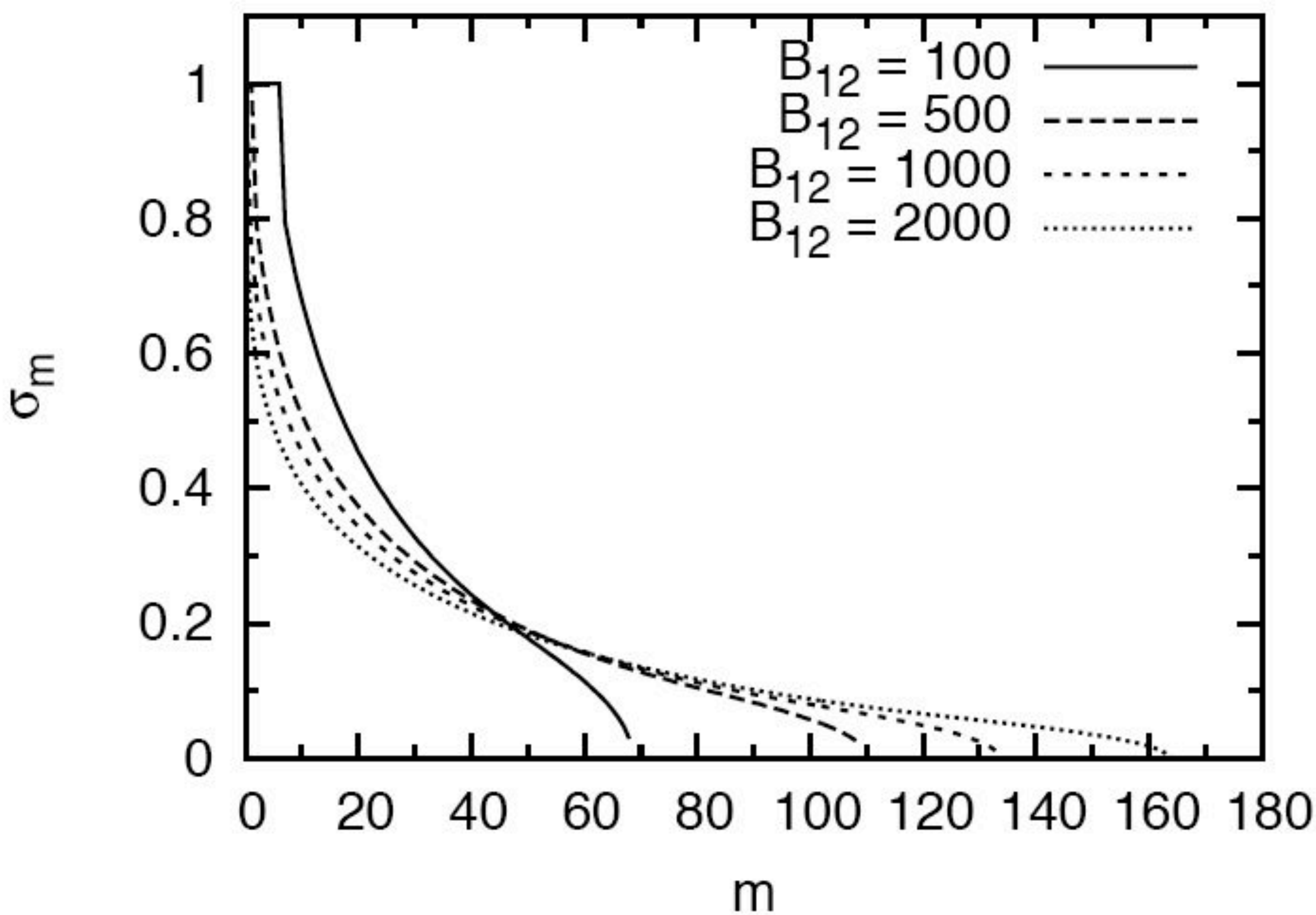


He_N

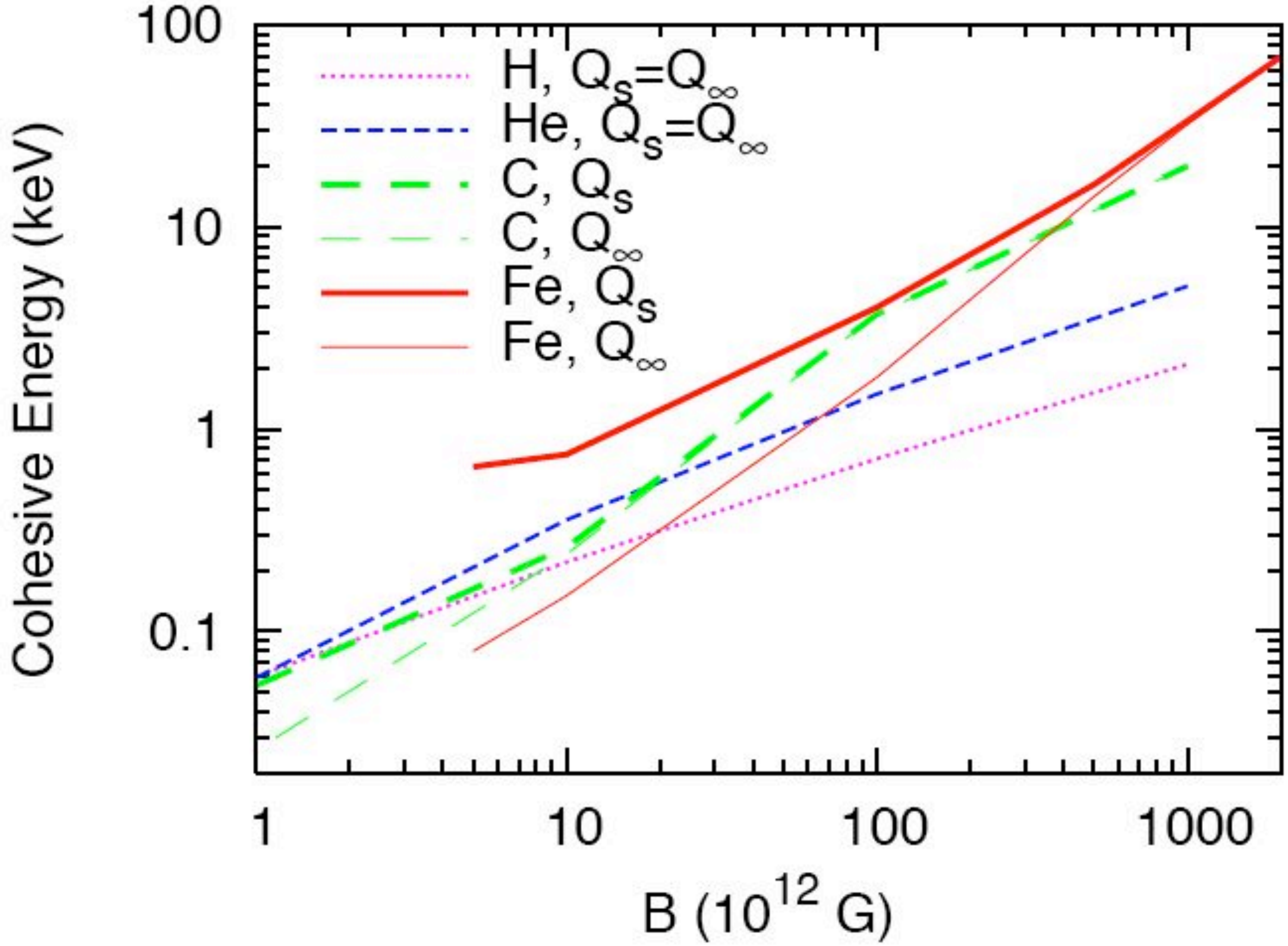


H_N

Fe solid



B_{12} = 100
B_{12} = 500
B_{12} = 1000
B_{12} = 2000
σ_m
m
0
0.2
0.4
0.6
0.8
1
0 20 40 60 80 100 120 140 160 180



H, Qs=Q∞
He, Qs=Q∞
C, Qs
C, Q∞
Fe, Qs
Fe, Q∞
Cohesive Energy (keV)
100
10
1
0.1
1
10
100
1000
B (10^12 G)

Medin & DL 06

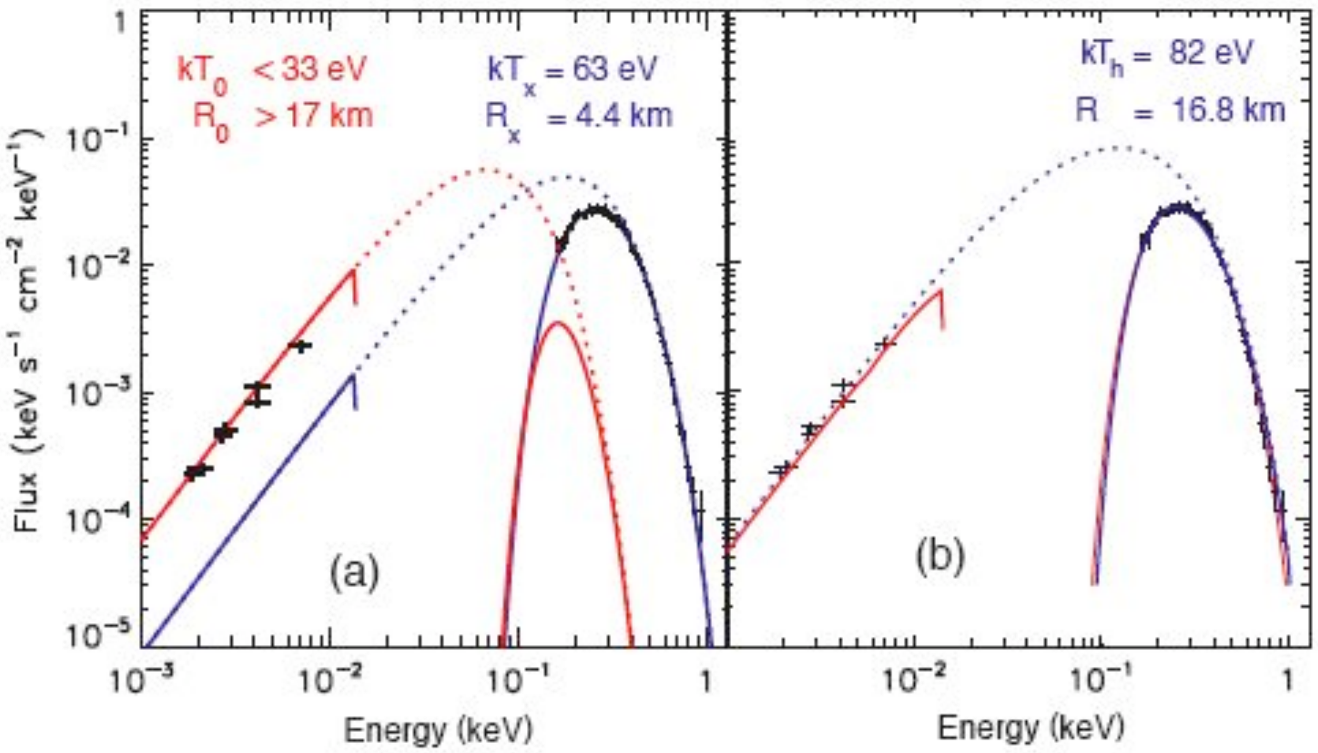
Implications…

Thermally Emitting Isolated NSs

"Perfect" X-ray blackbody:

RX J1856.5-3754

(T ~ 60 eV)

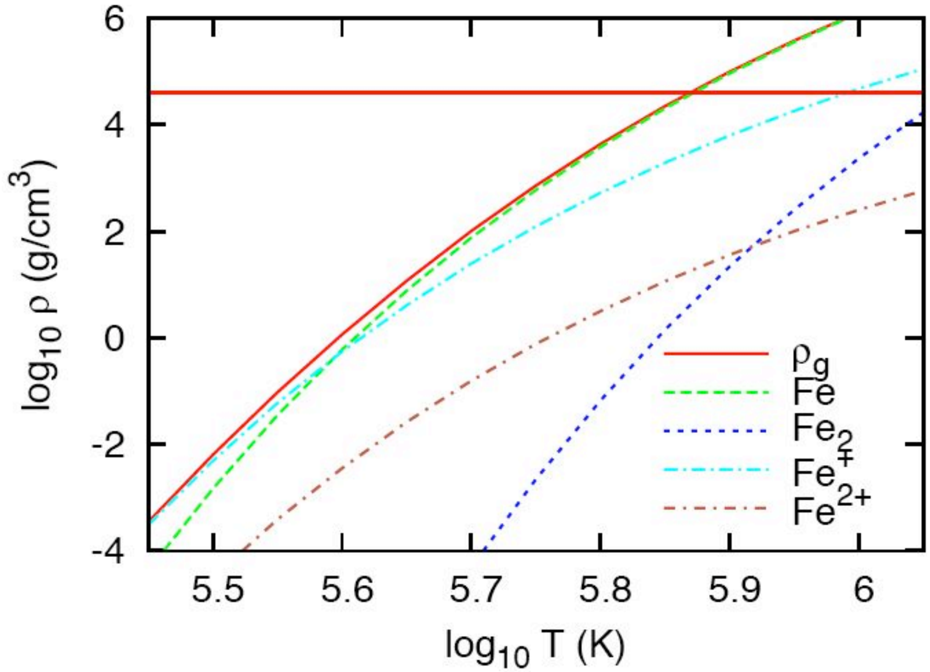


Burwitz et al. 03, Trumper et al 04

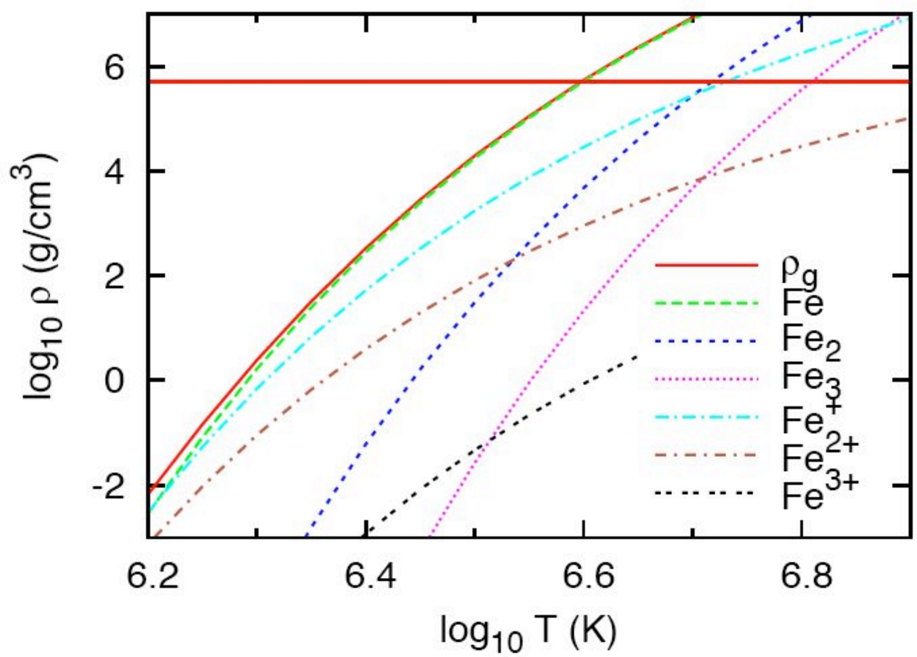
Emission from condensed surface (rather than atmosphere)?

Saturated Vapor of Condensed NS Surface

Fe at 10^{13}G

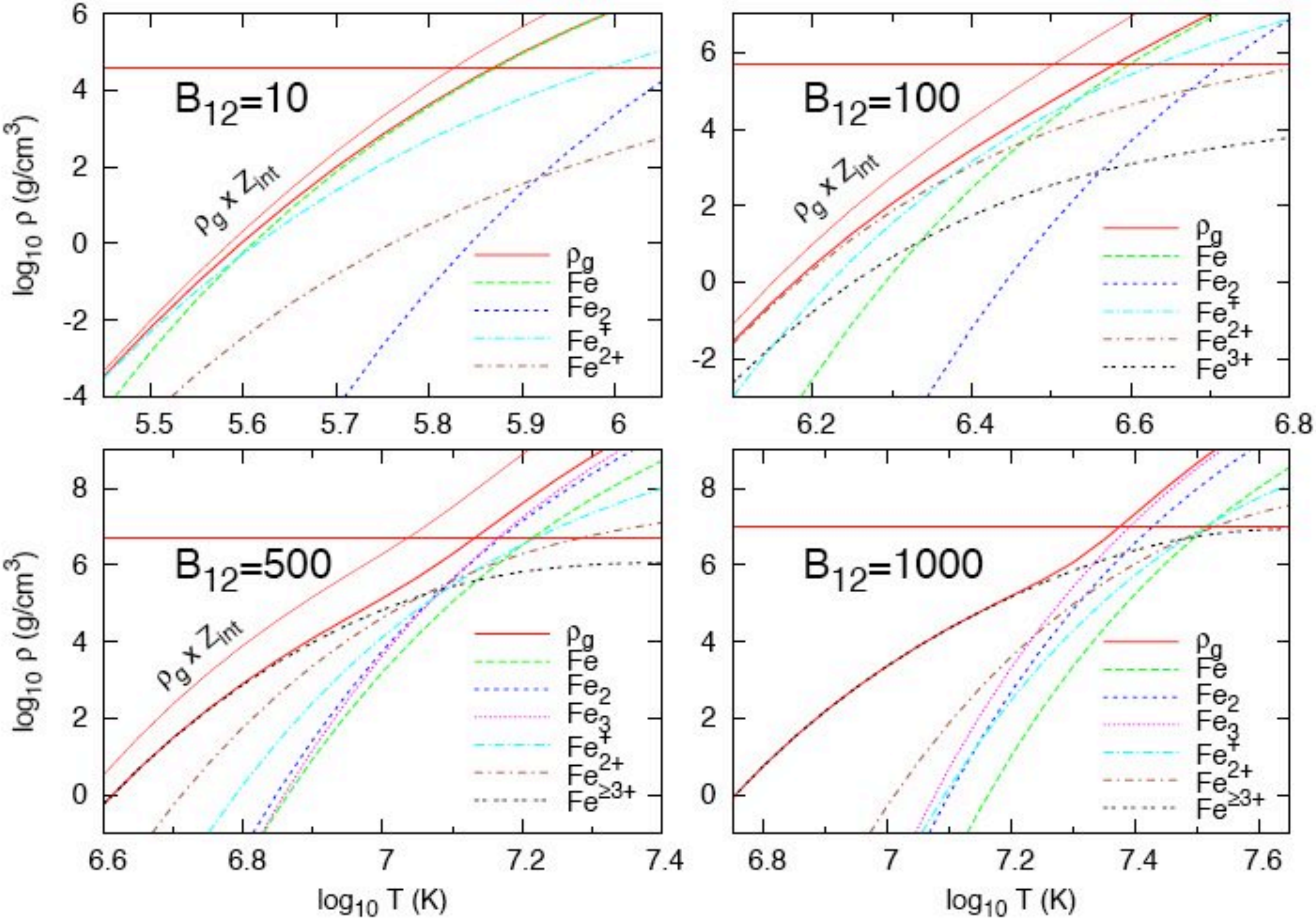


Fe at 10^{14}G

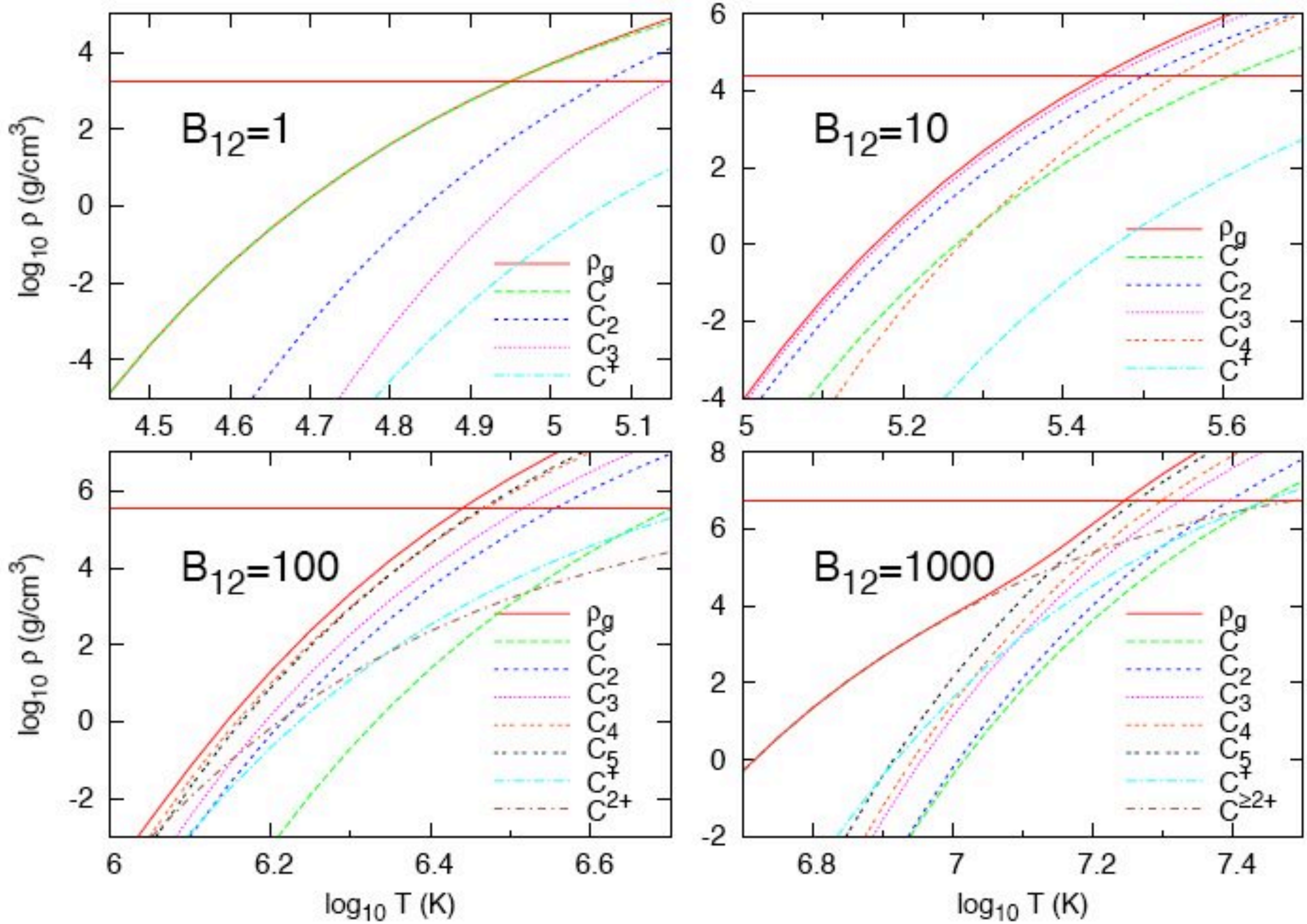


Medin & DL 2007 (in prep)

For high B/low T, NS surface in condensed form (with little vapor above)



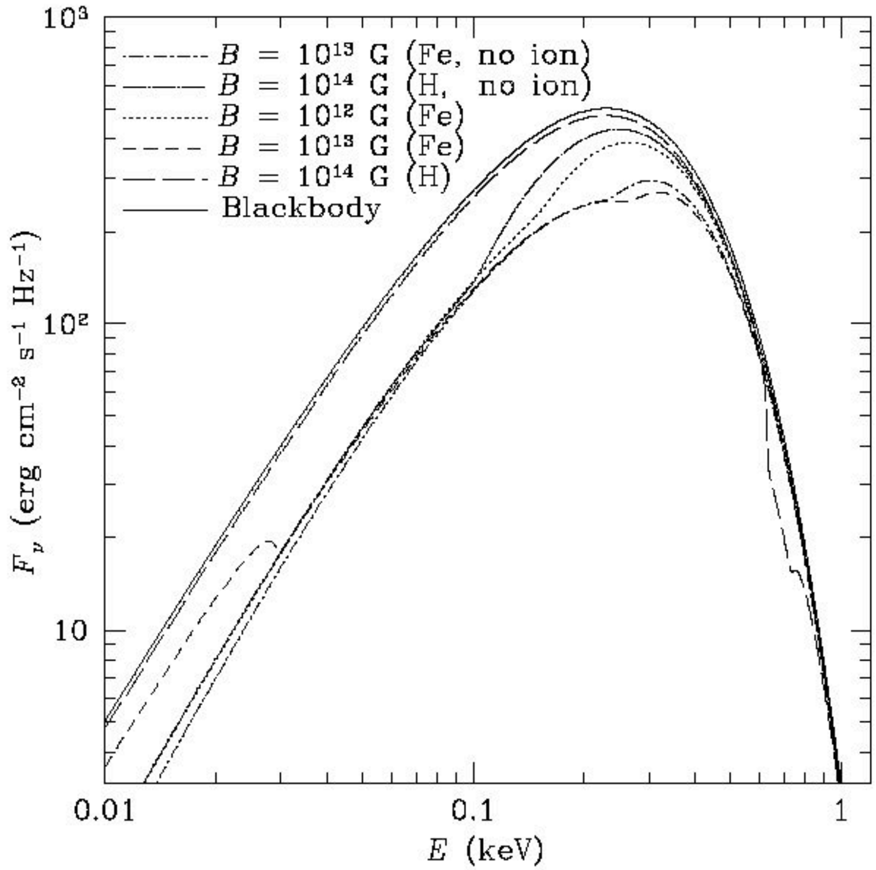
B12=10
B12=100
B12=500
B12=1000
ρg x Zint
ρg
Fe
Fe2
Fe3
Fe+
Fe2+
Fe3+
Fe≥3+
log10 ρ (g/cm3)
log10 T (K)

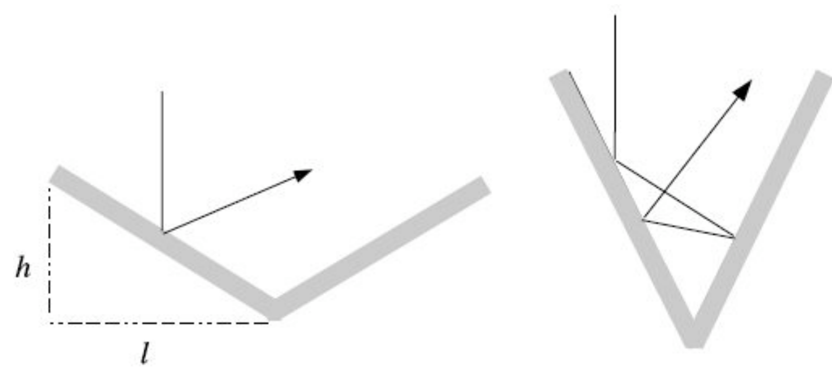


B12=1
B12=10
B12=100
B12=1000
ρg
C
C2
C3
C4
C5
C+
C2+
C≥2+
log10 ρ (g/cm3)
log10 T (K)

Emission from condensed NS surface:

Reflectivity R_E Emission $I_E=(1-R_E)B_E(T)$





van Adelsberg, Lai, Potekhin & Arras 05

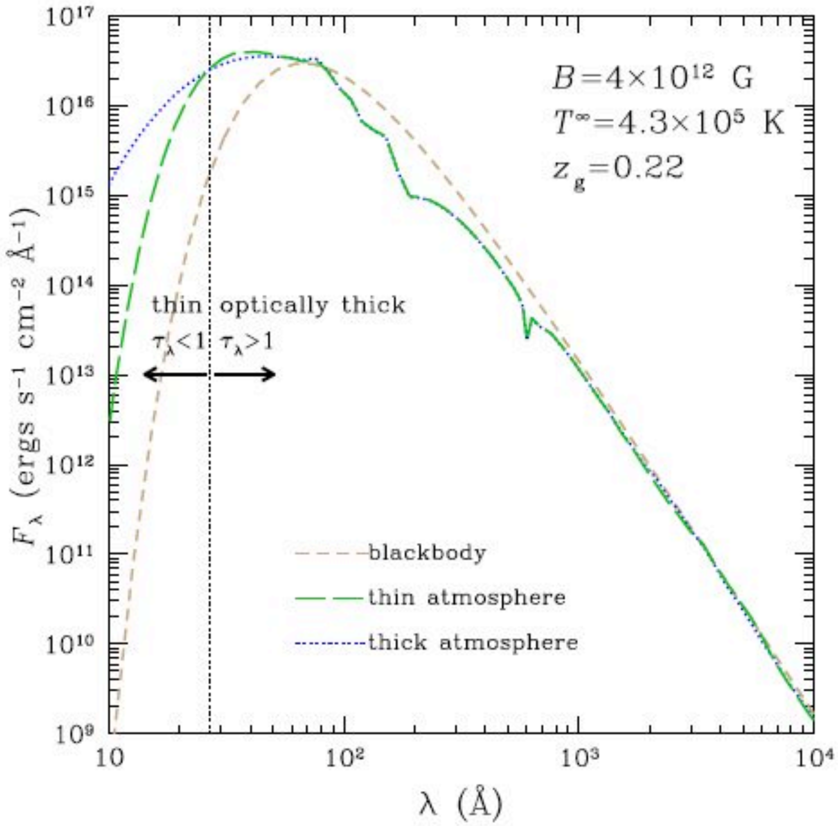


Figure 3. Spectra of hydrogen atmospheres with $B = 4\times10^{12}$ G and $T^\infty = 4.3\times10^5$ K. The dotted and long-dashed lines are the model spectra using the "thick" atmosphere and "thin" atmosphere with $y_{\rm H} = 1.2$ g cm^{-2}, respectively (see text for details). The short-dashed line is for a blackbody with the same temperature. All spectra are redshifted by $z_g = 0.22$. The vertical line separates the wavelength ranges where the atmosphere is optically thin ($\tau_\lambda < 1$) and optically thick ($\tau_\lambda > 1$).

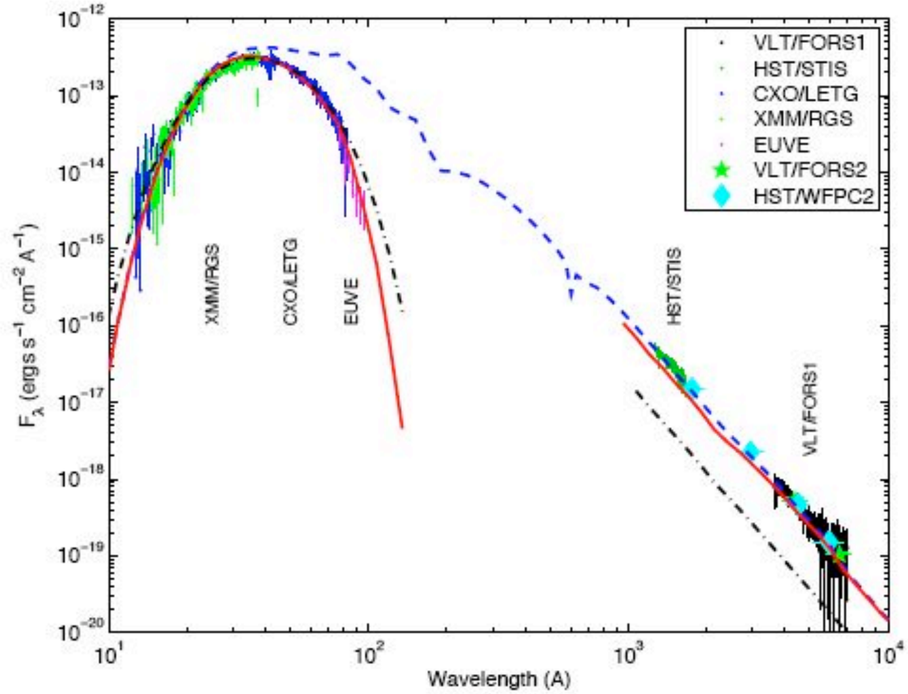
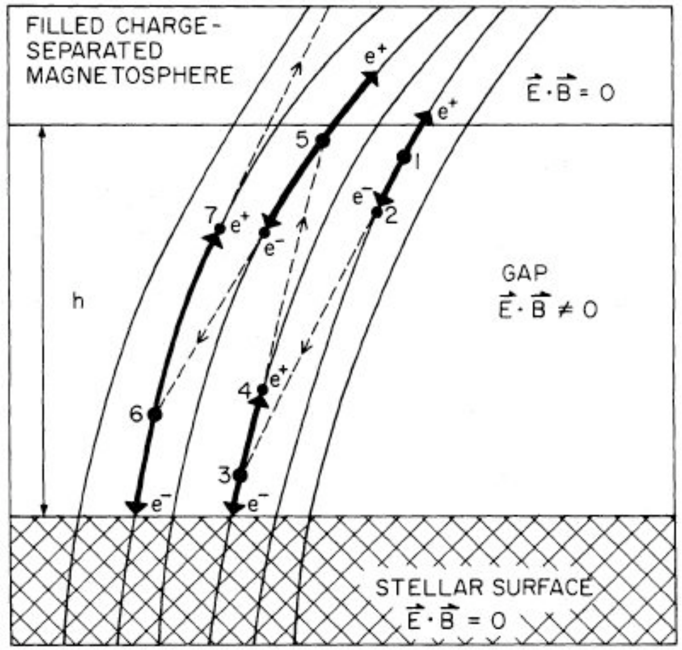


Figure 8. Spectrum of RX J1856.5−3754 from optical to X-ray wavelengths. The data points are observations taken from various sources. Error bars are one-sigma uncertainties. Optical spectra are binned for clarity: STIS data into 30 bins at a resolution of 12 Å and VLT data into 60 bins at 55 Å resolution. The solid line is the absorbed (and redshifted by $z_g = 0.22$) atmosphere model spectrum with $B = 4\times10^{12}$ G, $y_{\rm H} = 1.2$ g cm^{-2}, $T^\infty = 4.3\times10^5$ K, and $R^\infty = 17$ km. The dashed line is the unabsorbed atmosphere model spectrum. The dash-dotted line is the (absorbed) blackbody fit to the X-ray spectrum with $R^\infty = 5$ km.

Ho et al 2007

Polar Gap Accelerator of Radio Pulsars

(Ruderman & Sutherland 1975; ……)



Variant Model: Space-charge limited flow

(Arons & Scharleman 79; Muslimov & Tsygan 90; Harding & Muslimov 98; Qiao, Zhang et al …..)

- Does not require cohesive surface
- Not as efficient an accelerator (require GR, may require special field geometry)

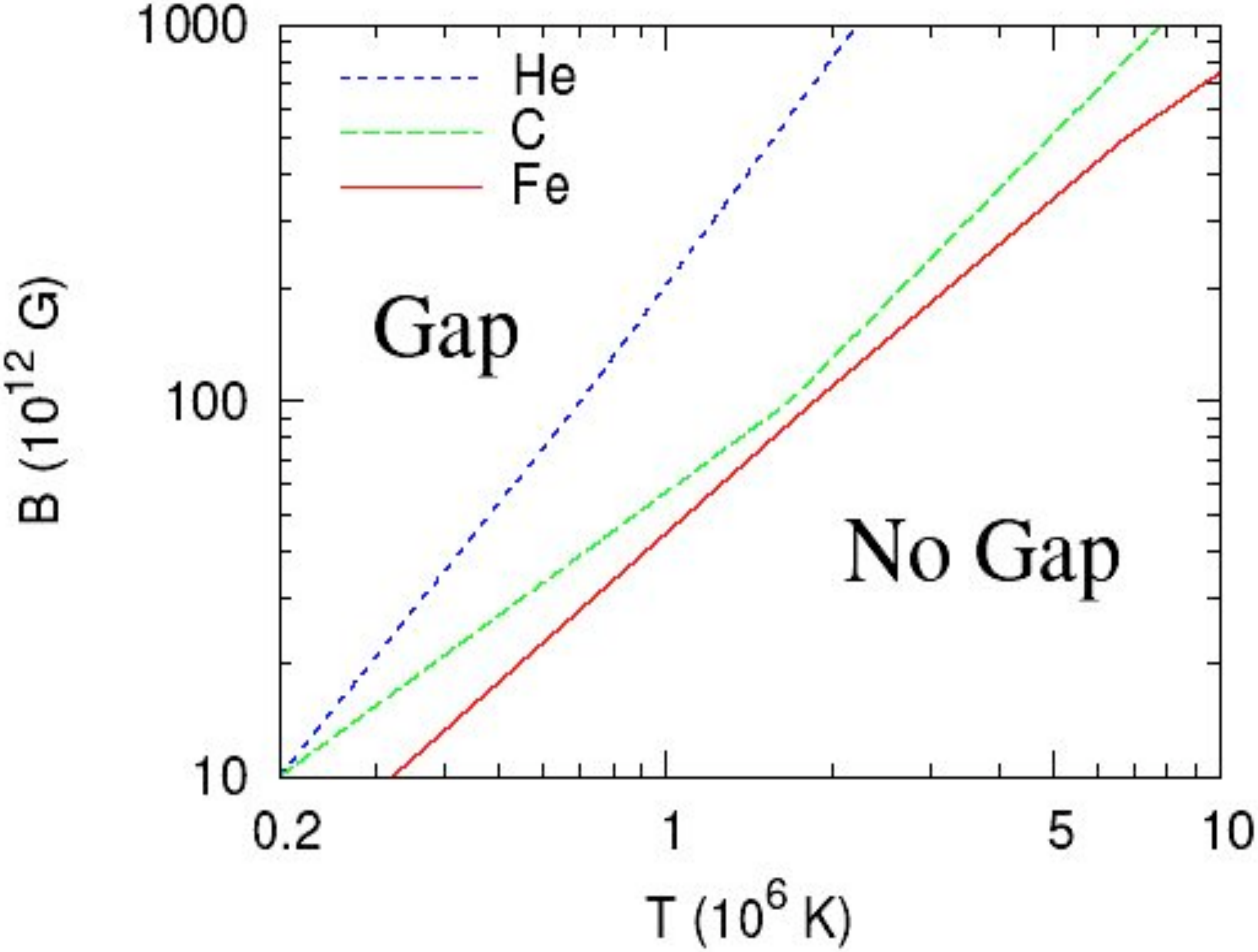
Existence of polar (vacuum) gap requires:

surface does not efficiently supply charges to magnetospheres

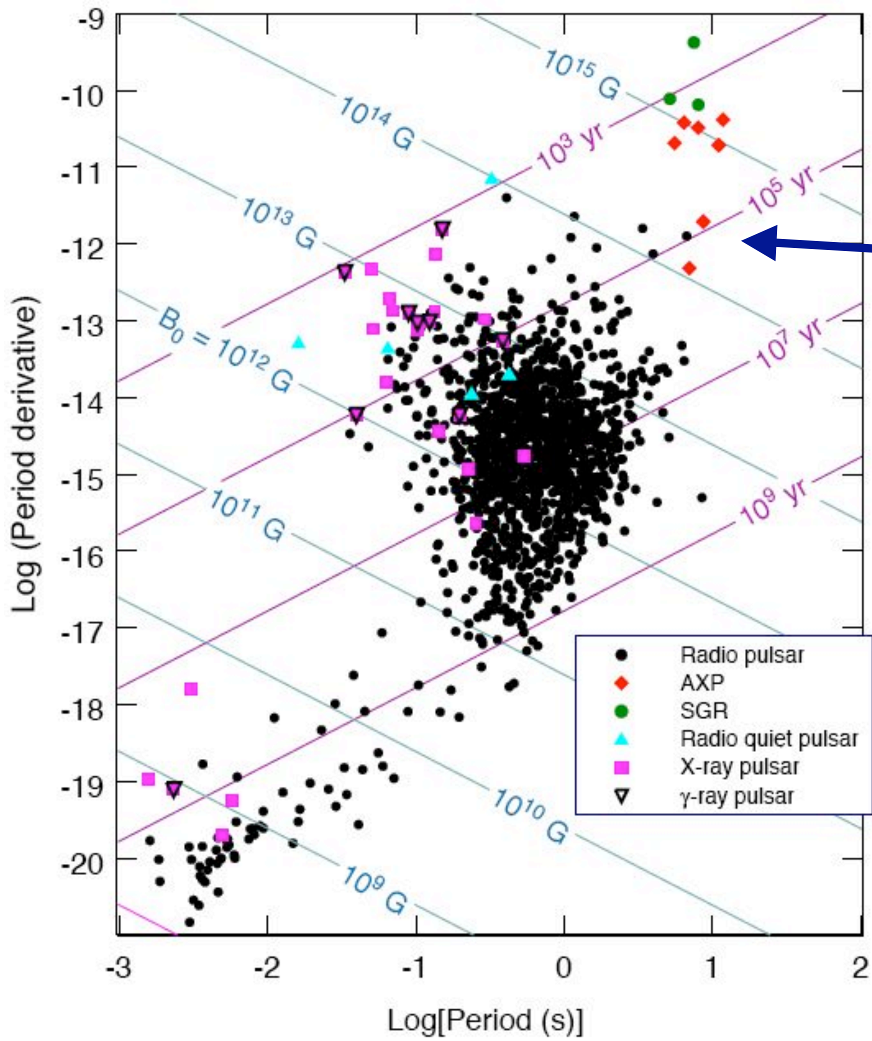
Ion emission from condensed surface:

Energy barrier $E_B = E_{\rm coh} + I - ZW$

Emission rate $\propto \exp(-E_B/kT)$



Medin & DL 2007

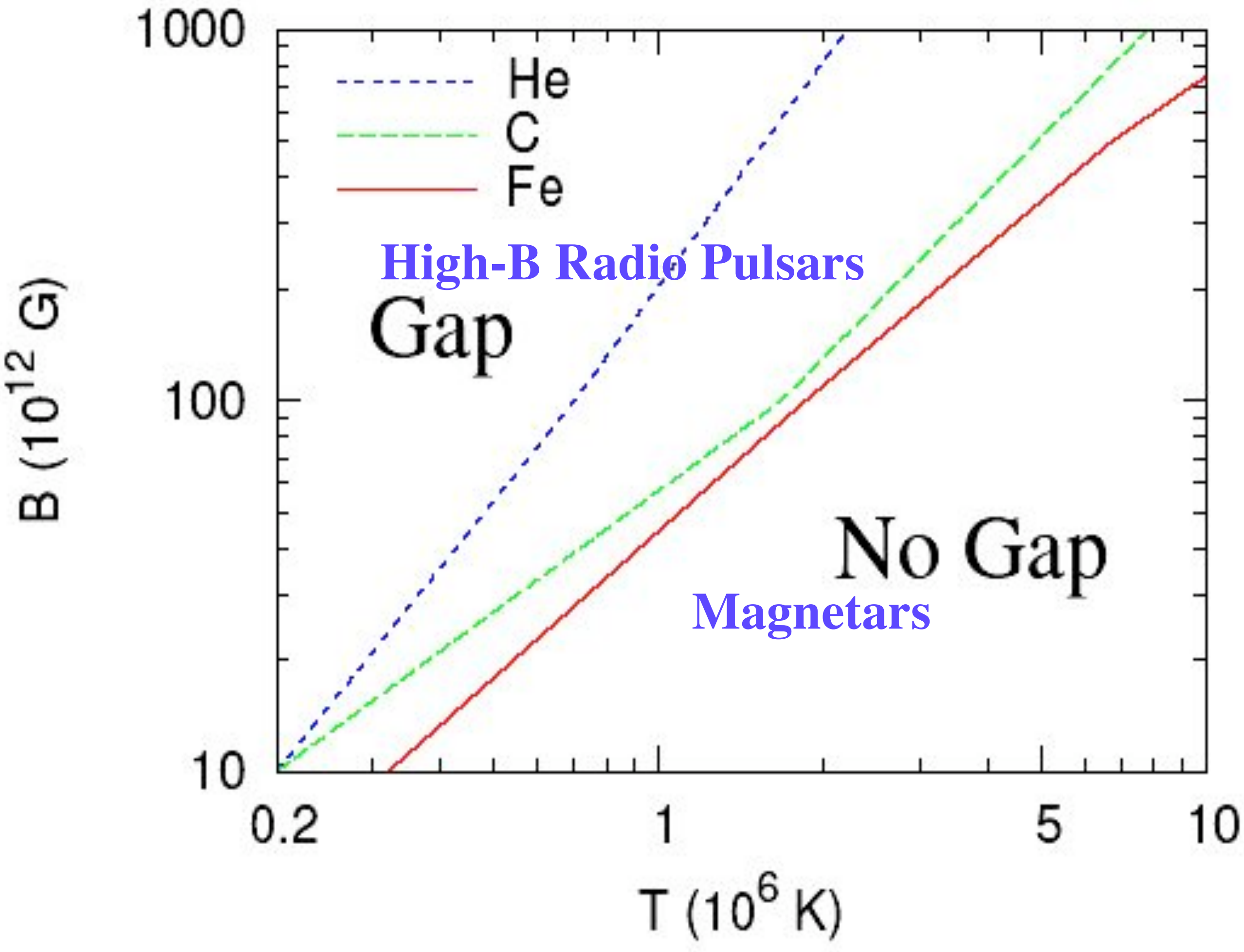


High-B pulsars vs Magnetars

Observationally, High-B radio pulsars T<1-2MK, magnetars T>5 MK

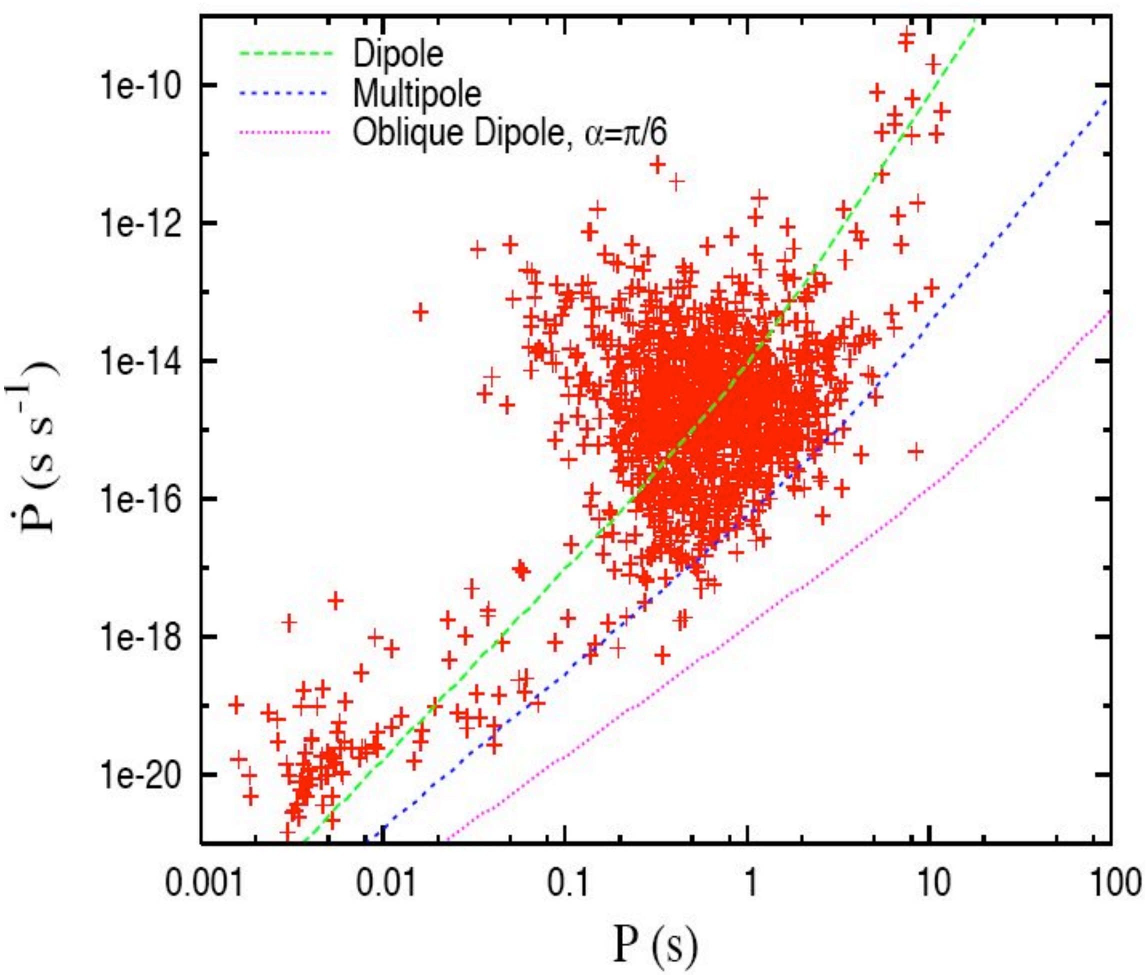
(Kaspi & McLaughlin 05)

Speculation:



Pulsar activity depends on T (in addition to P and B)?

Pulsar death line (vacuum gap cascade)



Medin & Lai 07 (in prep)

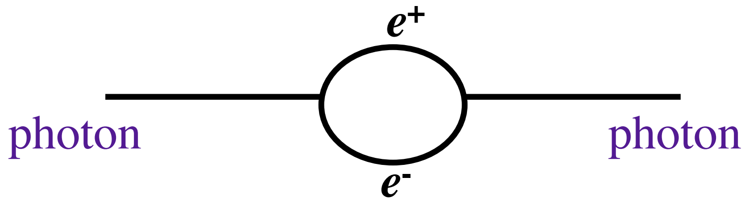
Modeling of Magnetic NS Atmospheres

Relevant to thermal emission of NSs

NS Atmospheres:

- Outermost ~cm of the star
- Density 0.1-10^3 g/cm^3: nonideal, partially ionized, magnetic plasma
- **Effect of QED: Vacuum polarization**
- **Partially ionized atmosphere models**

Vacuum Polarization in Strong B



Heisenberg & Euler, Weisskopf, Schwinger, Adler…

Dielectric tensor: $\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}_{\rm vac}$

$$|\Delta\varepsilon_{\rm vac}| \sim 10^{-4}(B/B_Q)^2, \text{ with } B_Q = 4.4\times10^{13}\ \text{G}$$

Two photon modes:

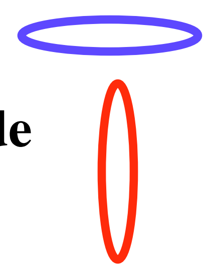
Ordinary mode (//)

Extraordinary mode (⊥)

Magnetic Plasma by itself (without QED) is birefringent:

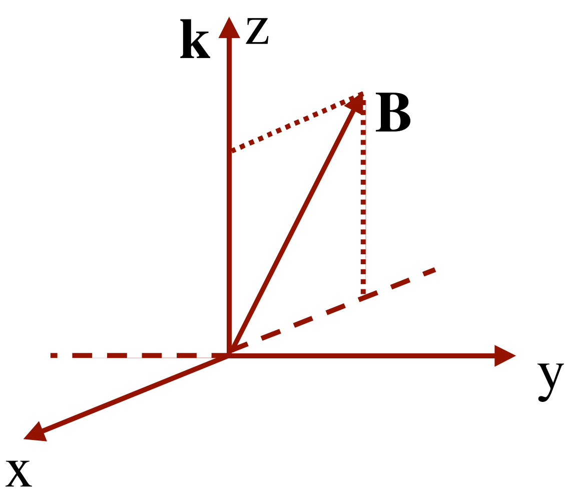
Ordinary mode

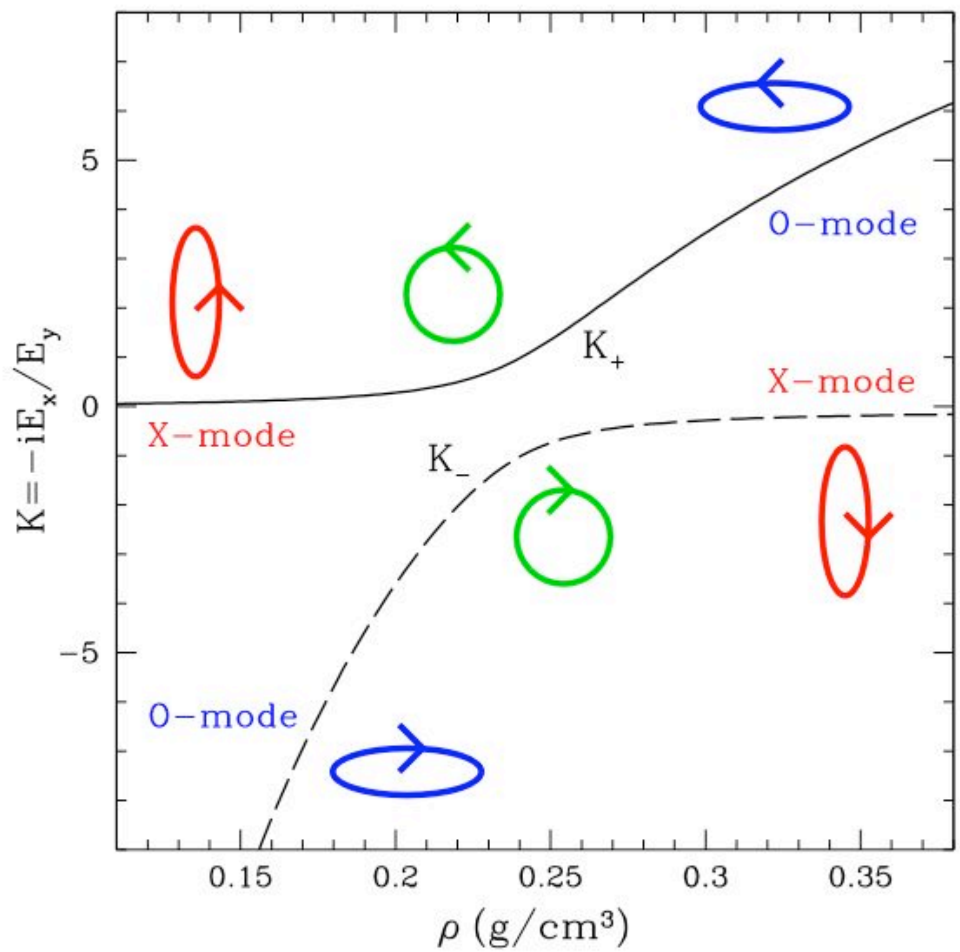
Extraordinary mode



"Plasma+Vacuum" ==> Vacuum resonance

e.g. Meszaros & Ventura 79; Pavlov & Shibanov 79; DL & Ho 02





DL & Wynn Ho 03

Why do we care?

The two photon modes have very different opacities

=> Mode conversion can affect radiative transfer significantly

=> Spectrum and polarization signal from the NS

A technical point:

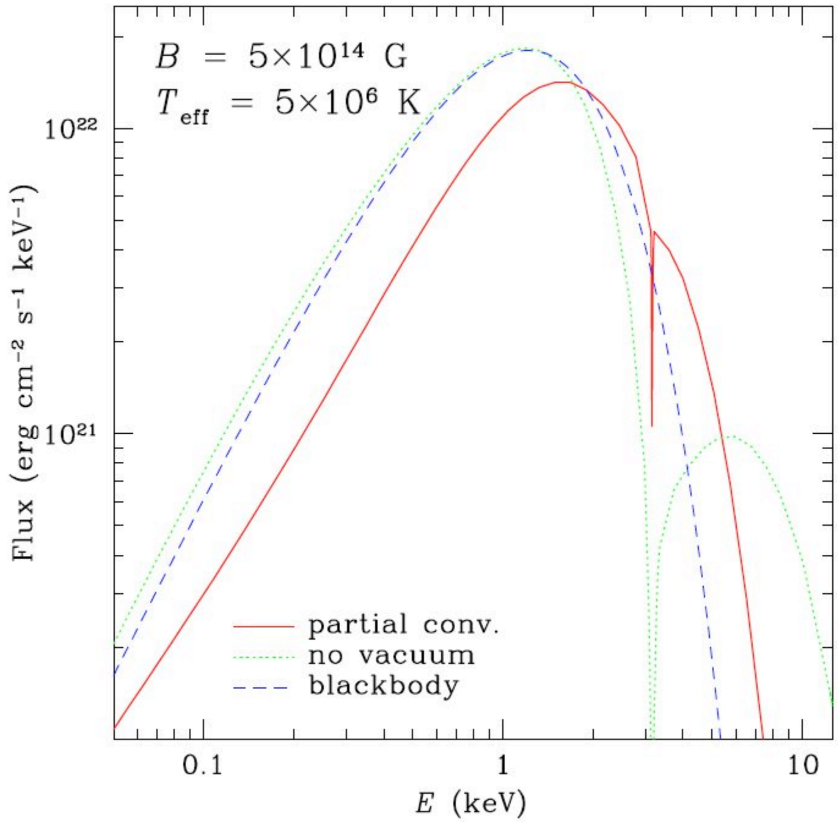
Mode conversion is a coherent phenomenon.

Need to go beyond the usual modal description of radiative transport:

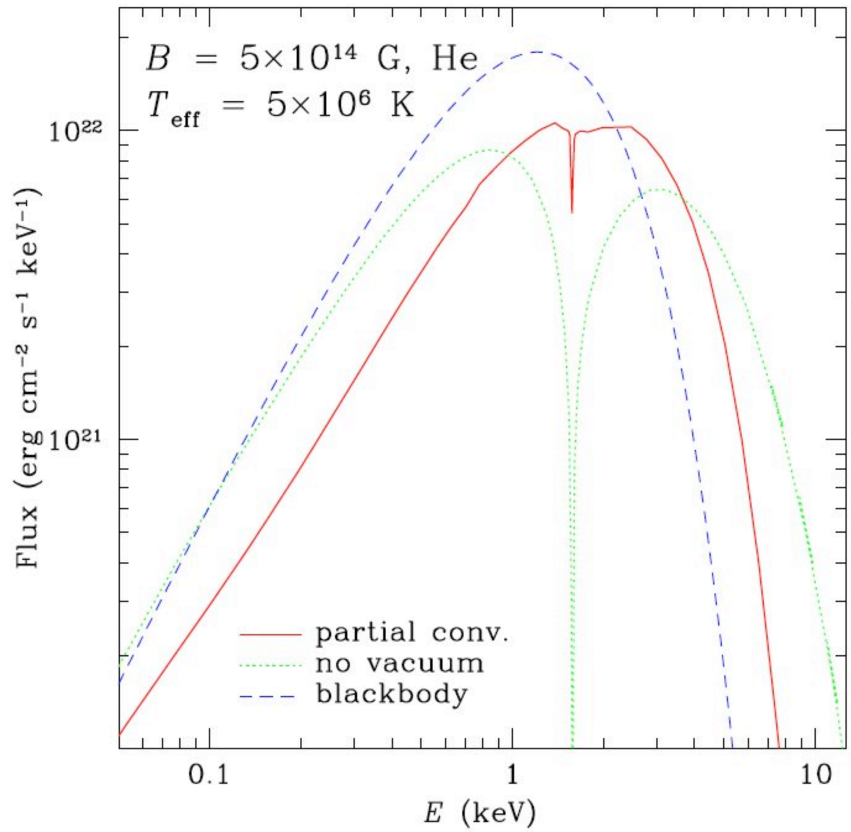
=> Take into account of the nontrivial conversion probability

=> Solve transfer equations for Stokes parameters (I,Q,U,V)

H



He

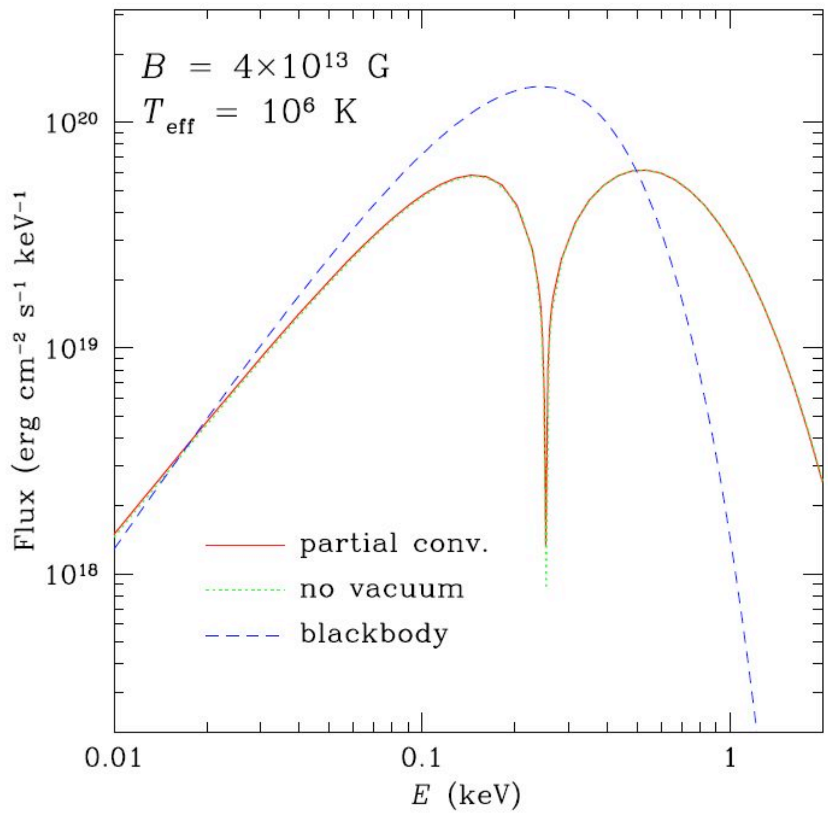


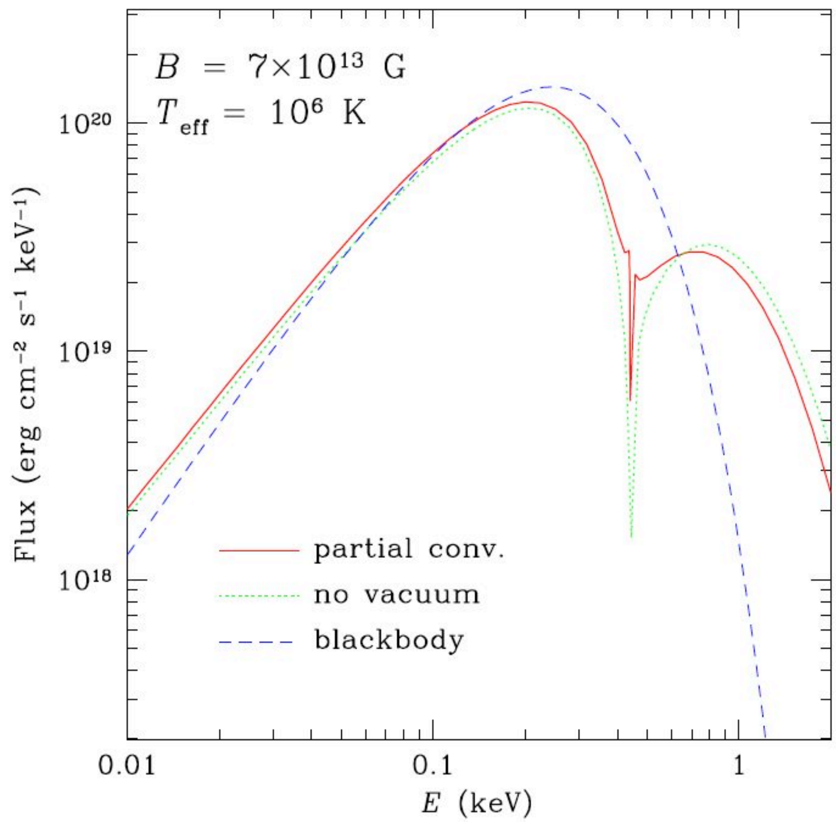
Matt Van Adelsberg & DL 2006

==> Magnetars do not show absorption features in thermal emission

(In qualitative agreement with approximate calculations by Wynn Ho & DL 03)

For B $\lesssim 7\times10^{13}$G, vacuum polarization has small effect on spectrum

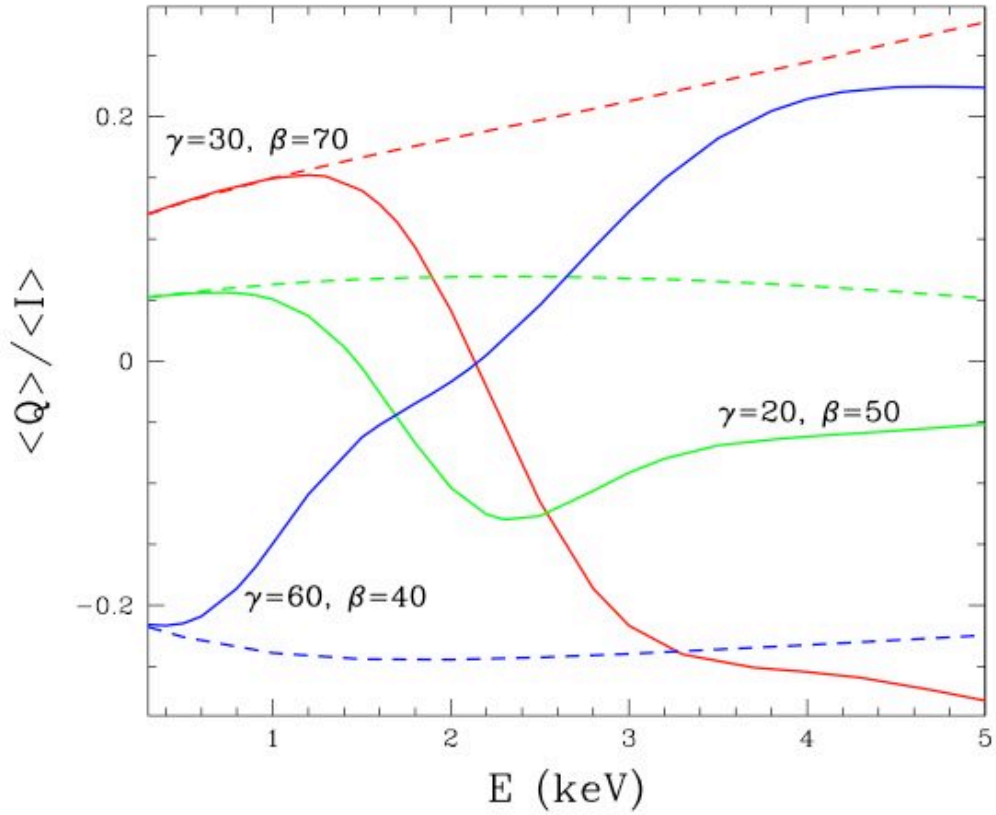




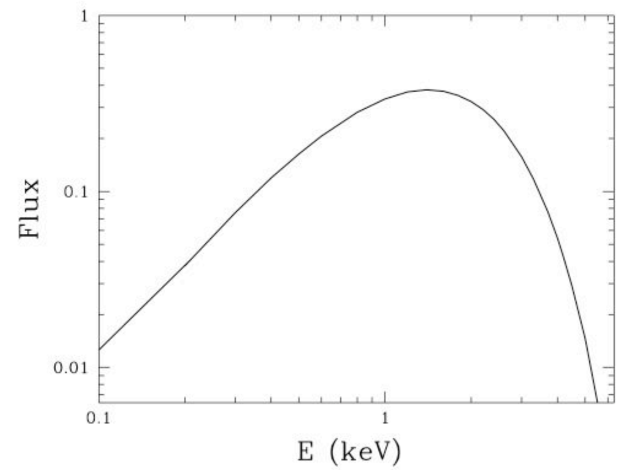
Matt Van Adelsberg & DL 2006

==> Absorption features observed in thermally emitting isolated NSs

Even for modest B's, vacuum resonance produces unique polarization signals



B=10^{13}G



"boring" spectrum & lightcurve,
but interesting/nontrivial polarization spectrum!

==> X-ray polarimeters

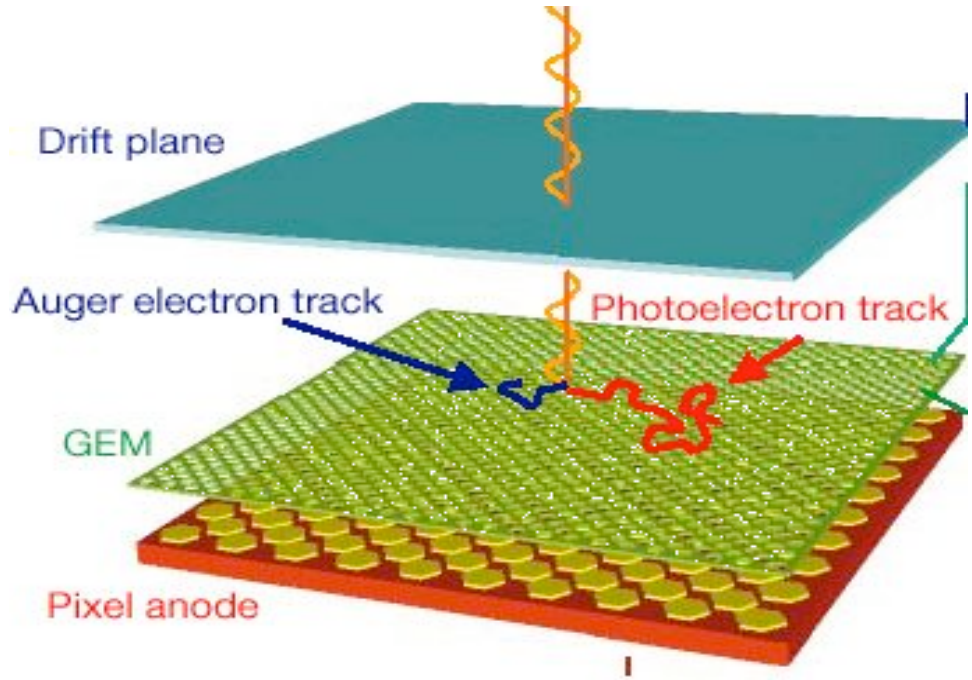
X-ray Polarimetry: Measurement Concept

Initial photo-electron direction has memory ($\cos^2\theta$) of incident polarization

Initial demonstration at INFN (Italy) Costa et al., Nature, 411, 662, (2001)

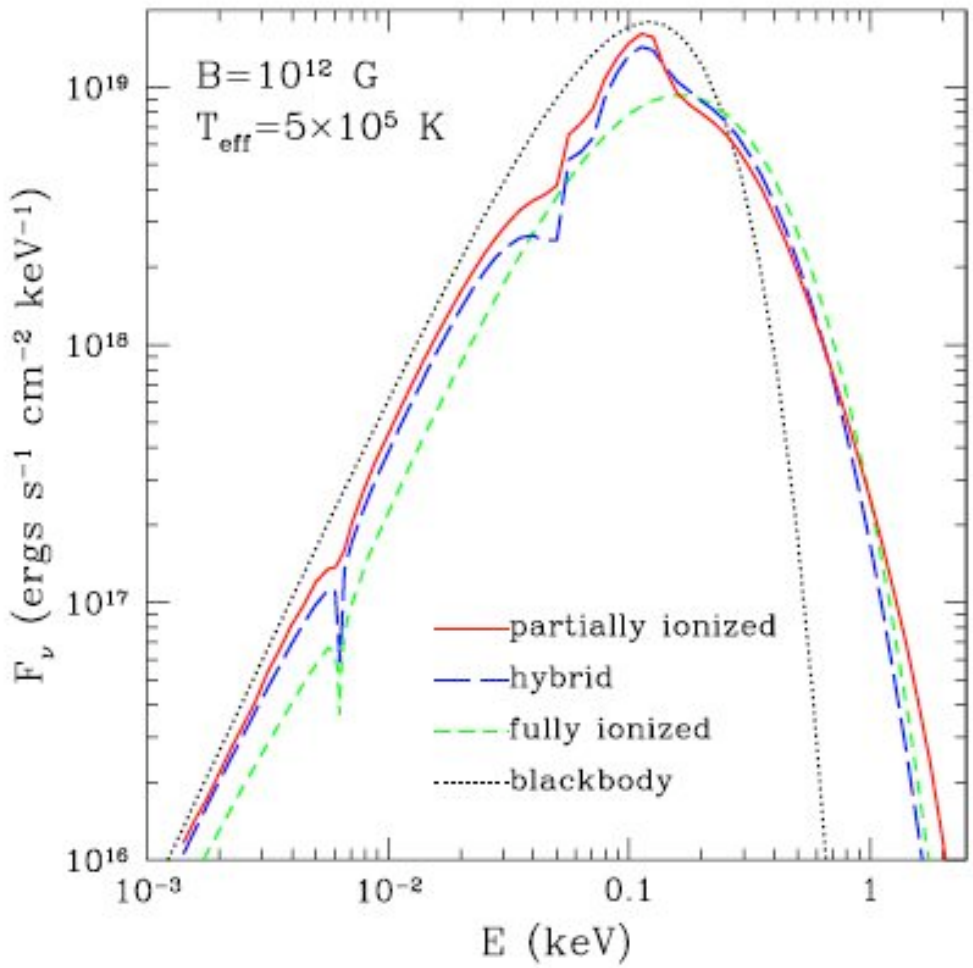
Individual photo-electron tracks are measured with a fine-spaced pixel proportional counter. The track crosses multiple pixels.

Gas filled counter can be tuned to balance length of photoelectron track and quantum efficiency



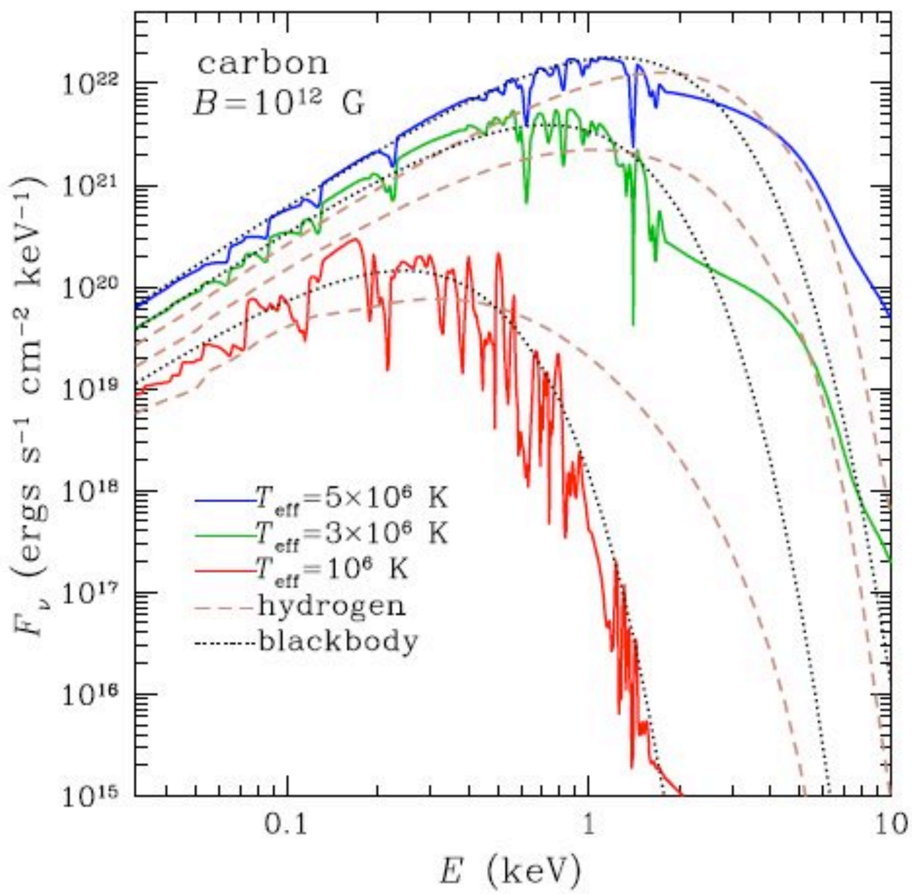
J. Swank & T. Kallman (GSFC)

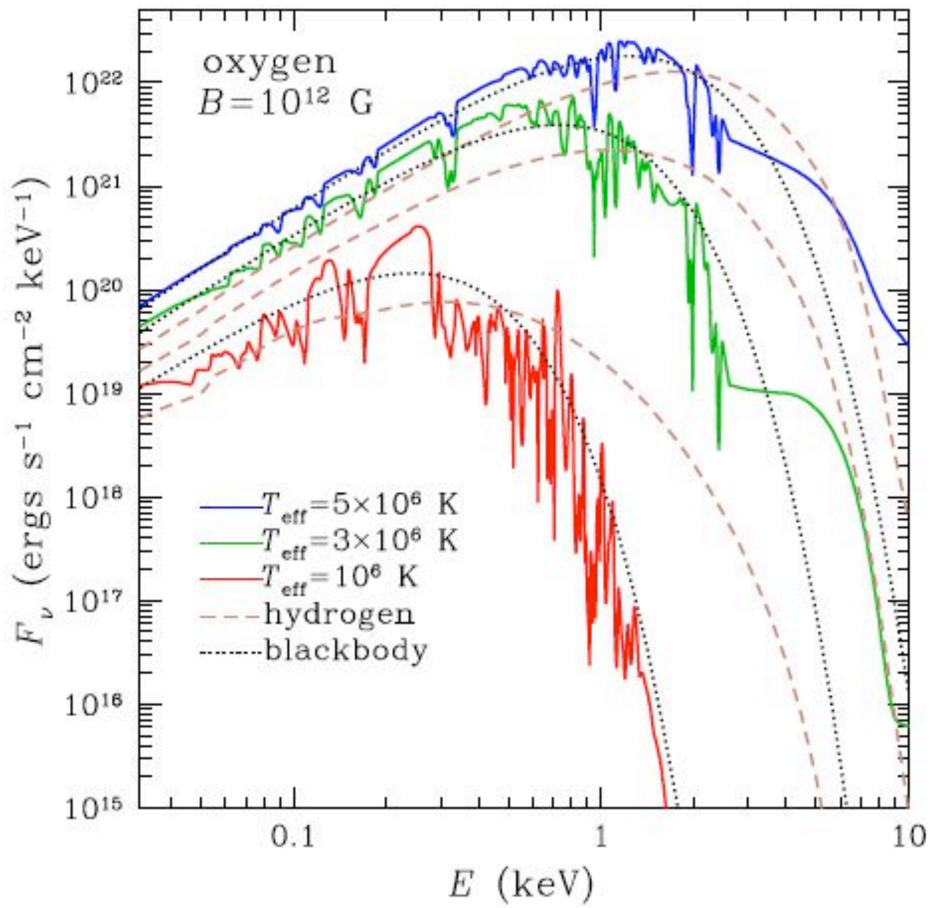
Partially Ionized magnetic H atmosphere models
with thermodynamically consistent EOS & opacities



Potekhin et al. 2004

Partially ionized C,O magnetic atmospheres





Mori & Ho 2007

Summary

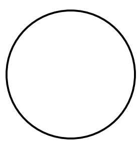
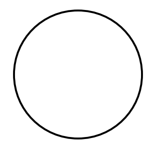
- The study of NS surface/envelope is important for understanding NS interiors ("Physics at extreme density")
- It is also important in its own right ("Physics at extreme B field"); constrain surface B etc.
- **NS crusts:** largely understood?? But
  - Impurities/defects?
  - Inner crusts: vortex/lattice coupling, nuclear pastas, …
  - Crust on top of quark star?
- Outermost layers:
  - Important for thermal emission and for magnetosphere physics
- **Matter in Strong B-Fields:**
  - Larger binding energies, molecular chains and condensed matter, dense plasma, phase transition …
  - Condensation of magnetic NS surface.
- **Radiative Transfer in Strong B-Fields:**
  - Vacuum polarization significantly affects radiative transfer
    - For $B>10^{14}$G, modify spectrum: soften hard tail; suppress spectral lines
    - For $B<10^{14}$G, negligible effect on spectrum (spectral lines possible, observed!) but dramatically affect X-ray polarization (unique signature of vacuum polarization, measurable with future X-ray polarimeters)
  - Partially ionized magnetic atmosphere models.

Landau Level Basics:

Classical → **Quantum Mechanics**

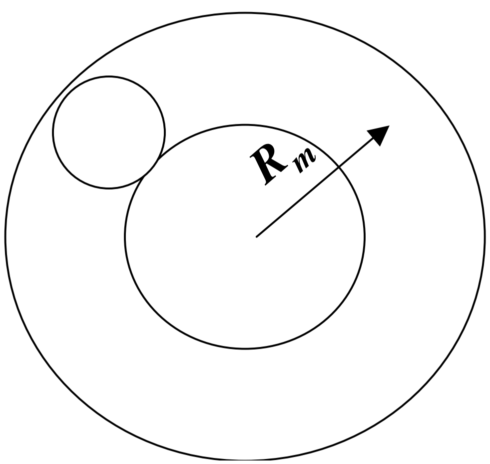
$$\frac{1}{2} m_e v^2 \longrightarrow \left(n + \frac{1}{2}\right)\hbar\omega_{ce}$$

$$R = \frac{m_e c v}{eB} \longrightarrow R_0 = \left(\frac{\hbar c}{eB}\right)^{1/2} = \frac{a_0}{b^{1/2}}$$

 → 

For b>>1, electrons settle in ground Landau level n=0

Degeneracy of Landau Level:

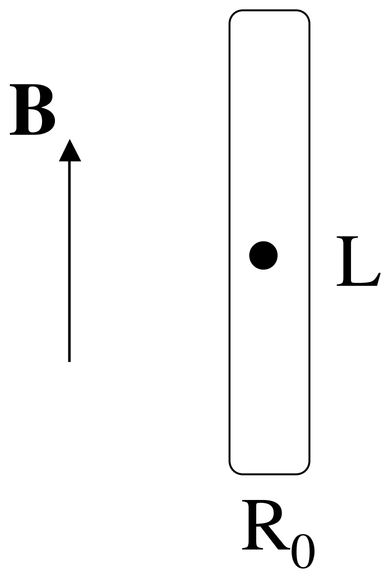


Number of states in area A is $\approx \dfrac{A}{\pi R_0^2}$

Label the states with R_m

$$R_m = (2m+1)^{1/2} R_0, \quad m = 0,1,2,\cdots$$

H Atom



$$R_0 \approx \frac{a_0}{b^{1/2}}, \quad L \approx \frac{a_0}{\ln b}$$

$$E \cong -0.16\,(\ln b)^2\,(a.u.)$$

E.g. $|E|$=160 eV at 10^{12}G

=540 eV at 10^{14}G

Excitations: (1) displace the electron guiding center

$$R_0 \;\rightarrow\; R_m = (2m+1)^{1/2} R_0 \qquad m = 0,1,2,\ldots$$

$$\Rightarrow E_m \cong -0.16\left(\ln\frac{b}{2m+1}\right)^{1/2}(a.u.)$$

Closely packed levels around ground state

(2) Weakly bound: $\nu>0$

Heavy Atoms

Filling in (m,ν) orbitals

Calculations:

Hartree-Fock
Density functional theory

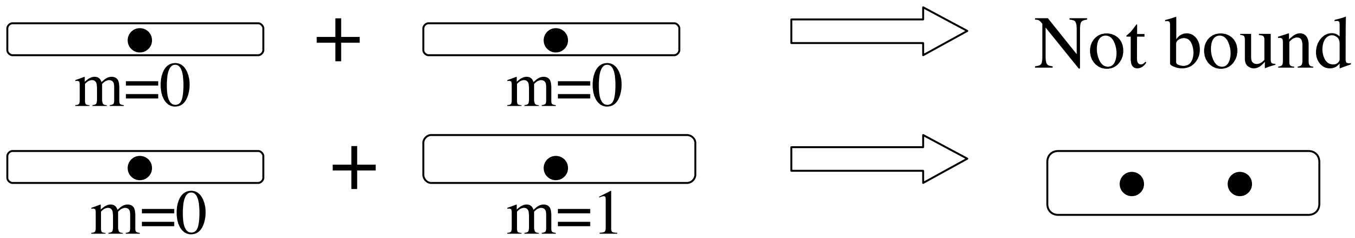
Unsolved Problem: Effect of Finite Ion Mass

- Coupling between internal structure and CM motion
- Even for stationary atom:

  H atom: $+ m E_{cp} = 630\ m\ B_{14}$ eV
- Not solved for Z>1 atoms

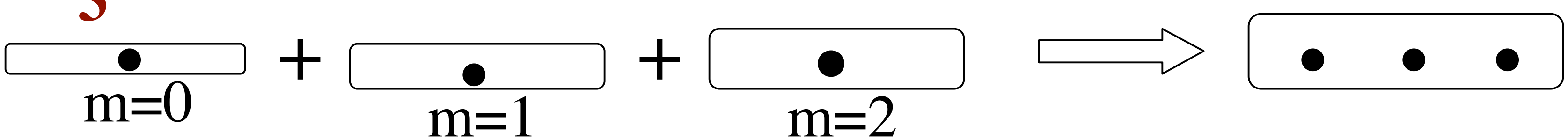
H_2 Molecule

Bonding mechanism very different from B=0 case



E.g. Dissociation energy: 40 eV at 10^{12}G
350 eV at 10^{14}G

H_3



H_4, H_5 · · · ·

Calculations: Hartree-Fock (with multi-configurations); Density-functional

Molecules of Heavy Elements

Fe_2 and Fe_3 are bound (relative to Fe) only for $B > 10^{14}$ G (Z. Medin)

Condensed Matter

As n increases, $|E_n|/n$ of H_n saturates ⟶ **1D chain**

Placing parallel chains together (in body-centered tetragonal lattice)

⟶ **3D condensed matter**

Basic scaling: Consider uniform electron gas in a lattice of ions (Z,A)

Energy per Wigner-Seitz cell (of radius R) is

$$E \sim Z^3/(b^2R^6) - Z^2/R$$

Minimizing E with respect to R ⟶

Binding Energy per cell $|E| \sim Z^{9/5}\, b^{2/5}$

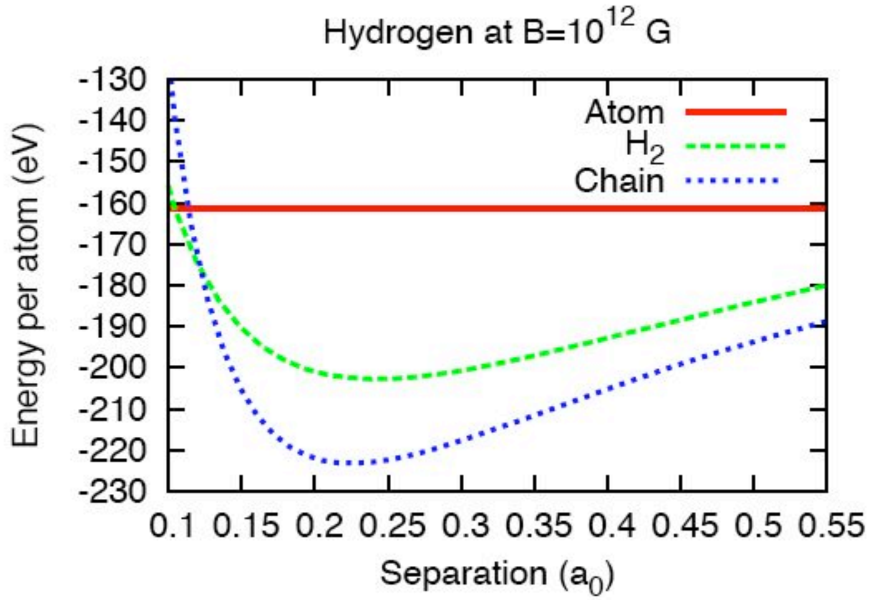
Radius of cell $R \sim Z^{1/5}\, b^{-2/5}$

⟶ Zero-pressure density $\approx 10^3\, AZ^{3/5} B_{12}^{6/5}$ g cm^{-3}

Quantitative Calculations of 1D Chain:
Band structure, density functional theory

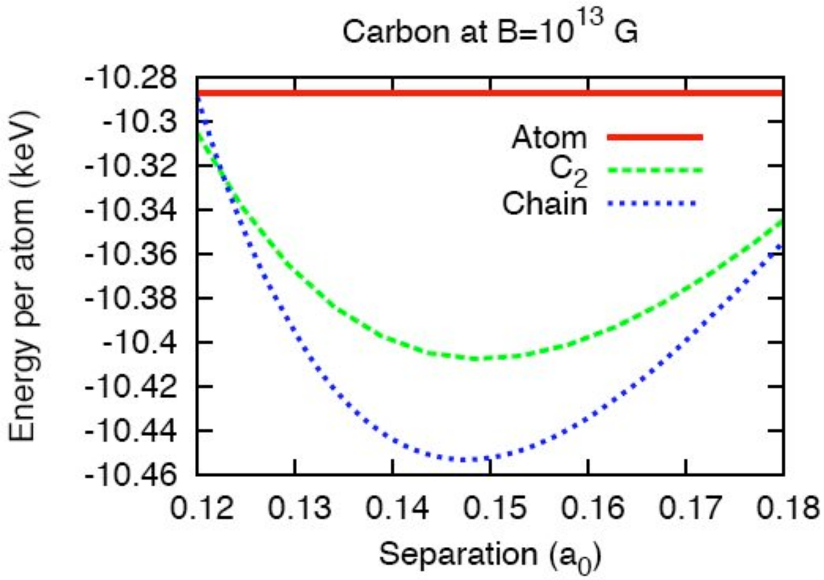
For H: 1D chain is bound relative to H atom for $B > 10^{11}$ G

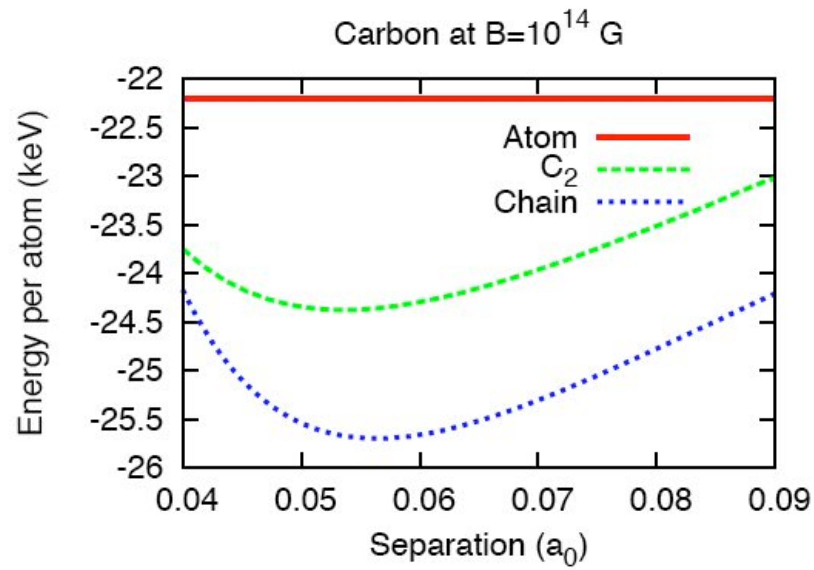
(How about Peierls instability? Dimer state?)

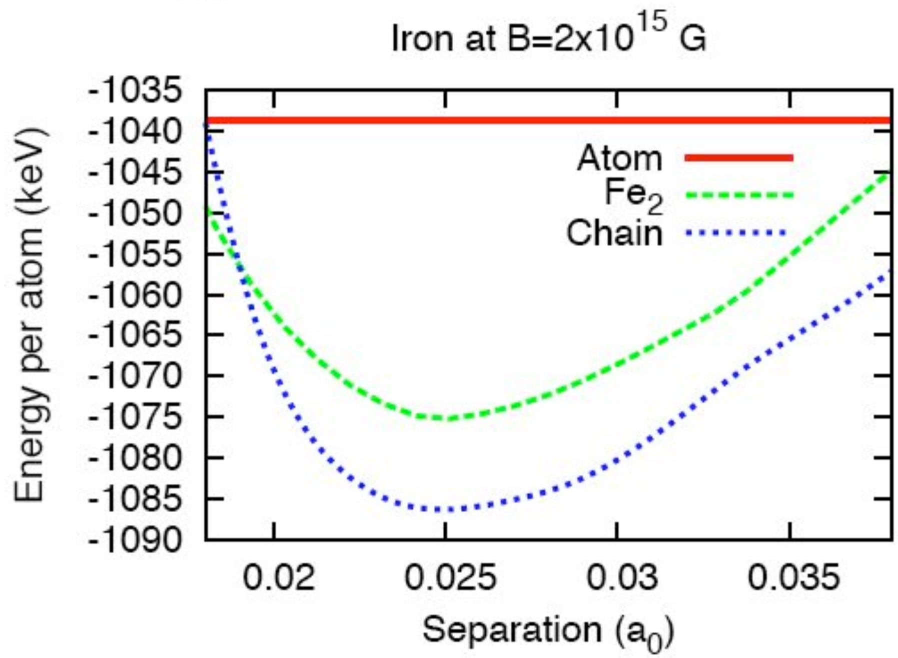


For heavy elements: require higher B

Density functional calculation of 1D condensed matter







Unsolved Problem:
Electron-Ion emission of condensed matter

Important for: charge supply to magnetosphere; polar gap accelerator …

- Electron emission (thermionic emission): depends on W
- Ion emission (evaporation):

  Energy barrier $E_B = E_{coh} + I - Z\,W$

  Emission rate per surface "atom" $\sim \omega_{vib} \exp(-E_B/kT)$?

  ω_{vib}=? Debye frequency (~ ion plasma freq)

  ion cyclotron frequency

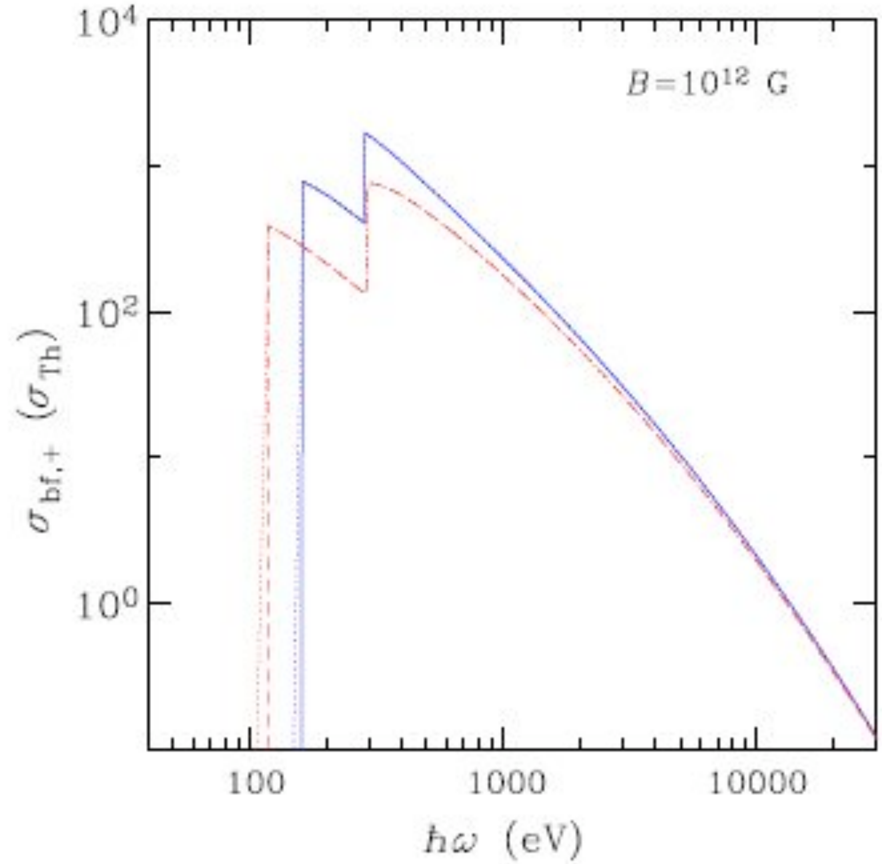


Figure 4. Total cross section σ_+ versus photon energy for helium photoionization, from initial states $(m_1, m_2) = (1, 0)$ (solid lines) and $(2, 0)$ (dashed lines). The field strength is 10^{12} G. The dotted lines extending from each cross section curve represent the effect of magnetic broadening on these cross sections, as approximated in Eq. (54), for $T = 10^6$ K.

Medin,DL & Potekhin 2007