Atmospheres and radiating surfaces of neutron stars with strong magnetic fields

Alexander Y. Potekhin

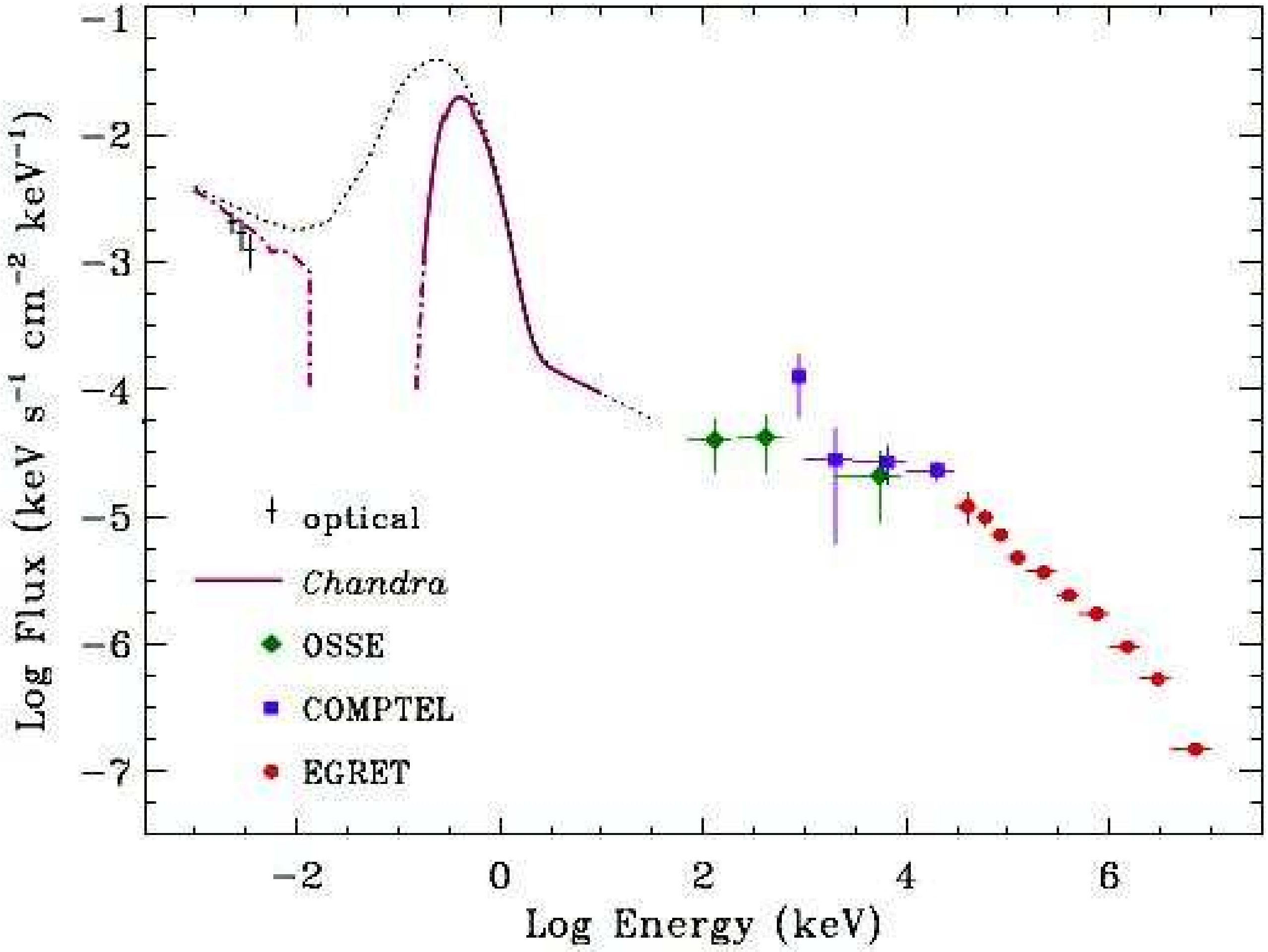
[1]*Ioffe Physical-Technical Institute, St.Petersburg*
[2]*Central Astronomical Observatory at Pulkovo*
[3]*CRAL, Ecole Normale Supérieure de Lyon*

Outline:

Introduction
1. Atmospheres: EOS, opacities, spectra
2. Radiation from condensed surface and symbiotic models
3. Applications to inerpretation of observations

Conclusions

Typical multiwavelength spectrum of an isolated neutron star

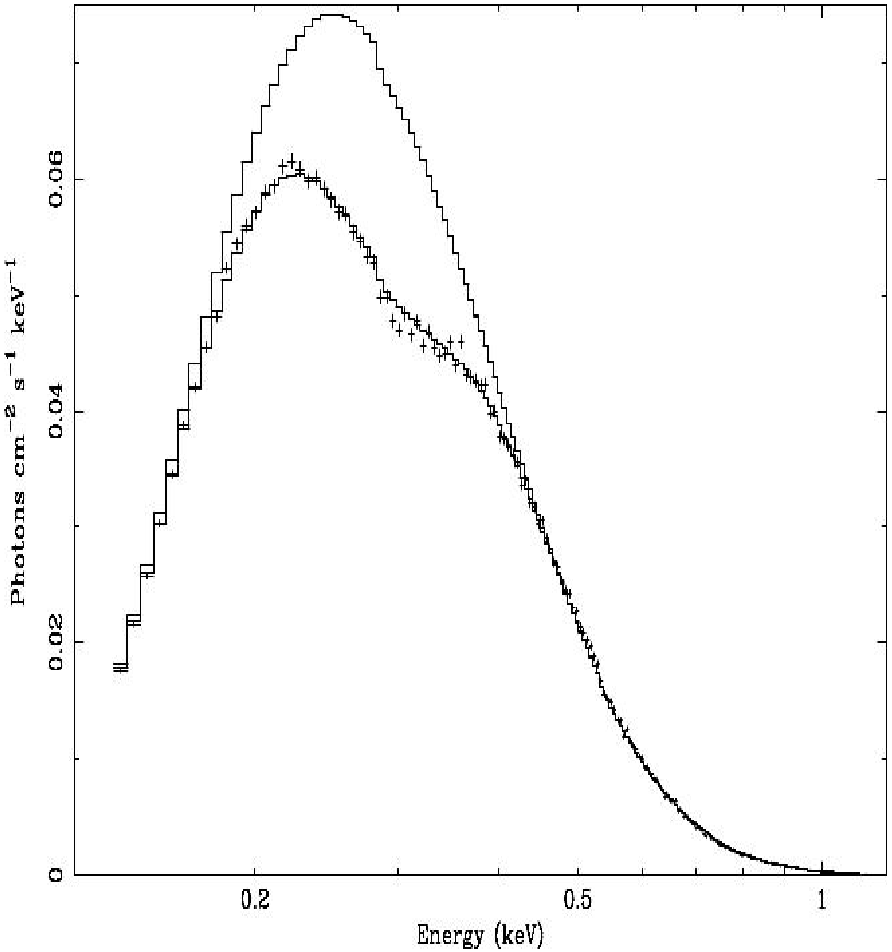


Multiwavelength spectrum of the Vela pulsar

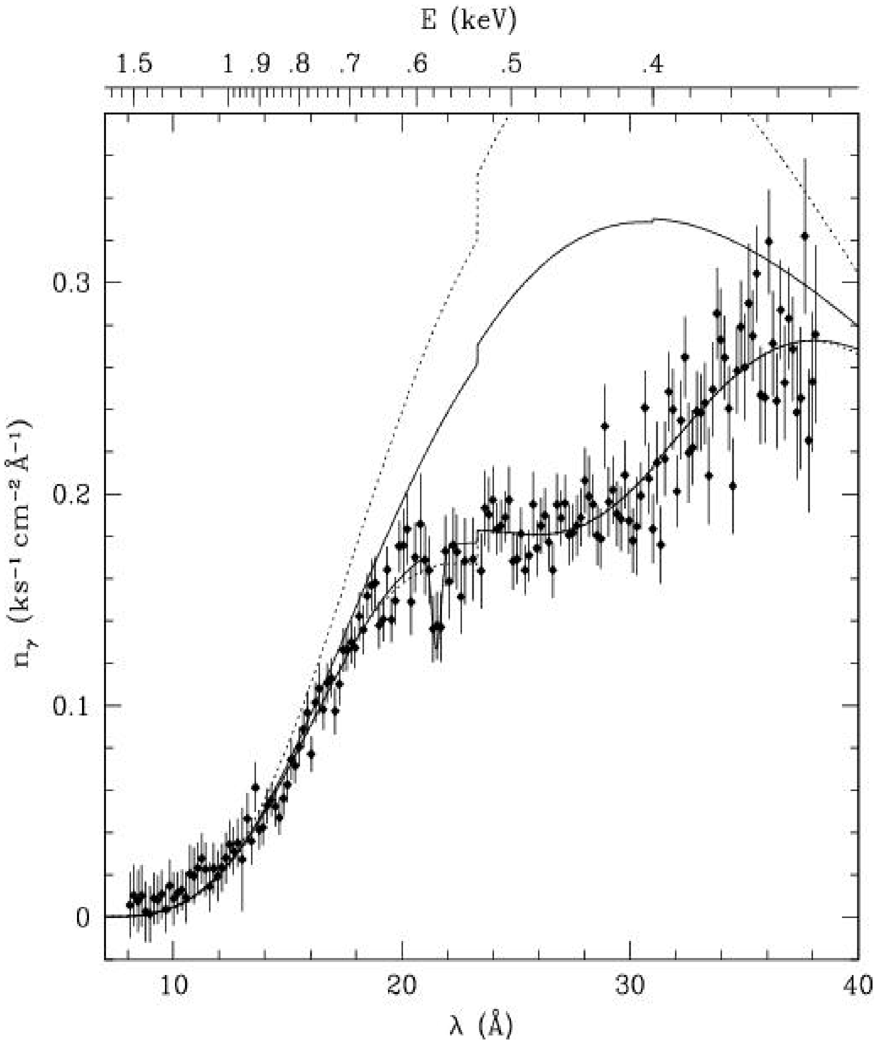
G.G.Pavlov, V.E.Zavlin, & D.Sanwal (2002) in *Neutron Stars, Pulsars, and Supernova Remnants*, ed. W.Becker, H.Lesch, & J.Trümper, *MPE Report* **278**, 273

Absorption features in spectra of isolated neutron stars

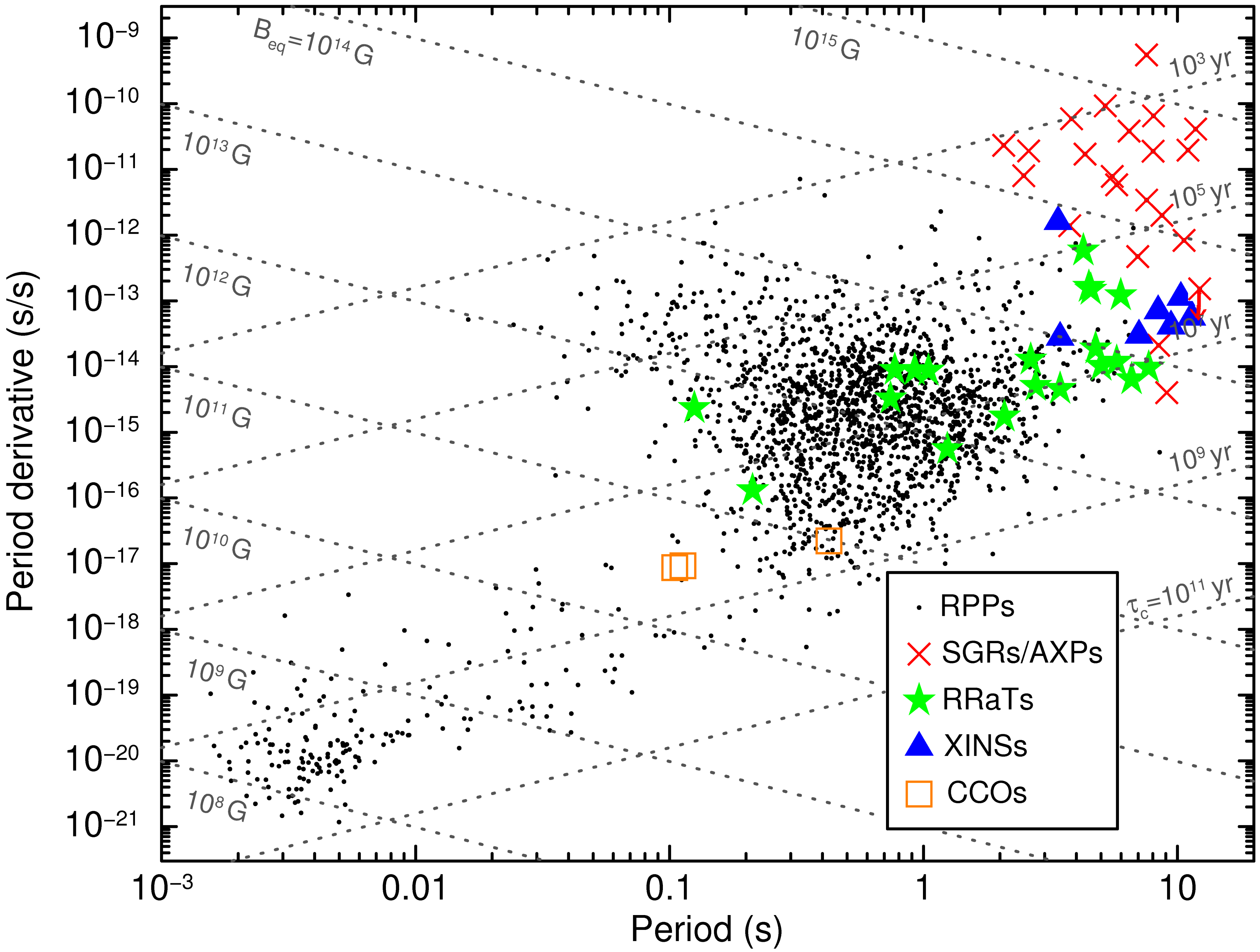
Examples for XDINSs



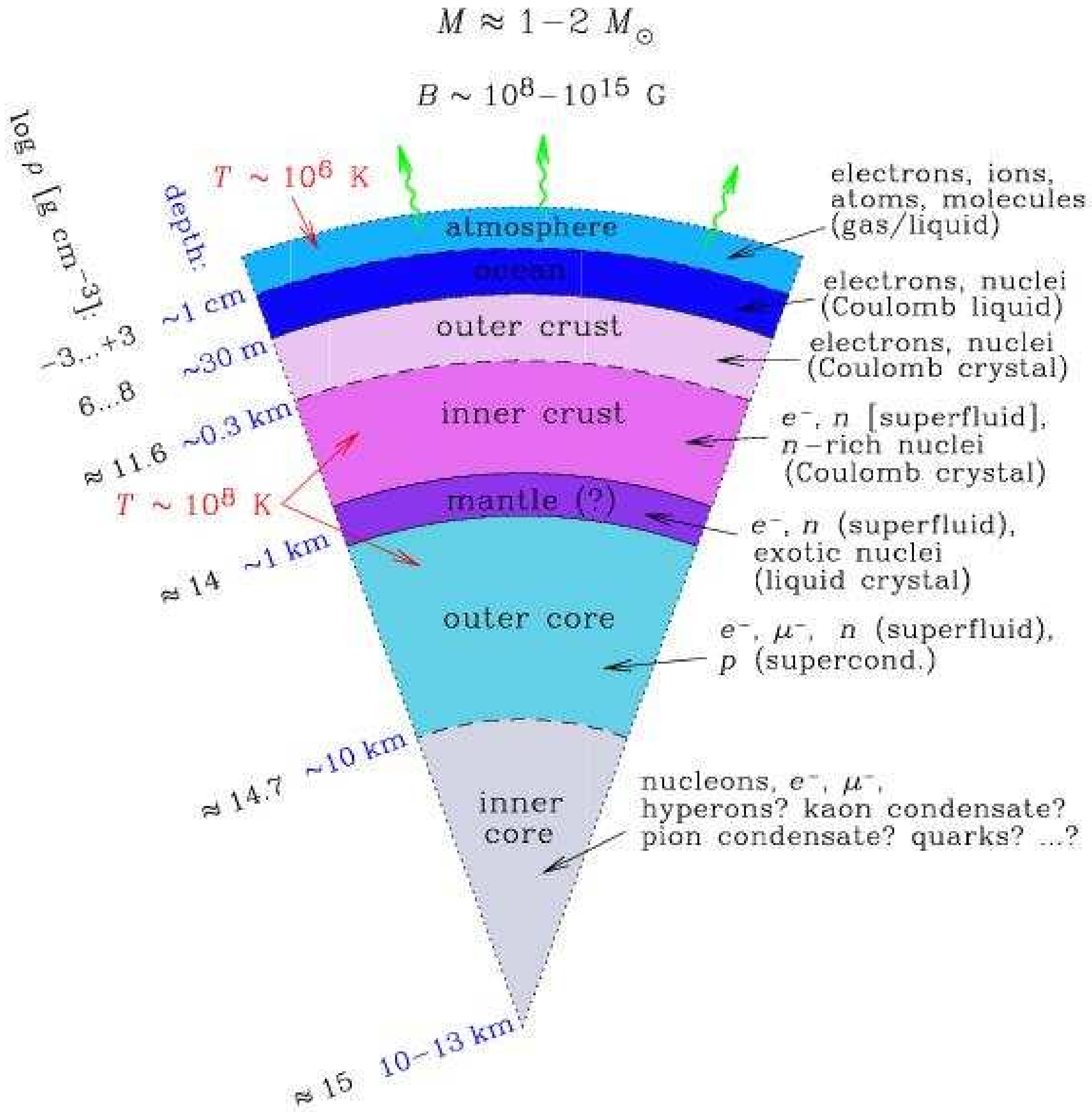
Haberl *et al*. (2004) *A&A* **419**, 1077:
absorption line in RX J0720.4–3125



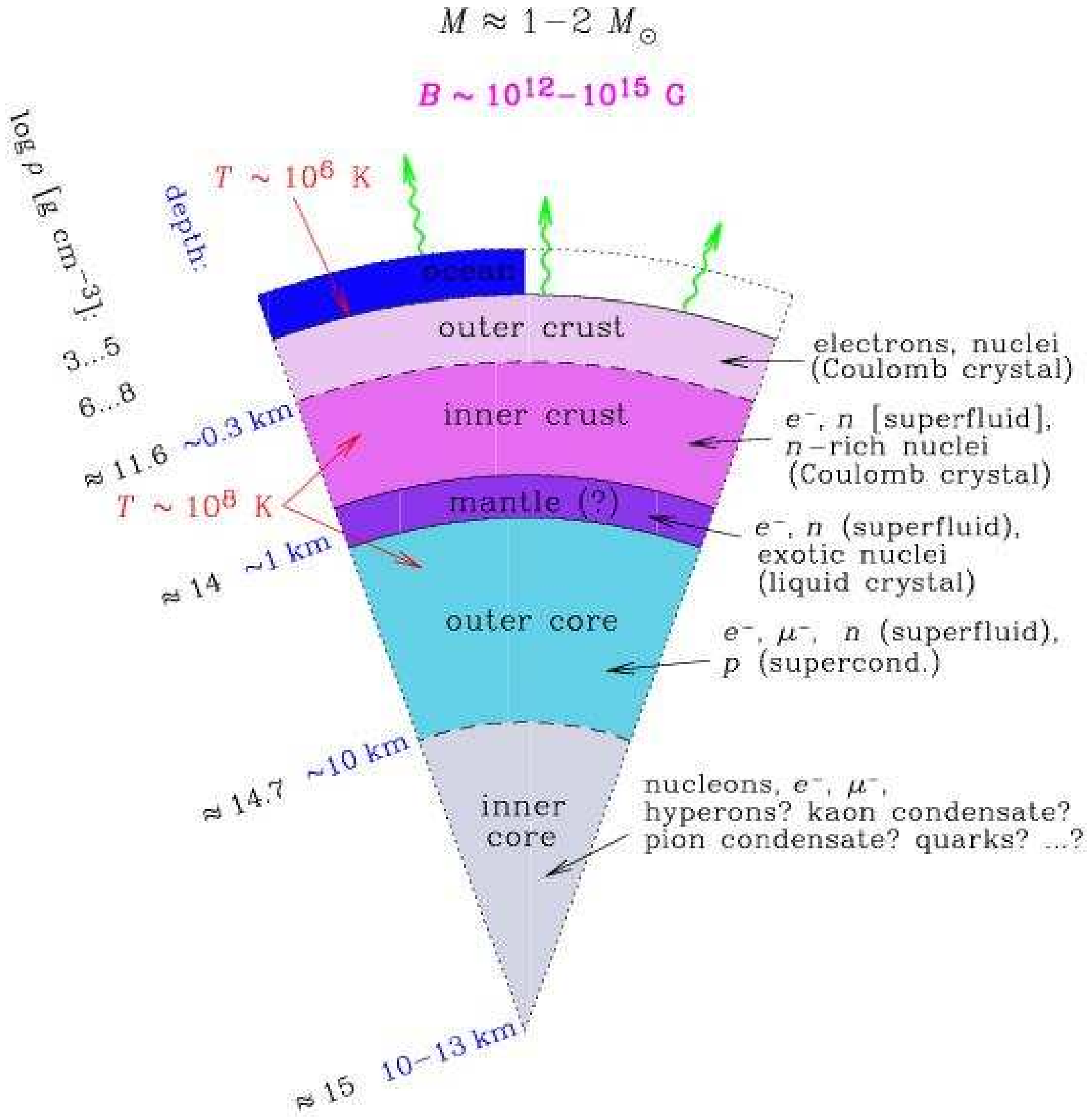
van Kerkwijk *et al*. (2004) *ApJ* **608**, 432:
absorption line in RX J1605.3+3249


$B_{eq}=10^{14}$ G
10^{15} G
10^{13} G
10^{12} G
10^{11} G
10^{10} G
10^{9} G
10^{8} G
10^{3} yr
10^{5} yr
10^{7} yr
10^{9} yr
$\tau_c=10^{11}$ yr
RPPs
SGRs/AXPs
RRaTs
XINSs
CCOs
Period derivative (s/s)
Period (s)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-3}
0.01
0.1
1
10

Neutron star structure



Neutron star without atmosphere: possible result of a phase transition



Characteristic values of the magnetic field

Strong magnetic field B:

$$E_{\mathrm{ce}}=\hbar\omega_{\mathrm{ce}} = \hbar eB/m_{\mathrm{e}}c = 115.77\ B_{13}\ \mathrm{keV} > 1\ \mathrm{a.u.} = 0.02721\ \mathrm{keV}$$

$$B > m_{\mathrm{e}}^2 ce^3/\hbar^3 = 2.35 \times 10^9\ \mathrm{G}$$

Superstrong field:

$$E_{\mathrm{ce}} > m_{\mathrm{e}}c^2$$

$$B > me^2c^3/e\hbar = 4.4 \times 10^{13}\ \mathrm{G}$$

Strongly quantizing magnetic field:

$$\rho < \rho_B = m_{\mathrm{ion}} n_B\, A/Z \approx 2.2 \times 10^5\ B_{13}^{3/2}\ (A/Z)\ \mathrm{g\ cm^{-3}}$$

$$T << T_B = \hbar\omega_{\mathrm{ce}} / k_{\mathrm{B}} \approx 1.3 \times 10^9\ B_{13}\ \mathrm{K}$$

Quantizing magnetic field for ions:

$$E_{\mathrm{ci}} = \hbar\omega_{\mathrm{ci}} = 0.06351\ B_{13}\ \mathrm{keV},$$

$$E_{\mathrm{ci}}/k_{\mathrm{B}} \approx 7.37 \times 10^5\ (Z/A)\ B_{13}\ \mathrm{K}$$

Atmospheres: general

Standard methods – D.Mihalas (1978) *Stellar Atmospheres*

General algorithm - solution of coupled equations:

- Hydrostatic equilibrium
- Energy balance
- Radiative transfer

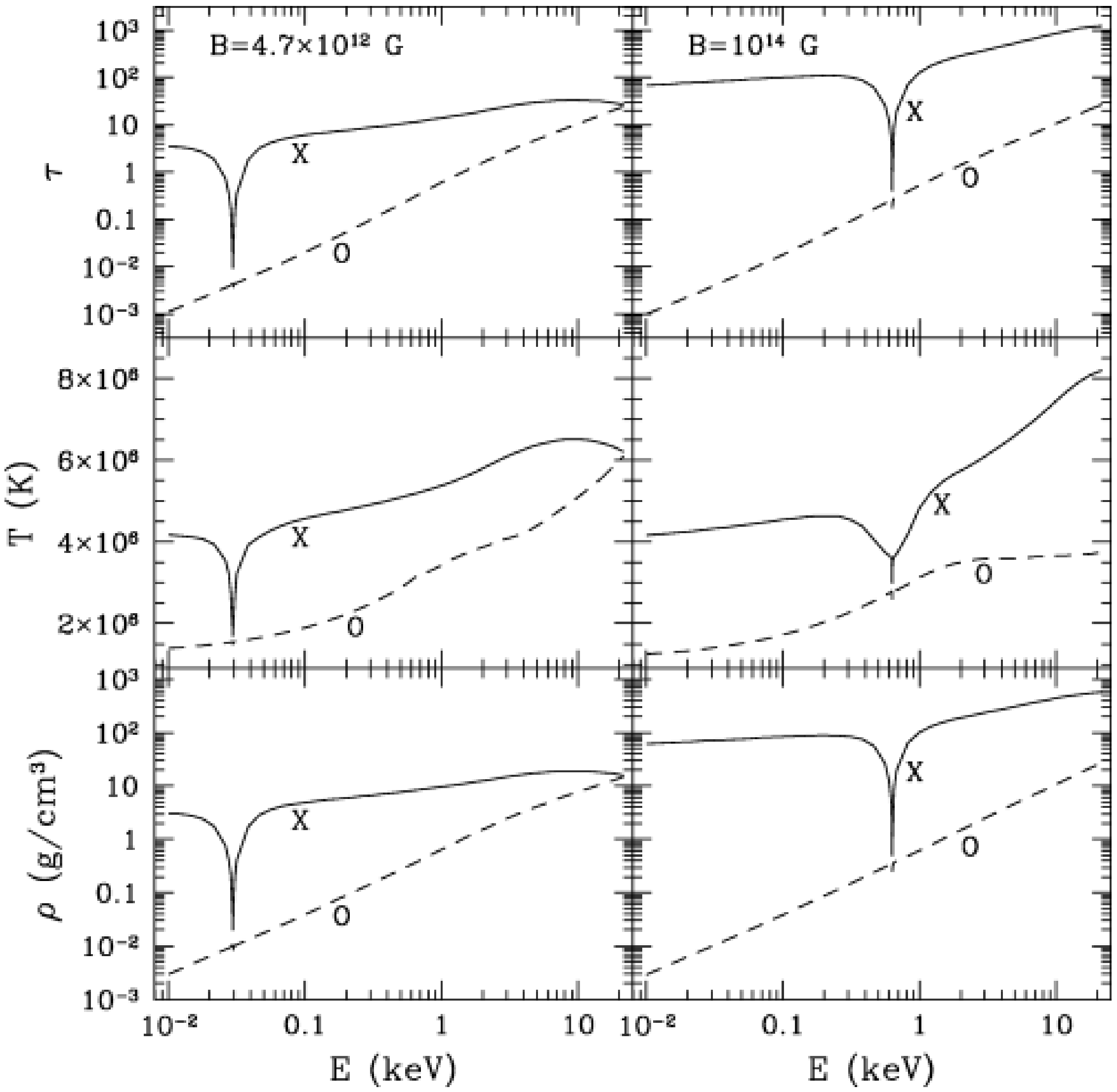
Basic ingredients:

- Equation of state
- Radiative opacities

This generally requires:

- Atomic and molecular data (binding energies, cross sections)
- Ionization and dissociation equilibrium
- Thermodynamic quantities
- Treatment of plasma effects (line broadening, pressure ionization, etc.)

Fully ionized neutron star atmospheres with strong magnetic fields



Yu.Gnedin,
G.G.Pavlov,
Yu.A.Shibanov,
A.D.Kaminker,
D.G.Yakovlev,
(1970s – 1980s)

V.E.Zavlin,
Yu.A.Shibanov,
G.G.Pavlov,
J.Ventura
(1990s)

S.Zane & R.Turolla,
W.C.G.Ho & D.Lai
(2000s)

Bottom of the atmosphere for X- and O-modes of polarization in strong magnetic fields

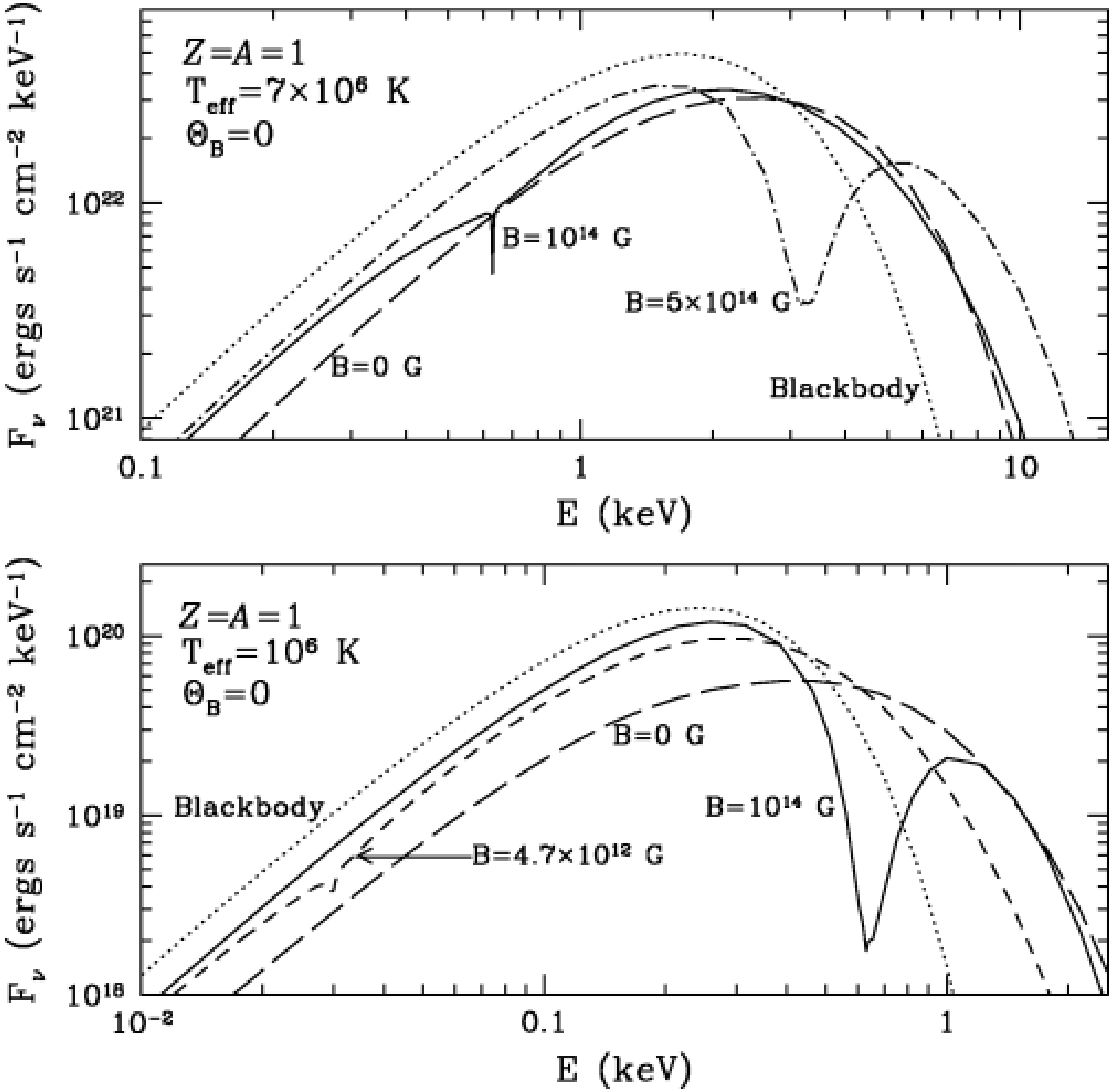
Ho & Lai (2001) *MNRAS* **327**, 1081

Fully ionized neutron star atmospheres with strong magnetic fields

Yu.Gnedin,
G.G.Pavlov,
Yu.A.Shibanov,
A.D.Kaminker,
D.G.Yakovlev,
(1970s – 1980s)

V.E.Zavlin,
Yu.A.Shibanov,
G.G.Pavlov,
J.Ventura
(1990s)

S.Zane & R.Turolla,
W.C.G.Ho & D.Lai
(2000s)

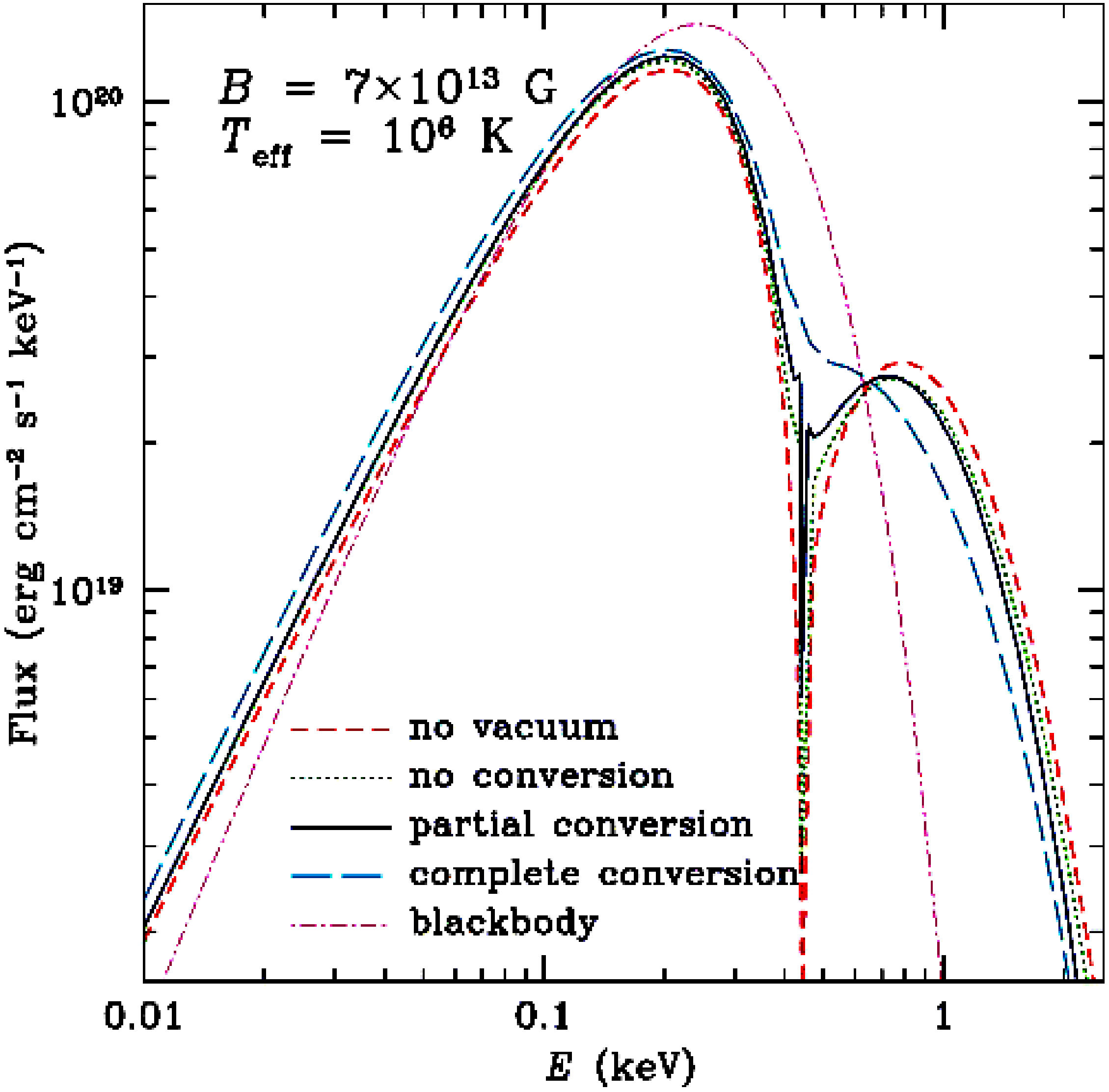


Comparison of spectra for non-magnetic and magnetic H atmospheres

W.C.G.Ho & D.Lai (2001) *MNRAS* **327**, 1081

The effect of vacuum polarization

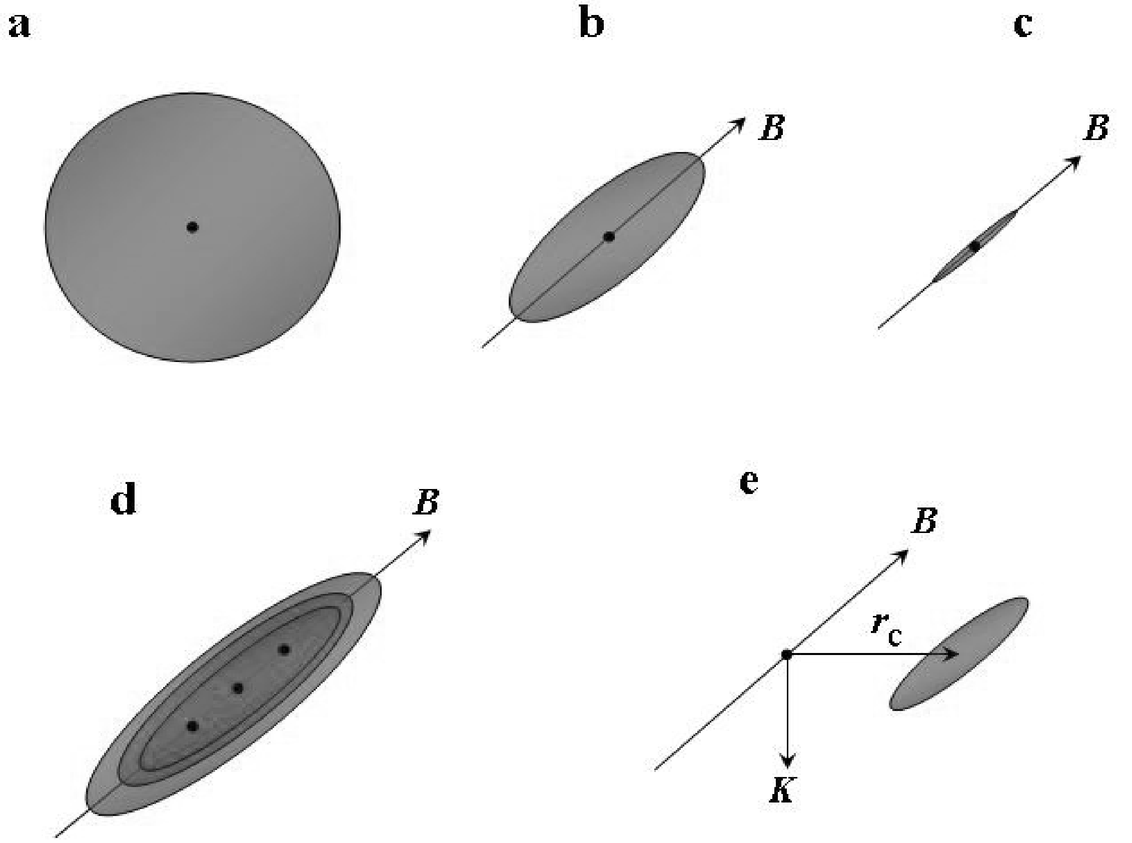
Yu.N.Gnedin & G.G.Pavlov
(1970s – 1984)



Ho & Lai (2003) *MNRAS* **338**, 233

van Adelsberg & Lai (2007)
MNRAS **373**, 495

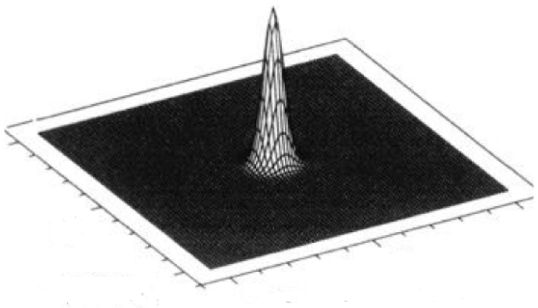
Bound species in a strong magnetic field



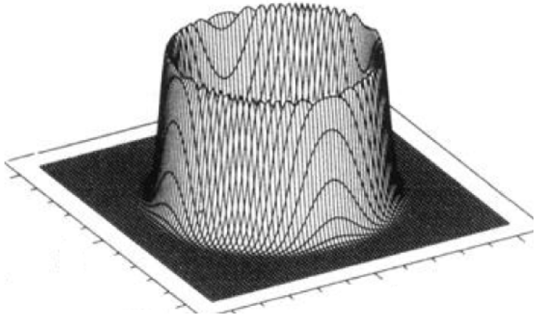
The effects of a strong magnetic field on the atoms and molecules.
a–**c**: H atom in the ground state (**a**: B<<10^9 G, **b**: B~10^{10} G, **c**: B~10^{12} G).
d: The field stabilizes the molecular chains (H_3 is shown).
e: H atom moving across the field becomes decentered.

non-moving atom

ground state

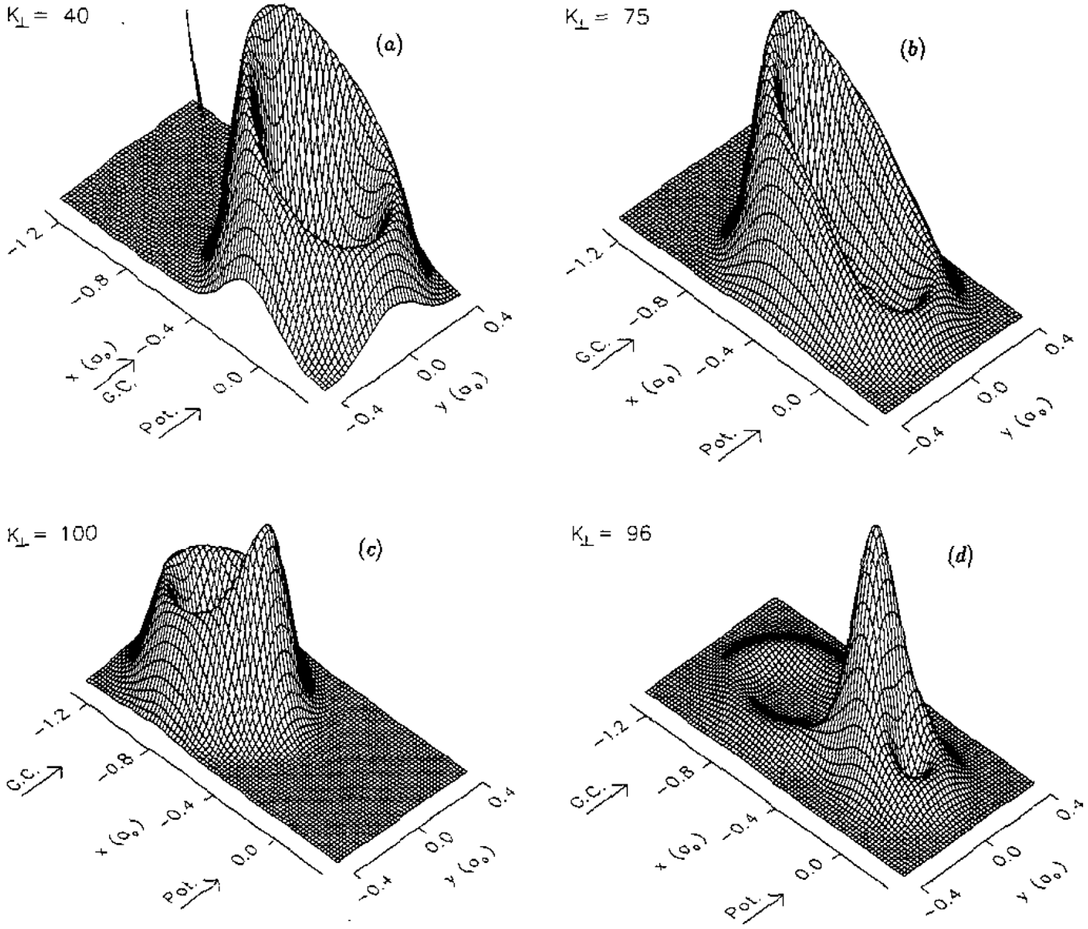


excited state *m* = –5



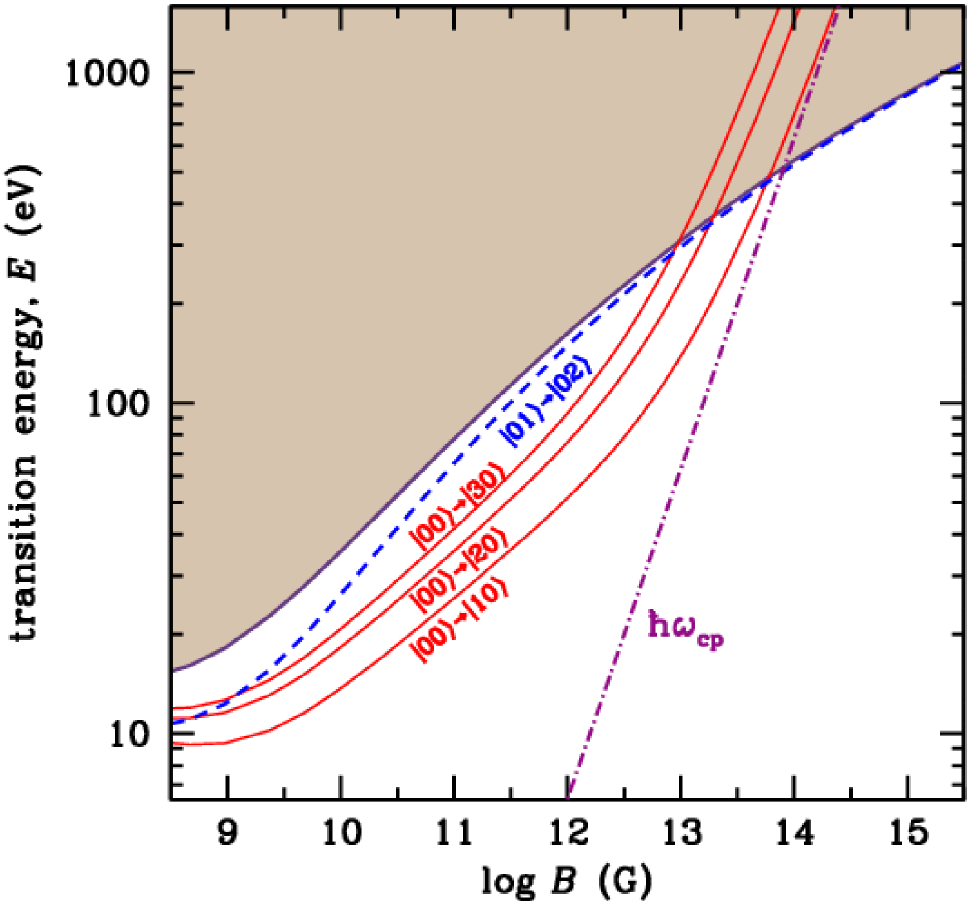
moving atom

excited state (*m* = –5) + motion



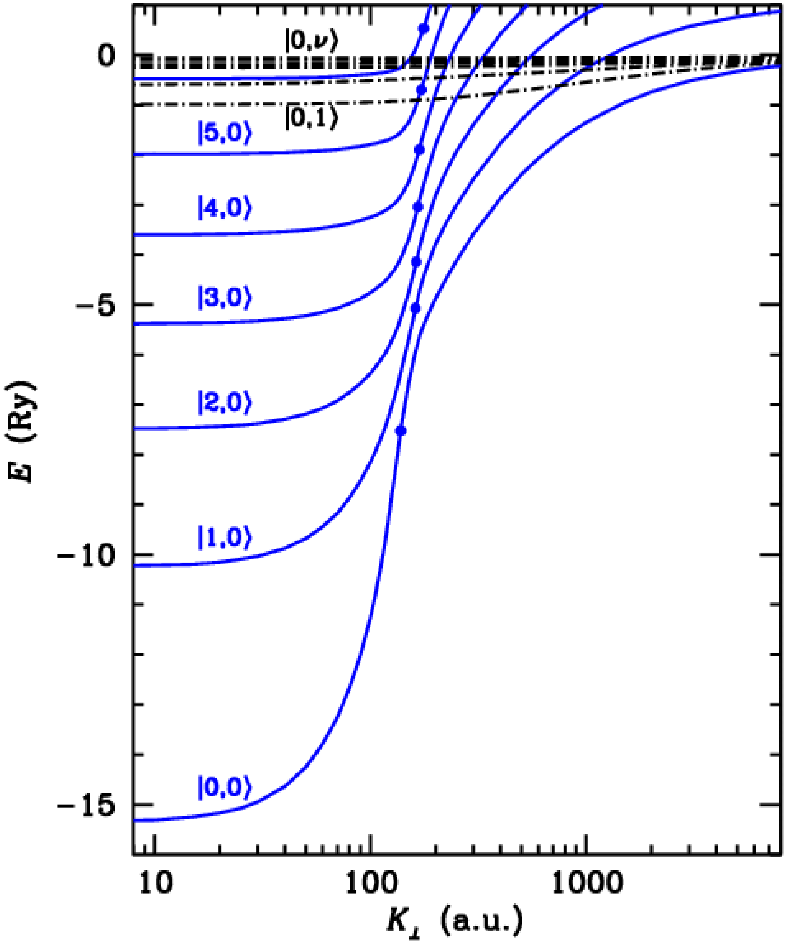
Square moduli of a non-moving and moving H atom in B=2.35x10^{11} G, in the field-perpendicular plane.

Bound-bound transitions of H atom in strong magnetic field

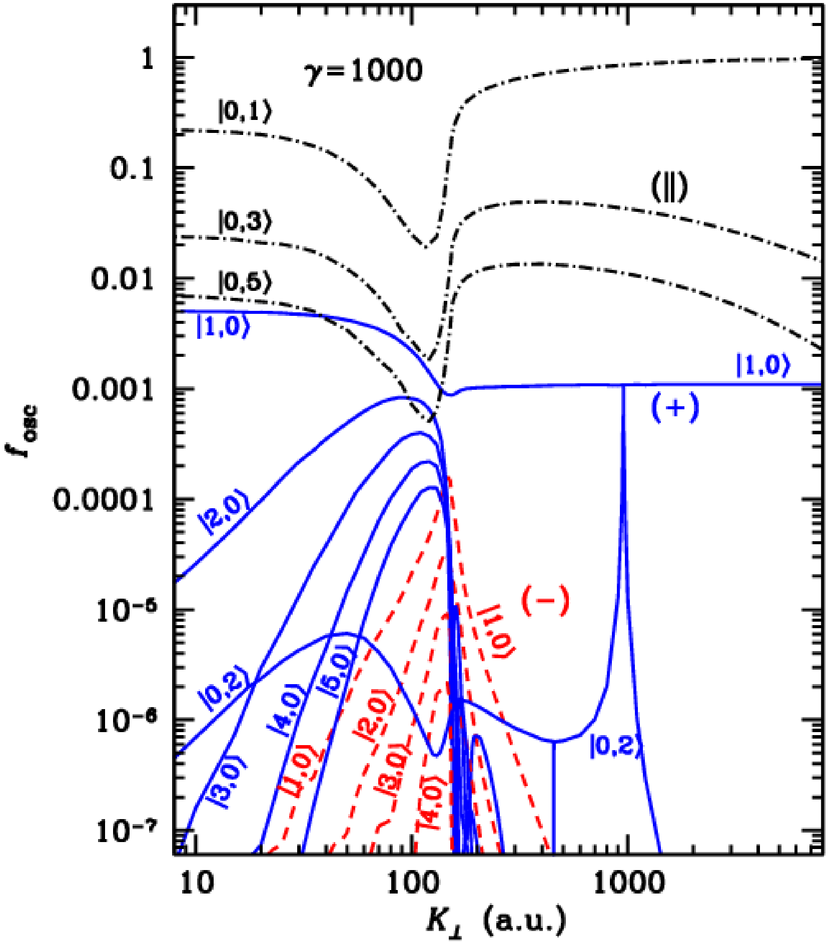


Main transition energies of the hydrogen atom in a magnetic field
[AYP & Chabrier (2004) *ApJ*, **600**, 317]

Bound-bound transitions in strong magnetic field

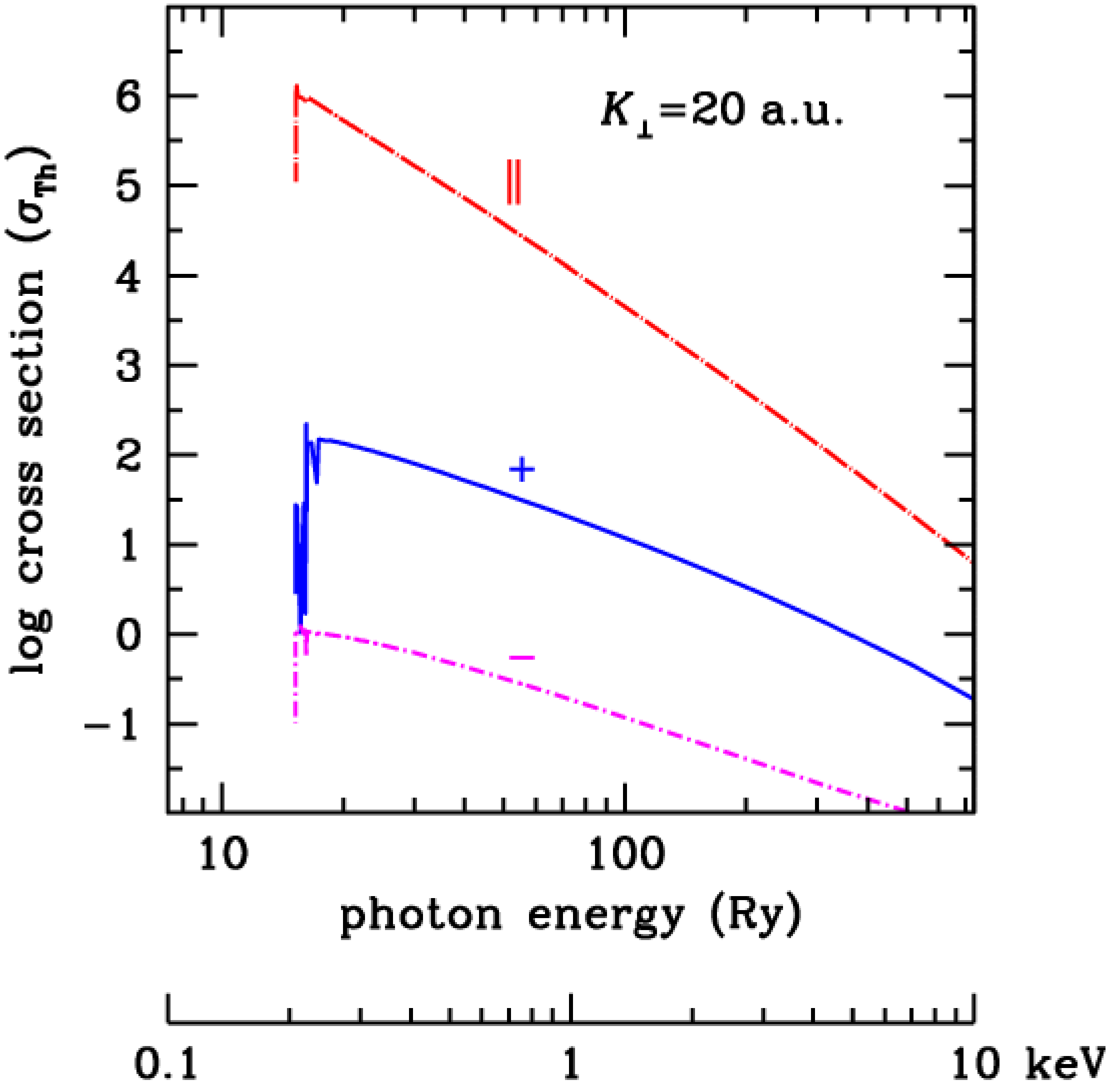


Binding energies of the hydrogen atom in the magnetic field $B=2.35\times10^{12}$ G as functions of its state of motion across the field



Oscillator strengths for transitions between the ground and excited levels of the hydrogen atom at $B=2.35\times10^{12}$ G, as functions of pseudomomentum

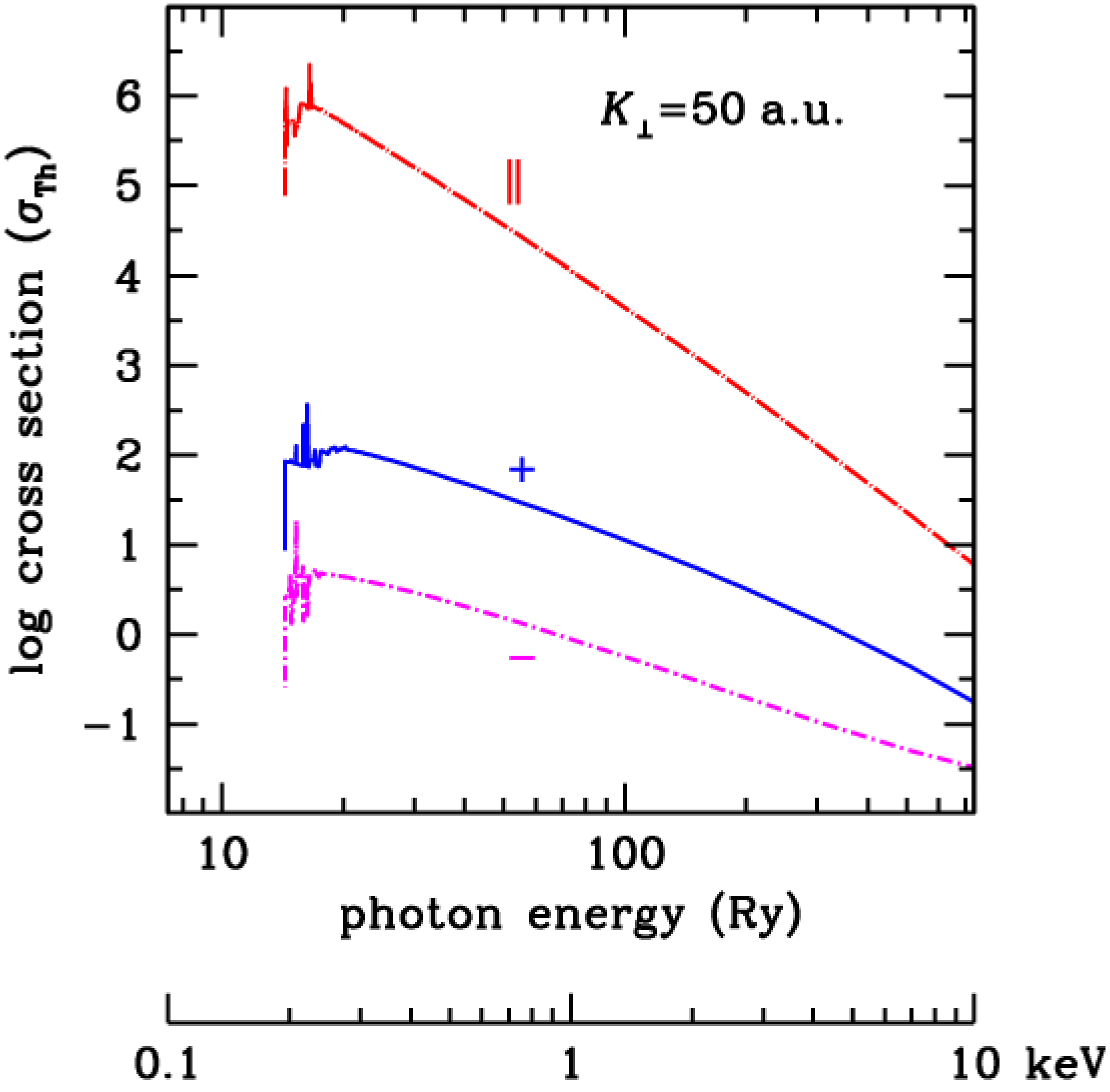
Bound-free transitions of H atom in strong magnetic field



Photoionization cross sections for the ground-state H atom at B=2.35x10^{12} G

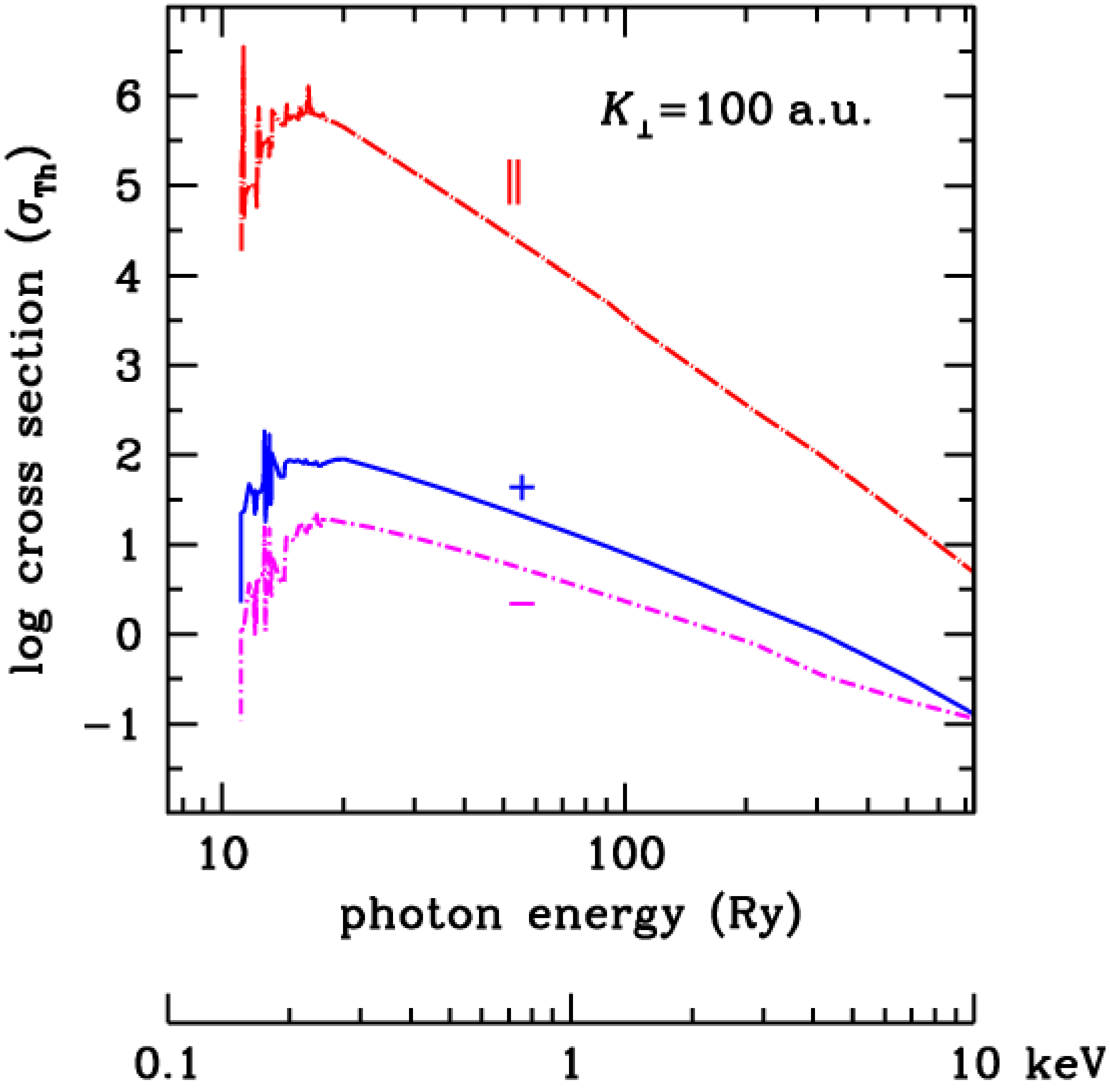
[AYP & Pavlov (1997) *Astrophys. J.* **483**, 414]

Bound-free transitions of H atom in strong magnetic field



Photoionization cross sections for the ground-state H atom at B=2.35x10^{12} G
[AYP & Pavlov (1997) *Astrophys. J.* **483**, 414]

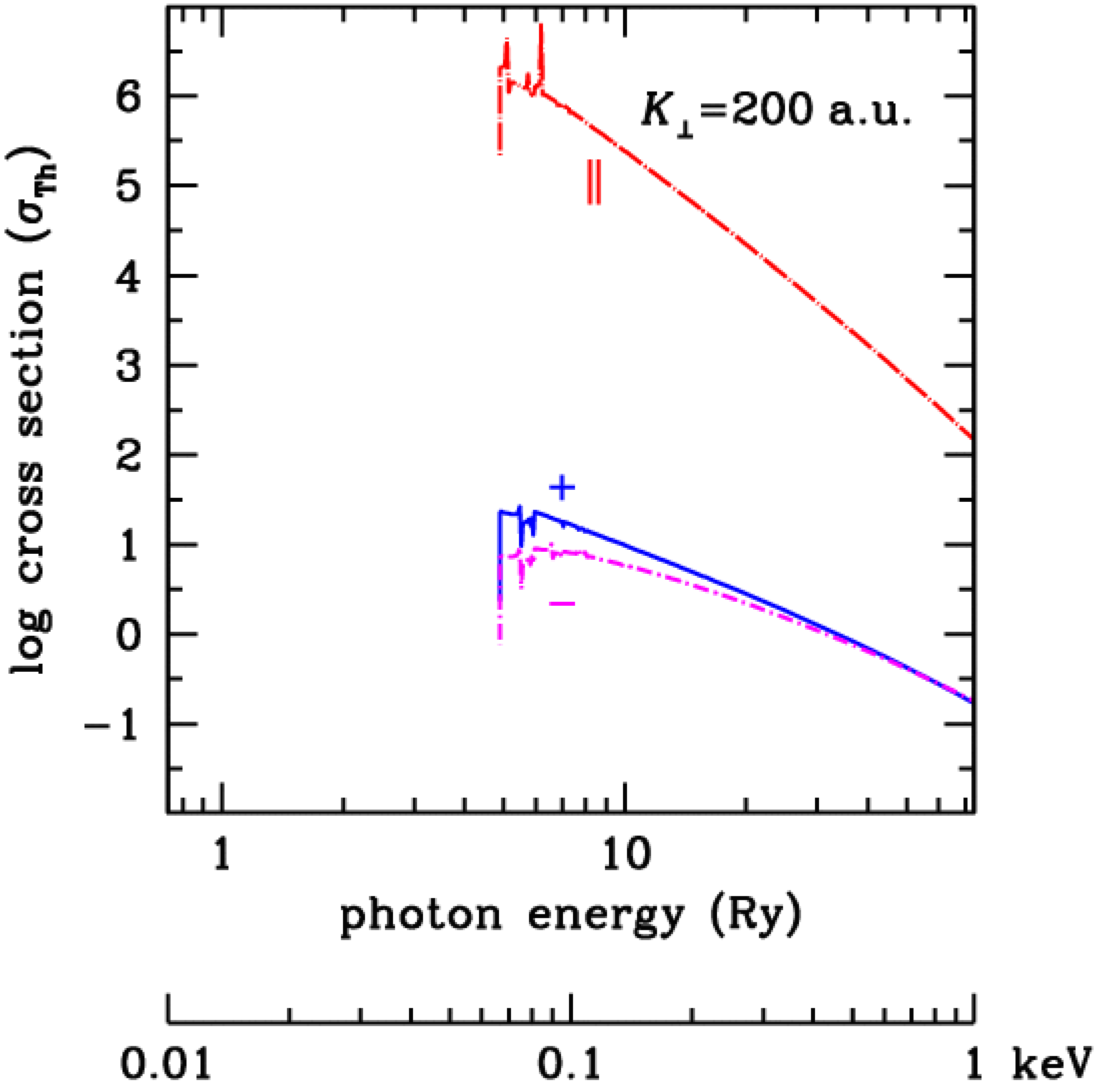
Bound-free transitions of H atom in strong magnetic field



Photoionization cross sections for the ground-state H atom at B=2.35x10^{12} G

[AYP & Pavlov (1997) *Astrophys. J.* **483**, 414]

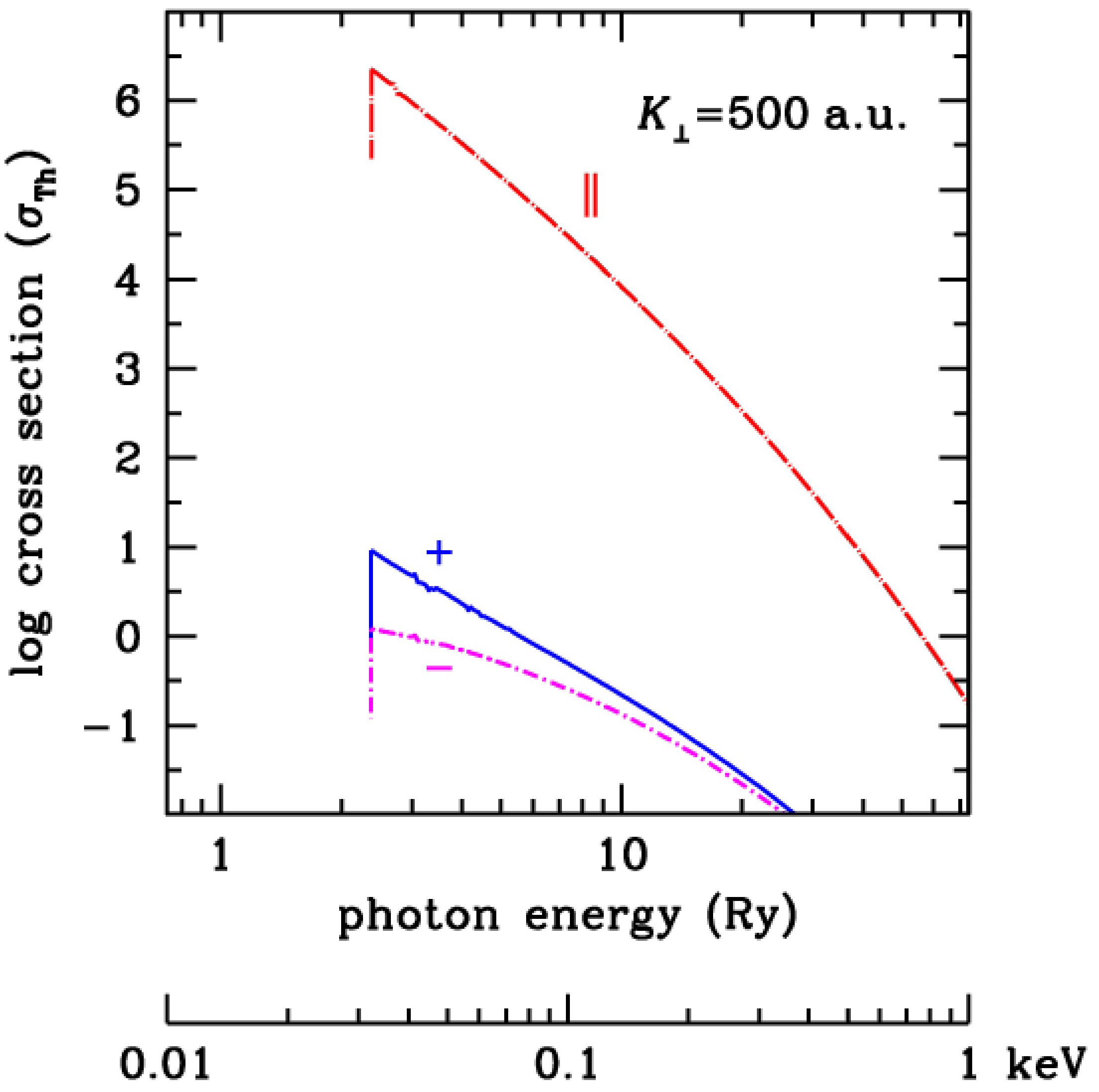
Bound-free transitions of H atom in strong magnetic field



Photoionization cross sections for the ground-state H atom at B=2.35×10^{12} G

[AYP & Pavlov (1997) *Astrophys. J.* **483**, 414]

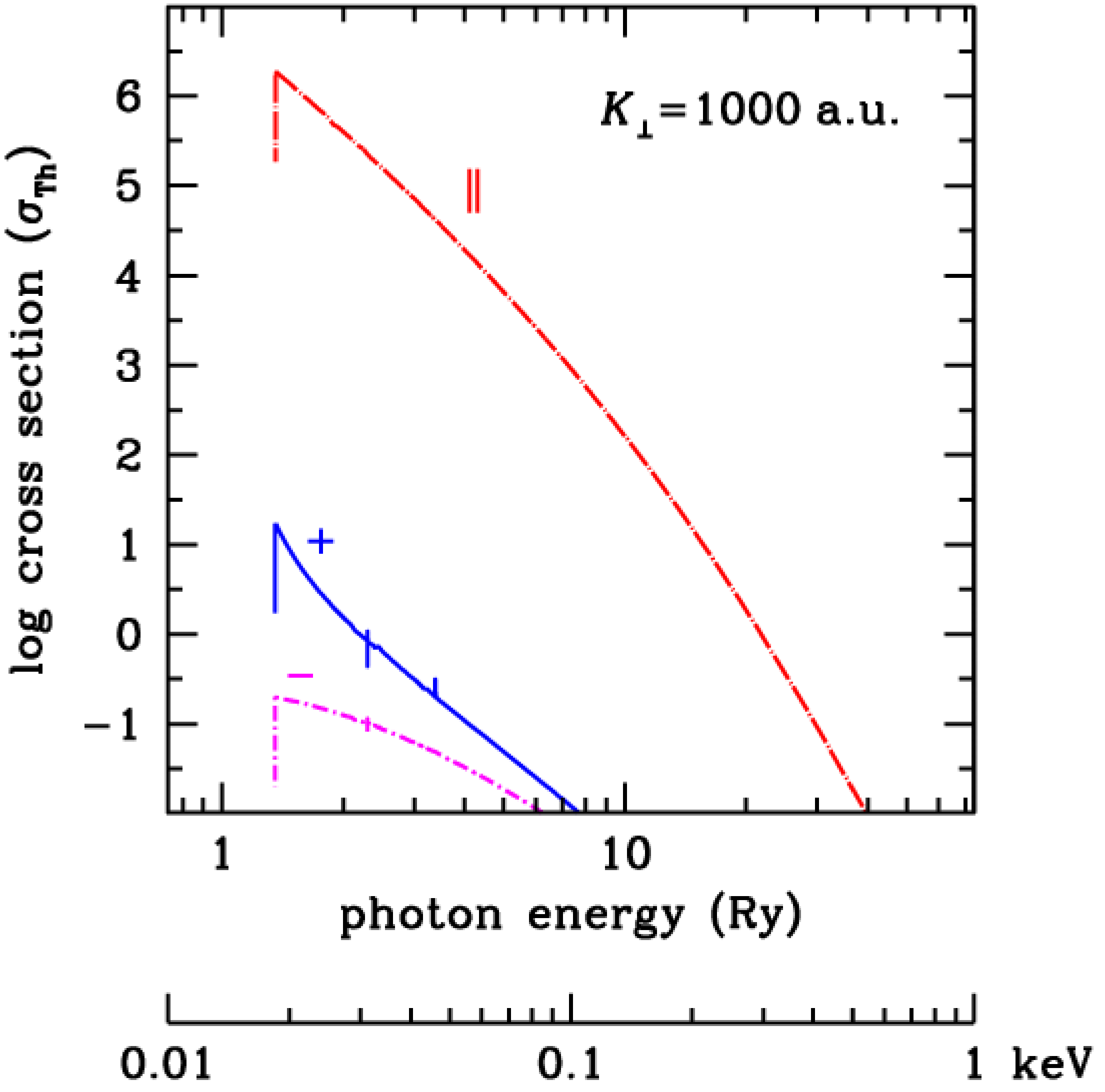
Bound-free transitions of H atom in strong magnetic field



Photoionization cross sections for the ground-state H atom at B=2.35×10^{12} G

[AYP & Pavlov (1997) *Astrophys. J.* **483**, 414]

Bound-free transitions of H atom in strong magnetic field



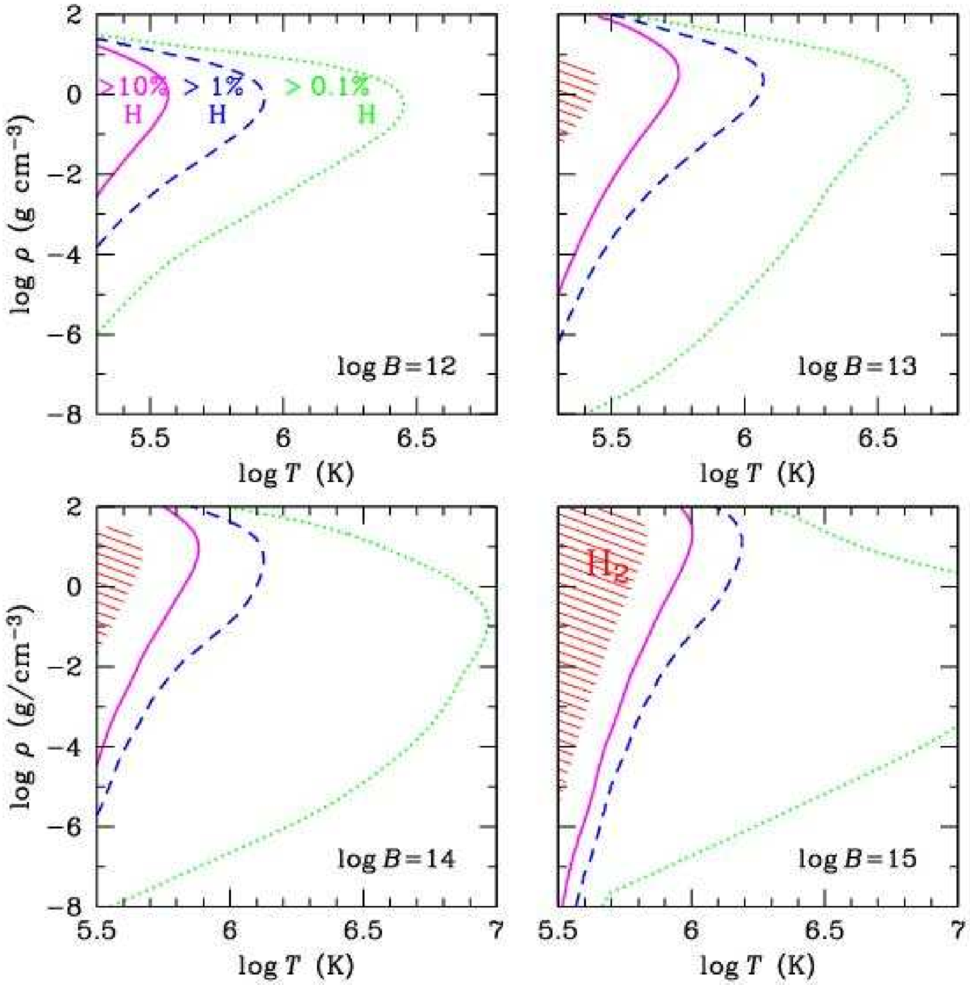
Photoionization cross sections for the ground-state H atom at $B=2.35\times10^{12}$ G

[AYP & Pavlov (1997) *Astrophys. J.* **483**, 414]

Ionization equilibrium in magnetized neutron star envelopes

$$z_i = \left(\frac{M_i kT}{2\pi\hbar^2}\right)^{1/2} \frac{\eta_i}{\sinh\eta_i} \int_0^\infty \frac{K_\perp \mathrm{d}K_\perp}{2\pi\hbar^2} \sum_\kappa w_{i,\kappa}(K_\perp) \exp\left[-\frac{\epsilon_{i,\kappa}(K_\perp)}{kT}\right]$$

Hydrogen



AYP & Chabrier (2004) *ApJ* **600**, 317

$$z_e = 2\left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} \frac{\eta_e}{\tanh\eta_e},$$

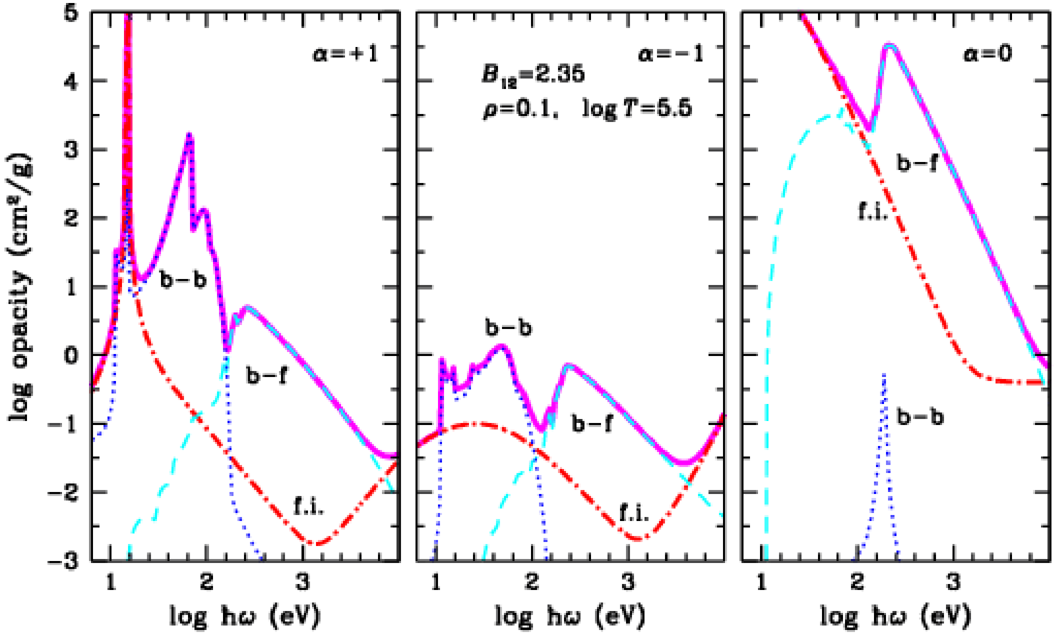
$$\eta_e = \hbar\omega_c / 2k_B T, \qquad \eta_i = \hbar\omega_{ci} / 2k_B T$$

$$\frac{n_i}{n_{i+1} n_e} = \frac{z_i}{z_{i+1} z_e},$$

Plasma absorption and polarizabilities in strong magnetic fields:

The effects of nonideality and partial ionization in magnetized hydrogen plasma

$$\kappa_j(\omega,\theta_B) = \sum_{\alpha=-1}^{1} \left|e_\alpha^j(\omega,\theta_B)\right|^2 \hat\kappa_\alpha(\omega), \qquad j=1,2 \text{ (X,O)}$$



Spectral opacities for 3 basic polarizations.

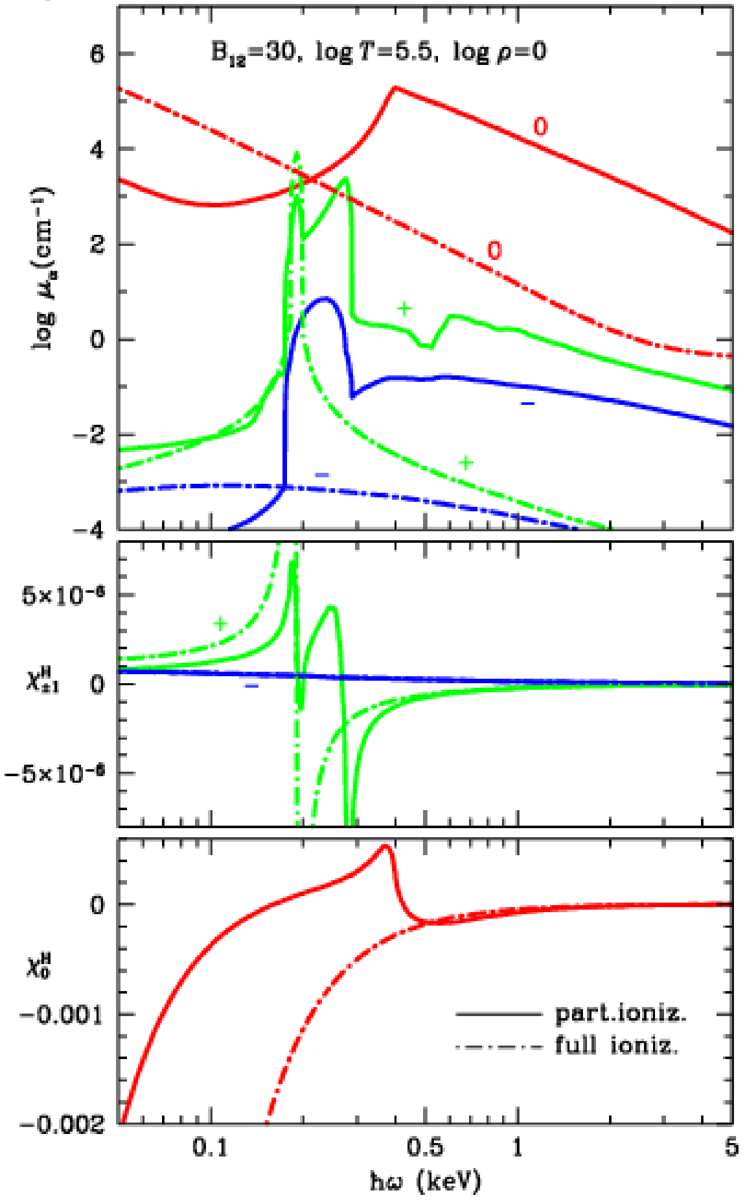
Solid lines – taking into account bound states,

dot-dashes –full ionization

[AYP & Chabrier (2003) *ApJ* **585**, 955]

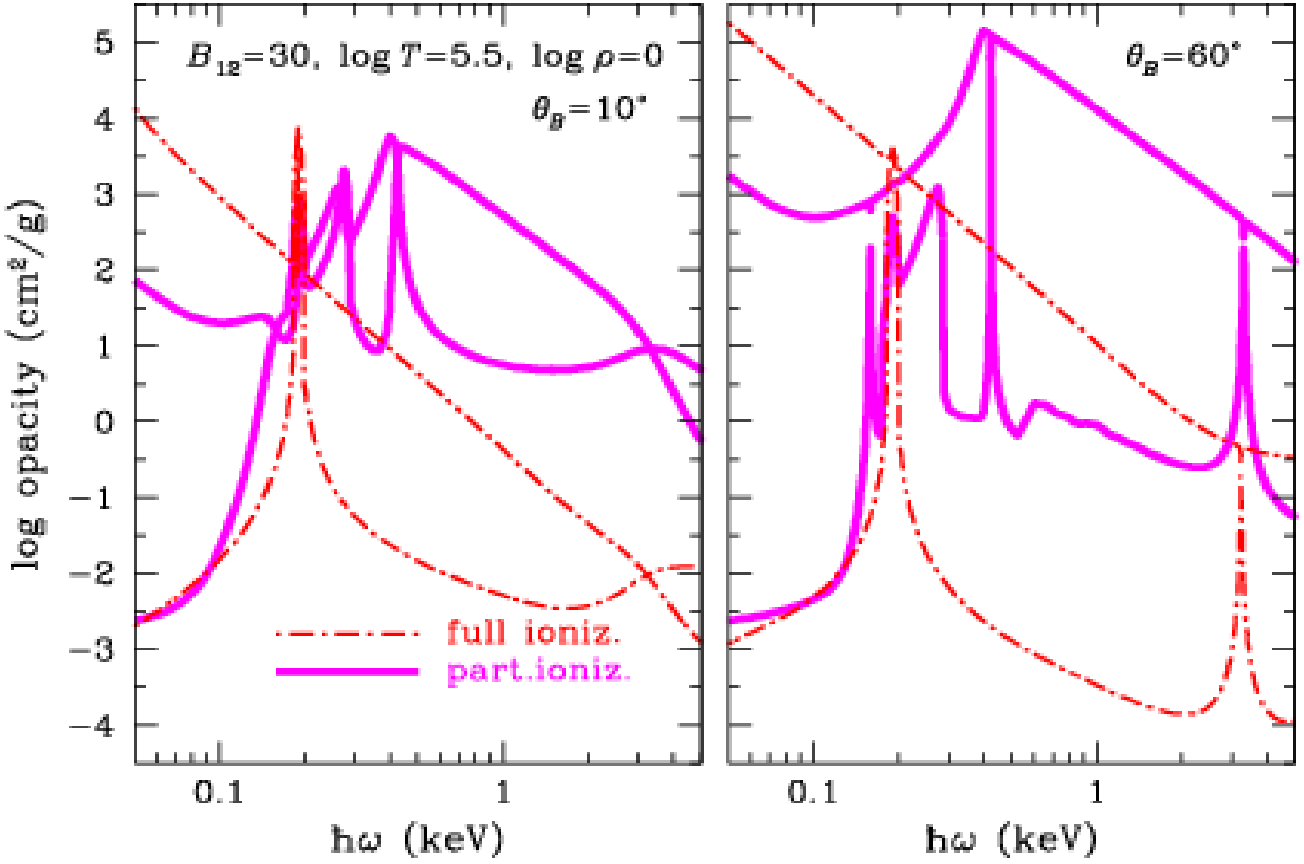
To the right: *top panel* – basic components of the absorption coefficients; *middle and bottom* – components of the polarizability tensor

[AYP *et al.* (2004) *ApJ* **612**, 1034]



Opacities for normal modes:

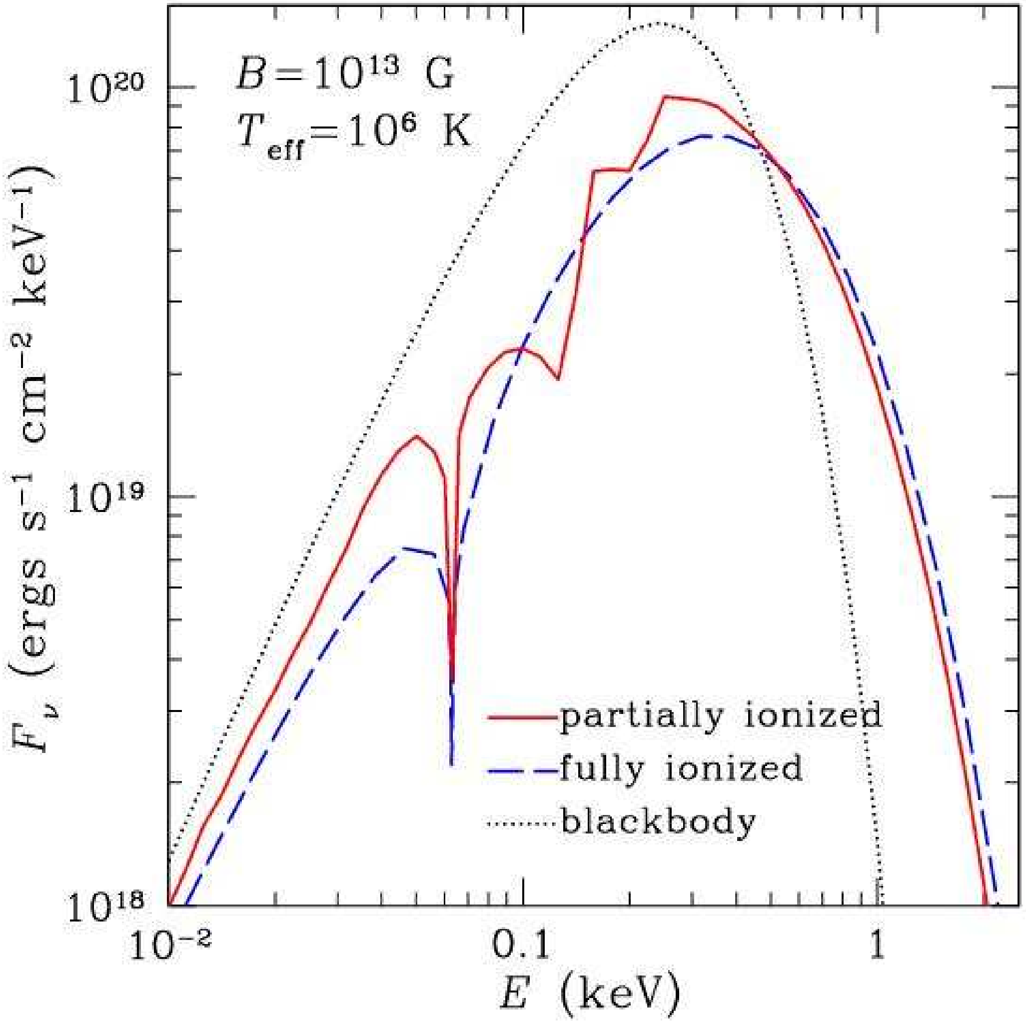
The effects of nonideality and partial ionization



Opacities for two normal modes of electromagnetic radiation in models of an ideal fully ionized (dash-dot) and nonideal partially ionized (solid lines) plasma

at the magnetic field strength B=3×10^{13} G, density 1 g/cc, and temperature 3.16×10^{5} K**.**
The 2 panels correspond to 2 different angles of propagation with respect to the magnetic field lines.
An upper/lower curve of each type is for the extraordinary/ordinary polarization mode, respectively
[AYP *et al.* (2004) *ApJ* **612**, 1034]

Result: the spectrum



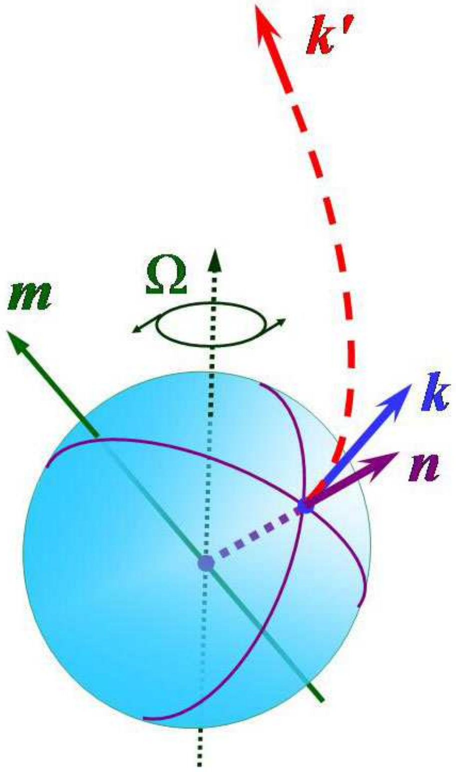
AYP, Lai, Chabrier, Ho, & van Adelsberg (2006) *J.Phys.A: Math. Gen* **39**, 4453

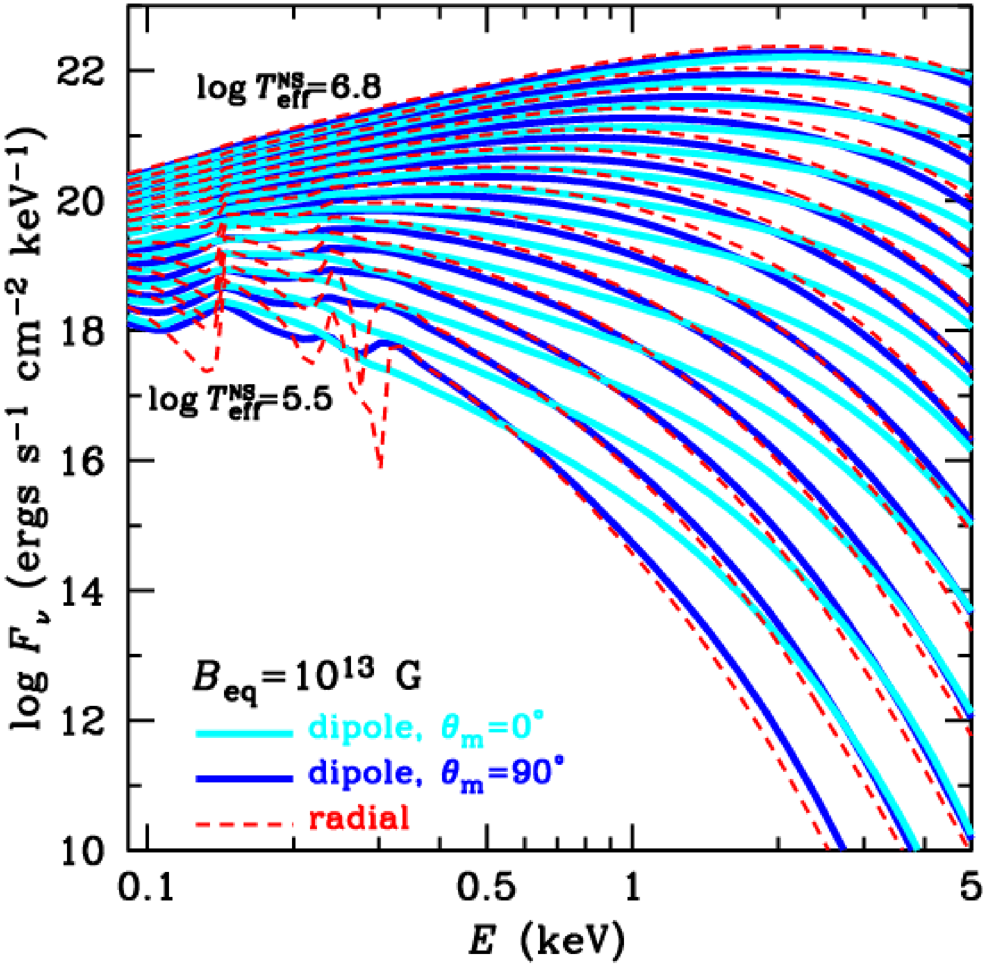
The effect of the atmosphere and its partial ionization on the spectrum of thermal radiation of a neutron star with B=10^{13} G, T= 10^6 K (the field is normal to the surface, the radiation flux is angle-averaged)

[courtesy of **W.C.G.Ho**]

Calculation of the observed spectrum requires an account of the T and B distribution over the surface, redshift, and ray bending

Result of modelling: spectra (dipole model)





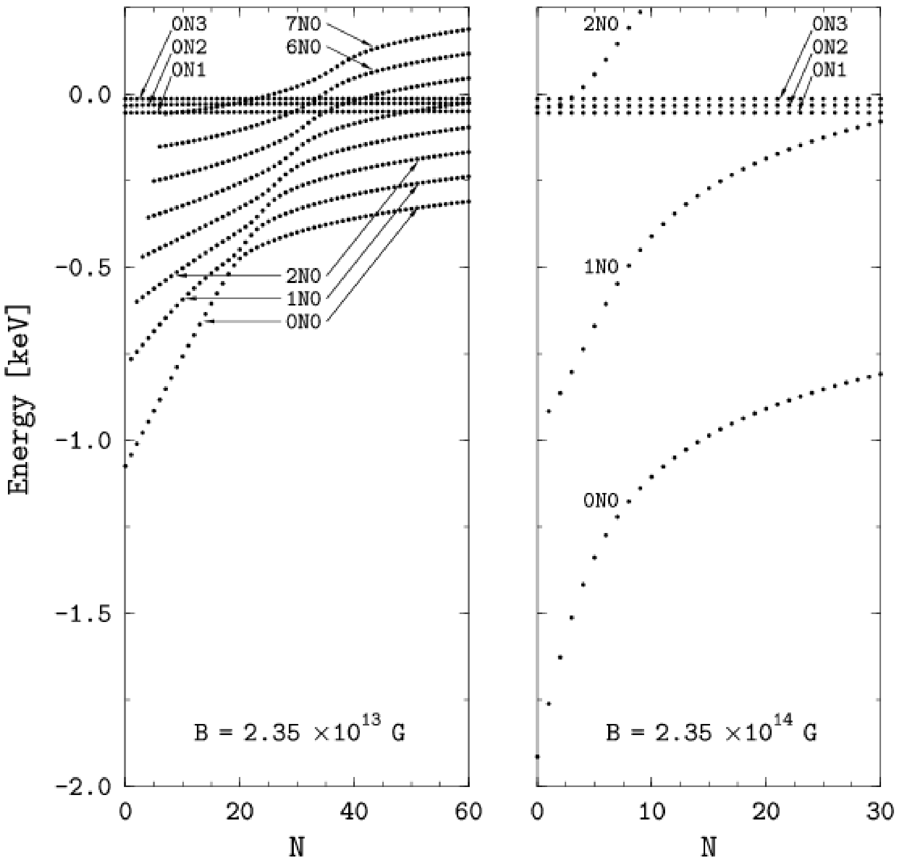
Spectral features are smoothed by surface field distribution.

XSPEC: NSMAX – http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/models/nsmax.html

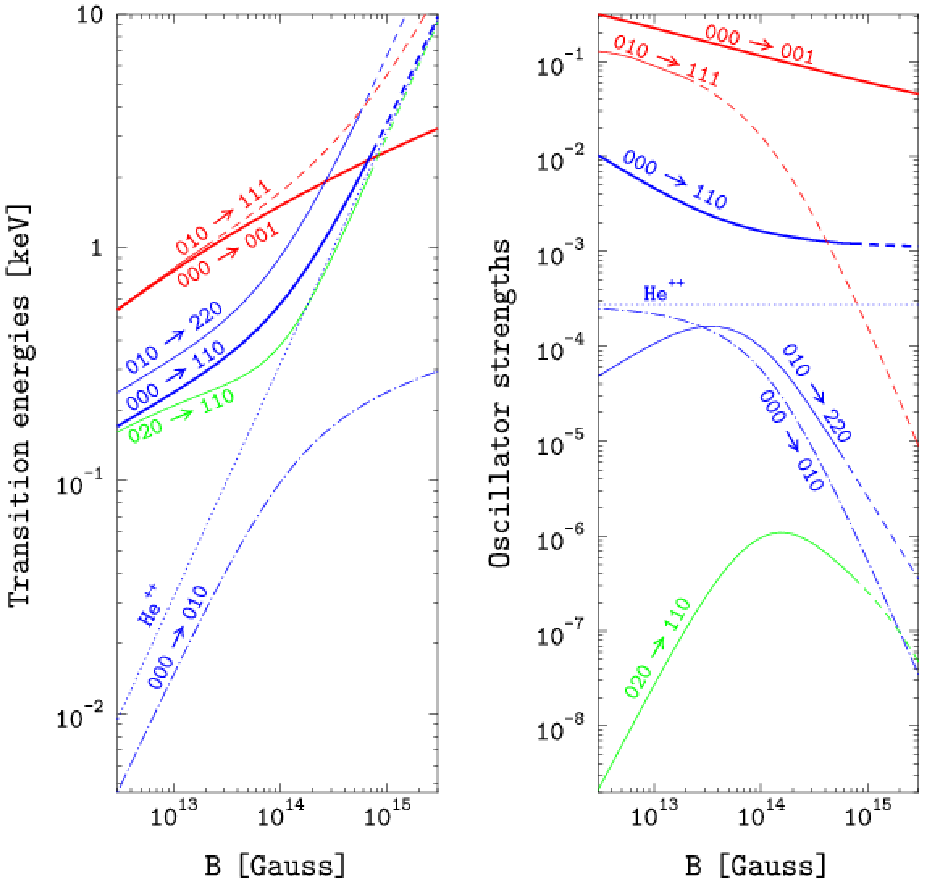
Ho, AYP, & Chabrier (2008) *ApJS* **178**, 102

Bound-bound transitions in strong magnetic field

Helium ion



Energies of the ion as functions of N, which characterizes the state of motion across ***B***

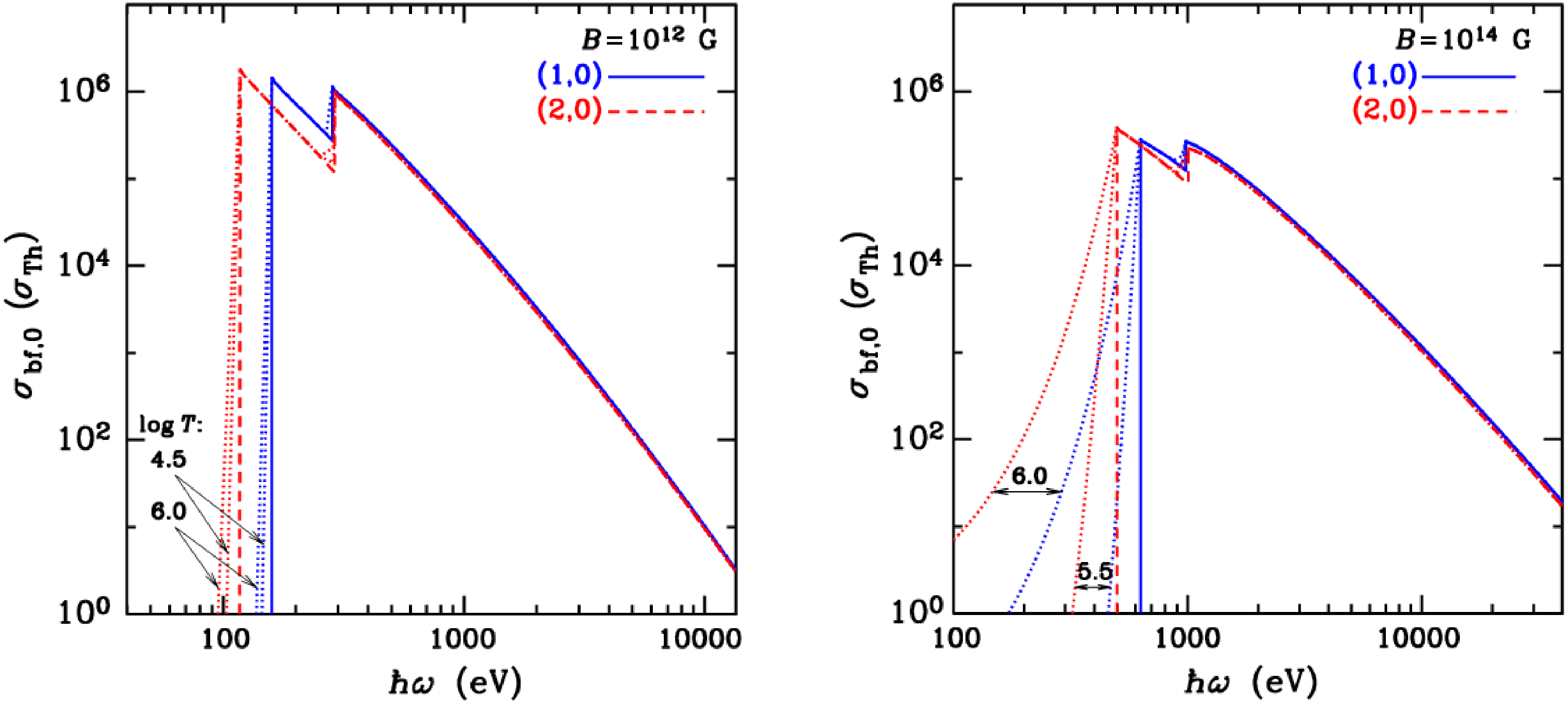


Transition energies and oscillator strengths as functions of *B*

Pavlov & Bezchastnov (2005) *ApJ* **635**, L61

Bound-free transitions of He atom in strong magnetic field

Medin, Lai, & AYP (2008) *MNRAS* **383**, 161



Photoionization cross sections for polarization along *B* without (solid and dashed lines) and with (dots) account of magnetic broadening.

$$\sigma(\omega) \approx \sigma(\omega_{\mathrm{thr}}) \exp\left[-\frac{M_\perp}{M}\frac{\omega_{\mathrm{thr}}-\omega}{\Omega_{\mathrm{c}}} - \frac{\hbar(\omega_{\mathrm{thr}}-\omega)}{k_{\mathrm{B}}T}\right]$$

Ionization equilibrium in magnetized neutron star envelopes

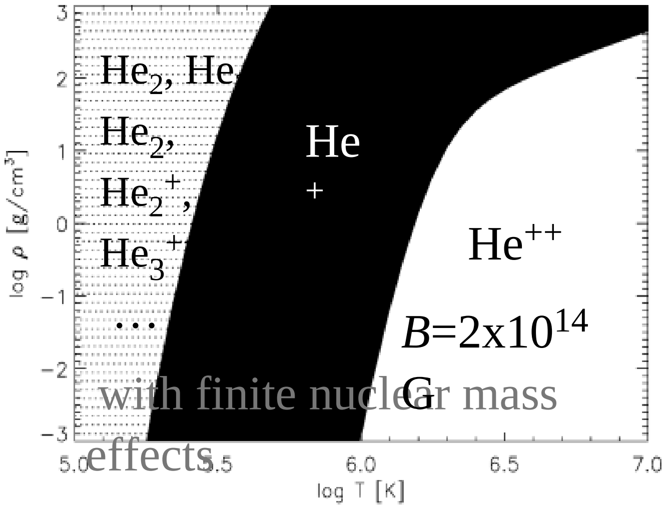
$$z_i = \left(\frac{M_i kT}{2\pi\hbar^2}\right)^{1/2} \frac{\eta_i}{\sinh\eta_i} \int_0^\infty \frac{K_\perp \mathrm{d}K_\perp}{2\pi\hbar^2} \sum_\kappa w_{i,\kappa}(K_\perp) \exp\left[-\frac{\epsilon_{i,\kappa}(K_\perp)}{kT}\right]$$

Helium

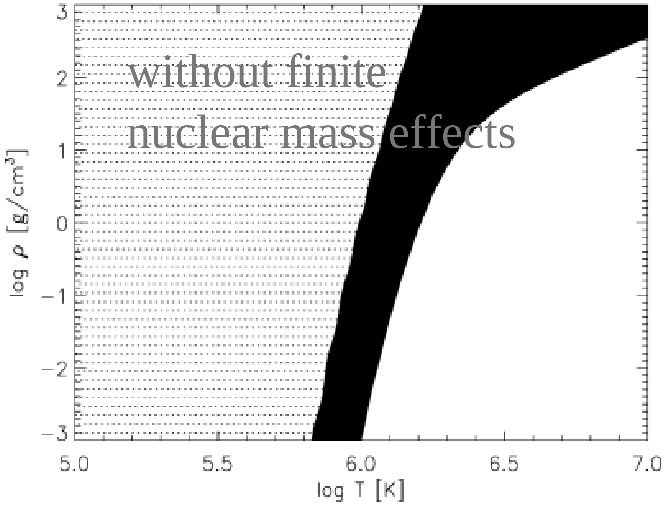
$$z_e = 2\left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} \frac{\eta_e}{\tanh\eta_e},$$

$\eta_e = \hbar\omega_c / 2k_BT$, $\eta_i = \hbar\omega_{ci} / 2k_BT$

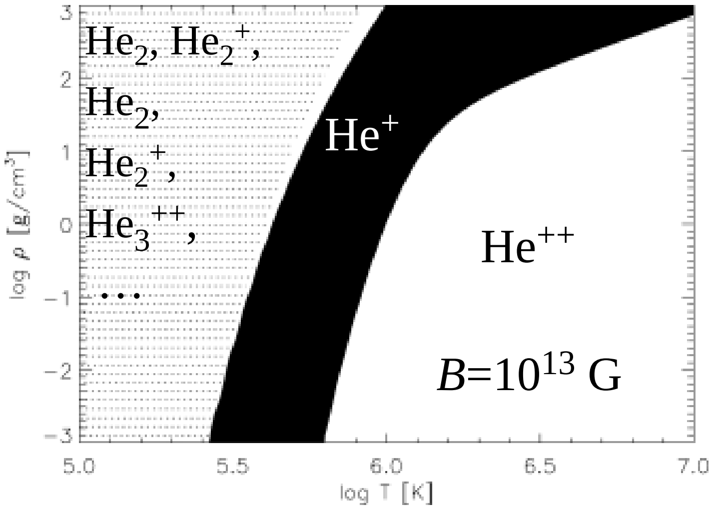
$$\frac{n_i}{n_{i+1}n_e} = \frac{z_i}{z_{i+1}z_e},$$



with finite nuclear mass effects



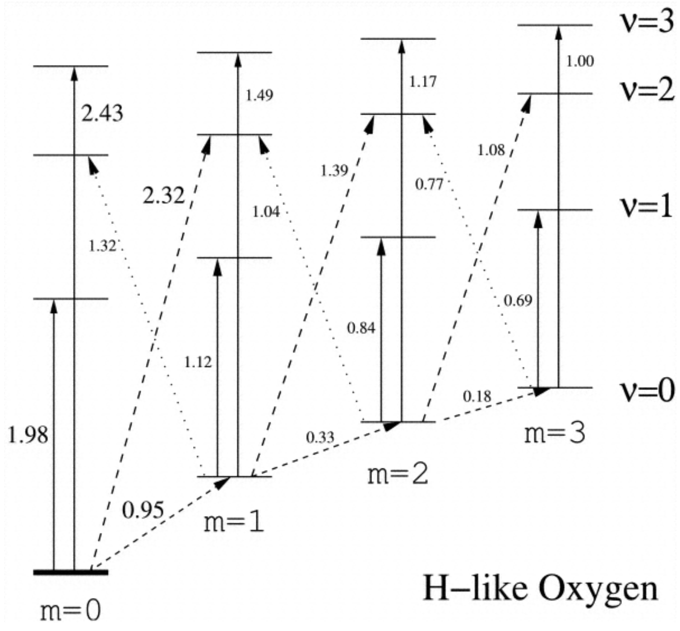
without finite nuclear mass effects



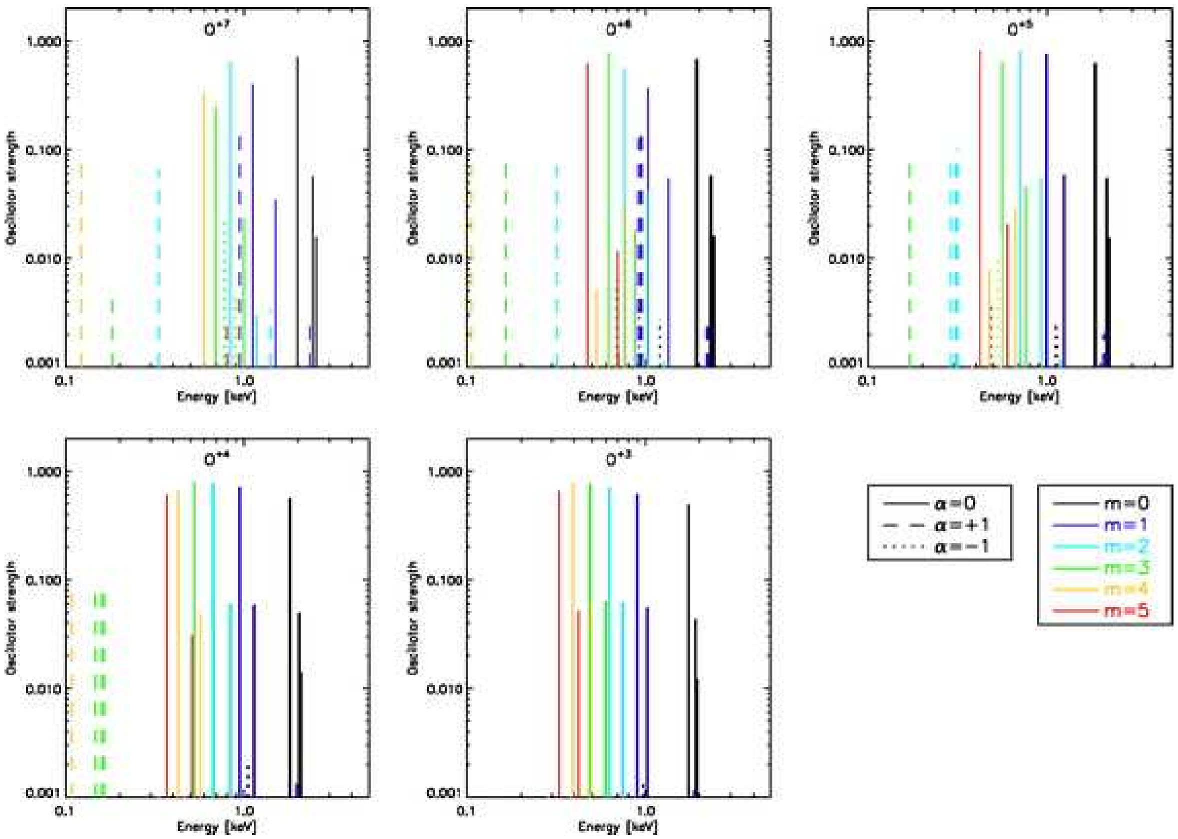
Mori & Heyl (2007) *MNRAS* **377**, 905

Energies and oscillator strengths of heavier species: *the effects of motion are calculated only as perturbation* (⇒ low T)

Mori & Hailey (2006) *ApJ* **648**, 1139



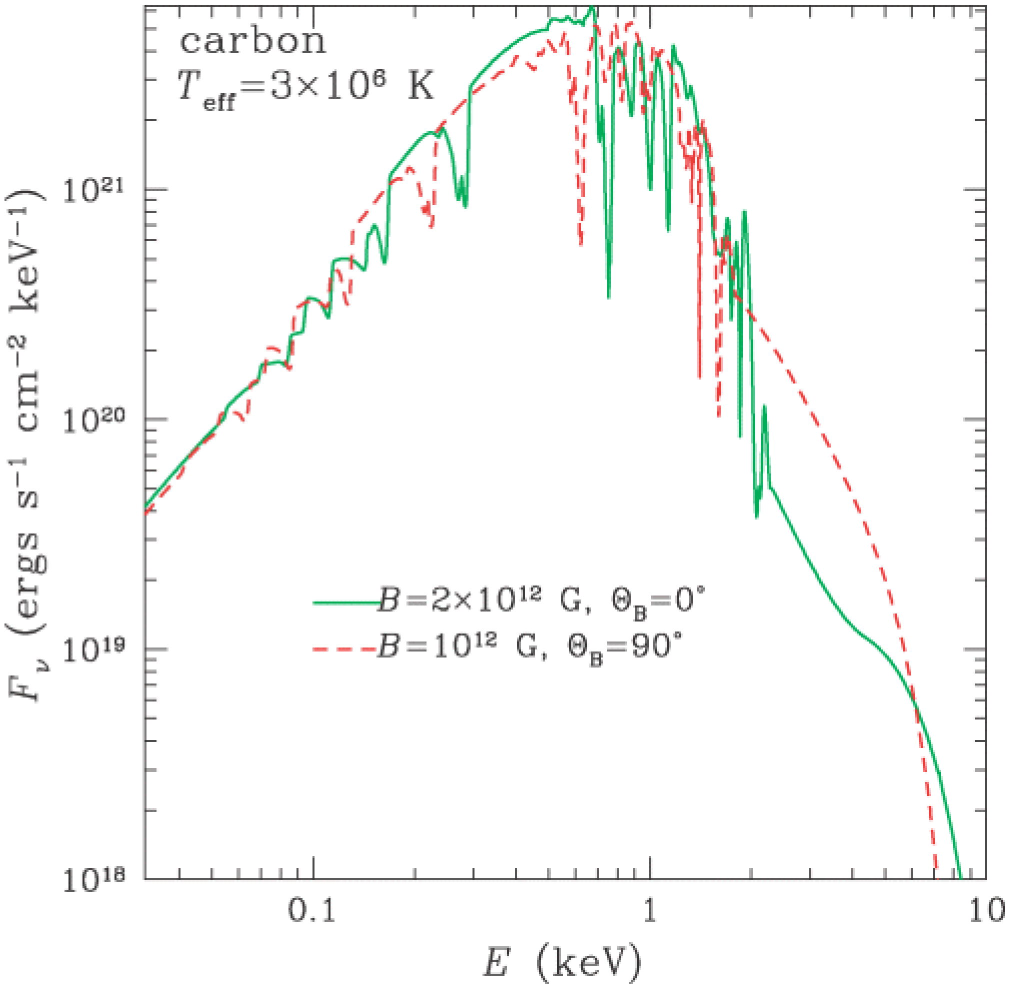
Energies of allowed transitions from the ground state, at $B=10^{12}$ G



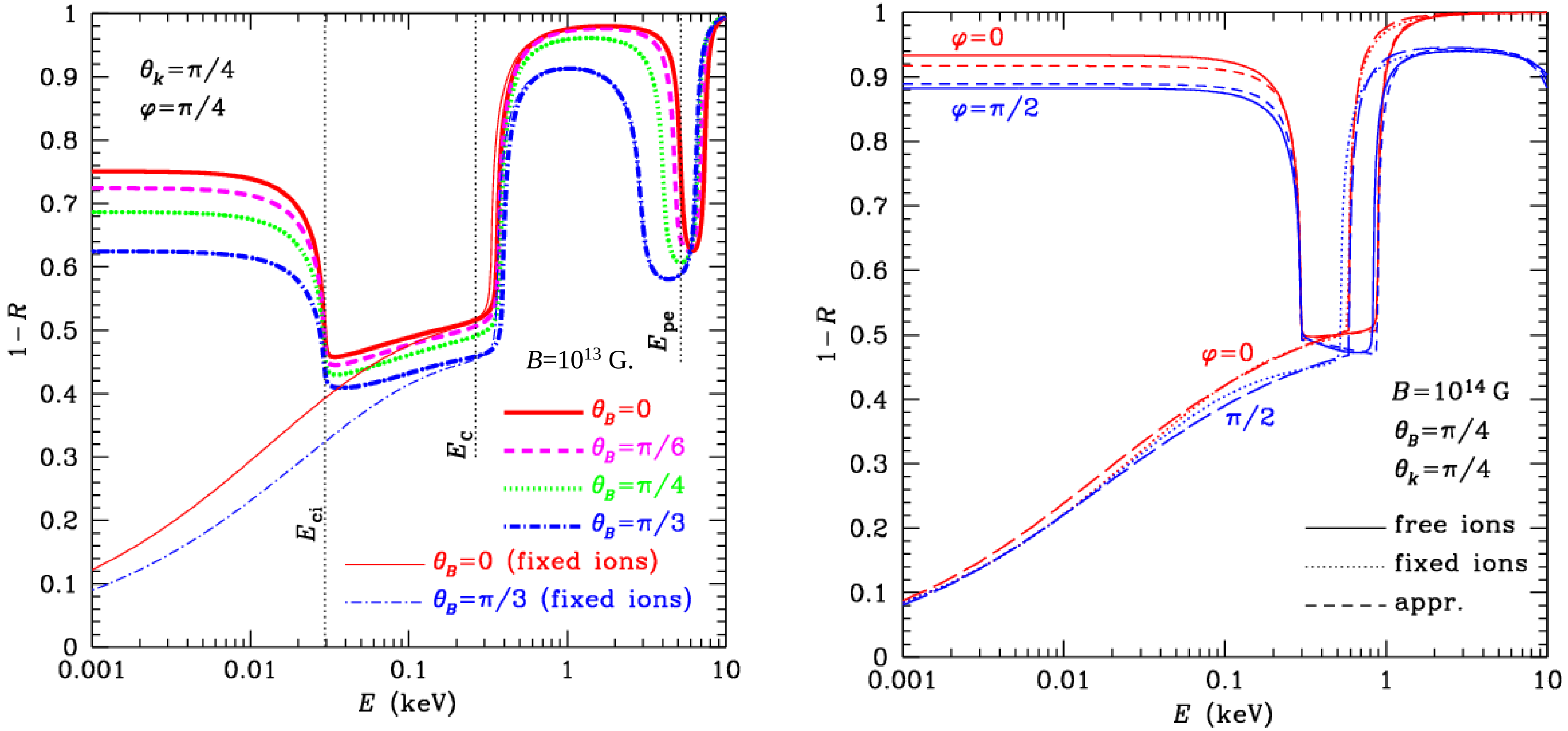
Energies and oscillator strengths of allowed transitions from the various tightly bound states

Atmosphere models for heavier elements

Mori & Ho (2007) *MNRAS* **377**, 905



Radiation from condensed surface



Dimensionless emissivity of iron surface as function of photon energy.

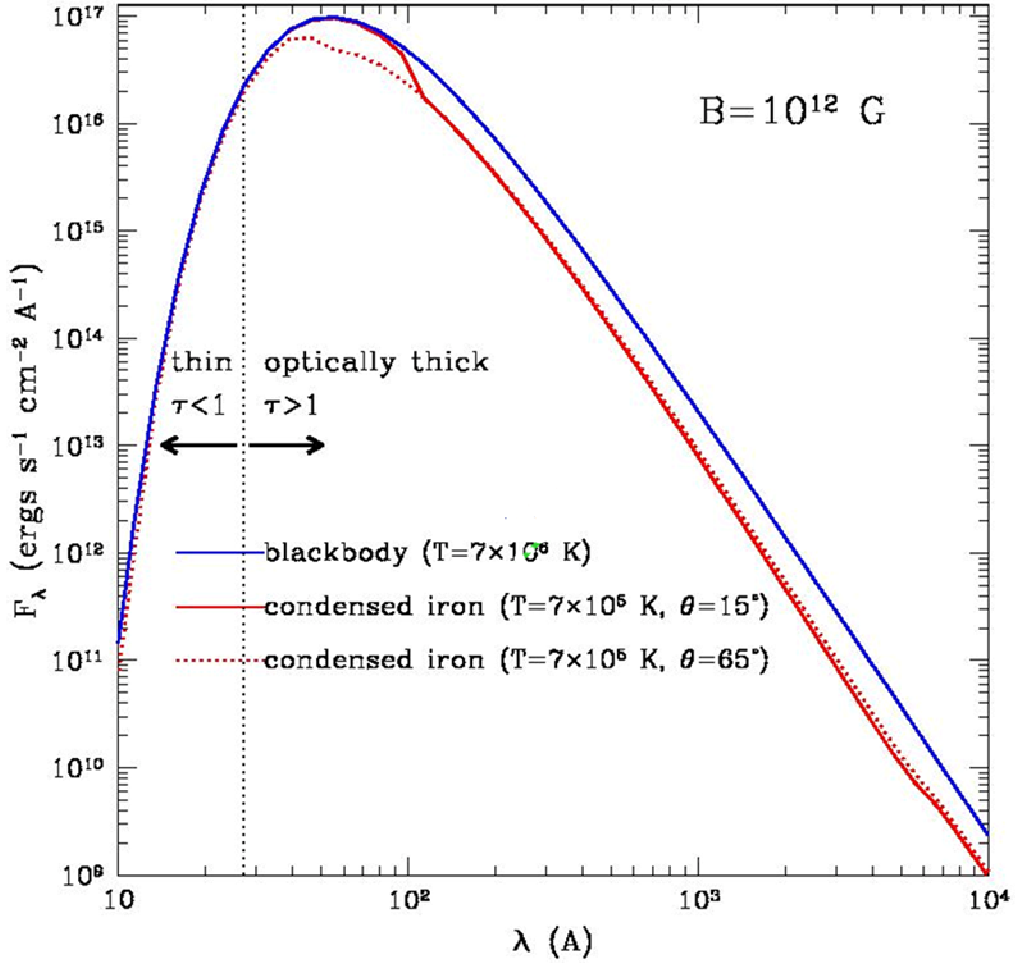
van Adelsberg *et al.* (2005) *ApJ* **628**, 902, improved in 2011:

AYP, Suleimanov, van Adelsberg, & Werner (2012) *A&A* **546**, A121

“Thin atmospheres”

= condensed surface covered by an atmosphere, so that neither is negligible

Idea by Motch, Zavlin, & Haberl (2003);
realized by Wynn Ho (2004 – 2007) and by Valery Suleimanov (2008 – 2012), with coauthors



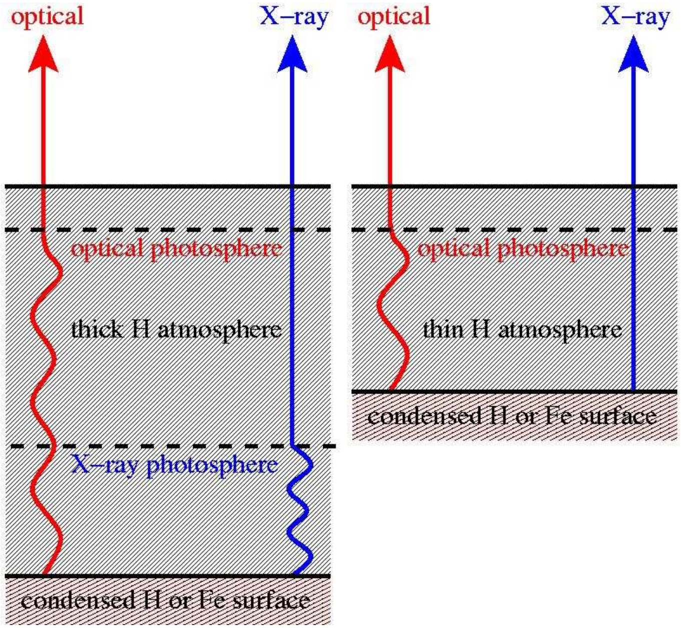
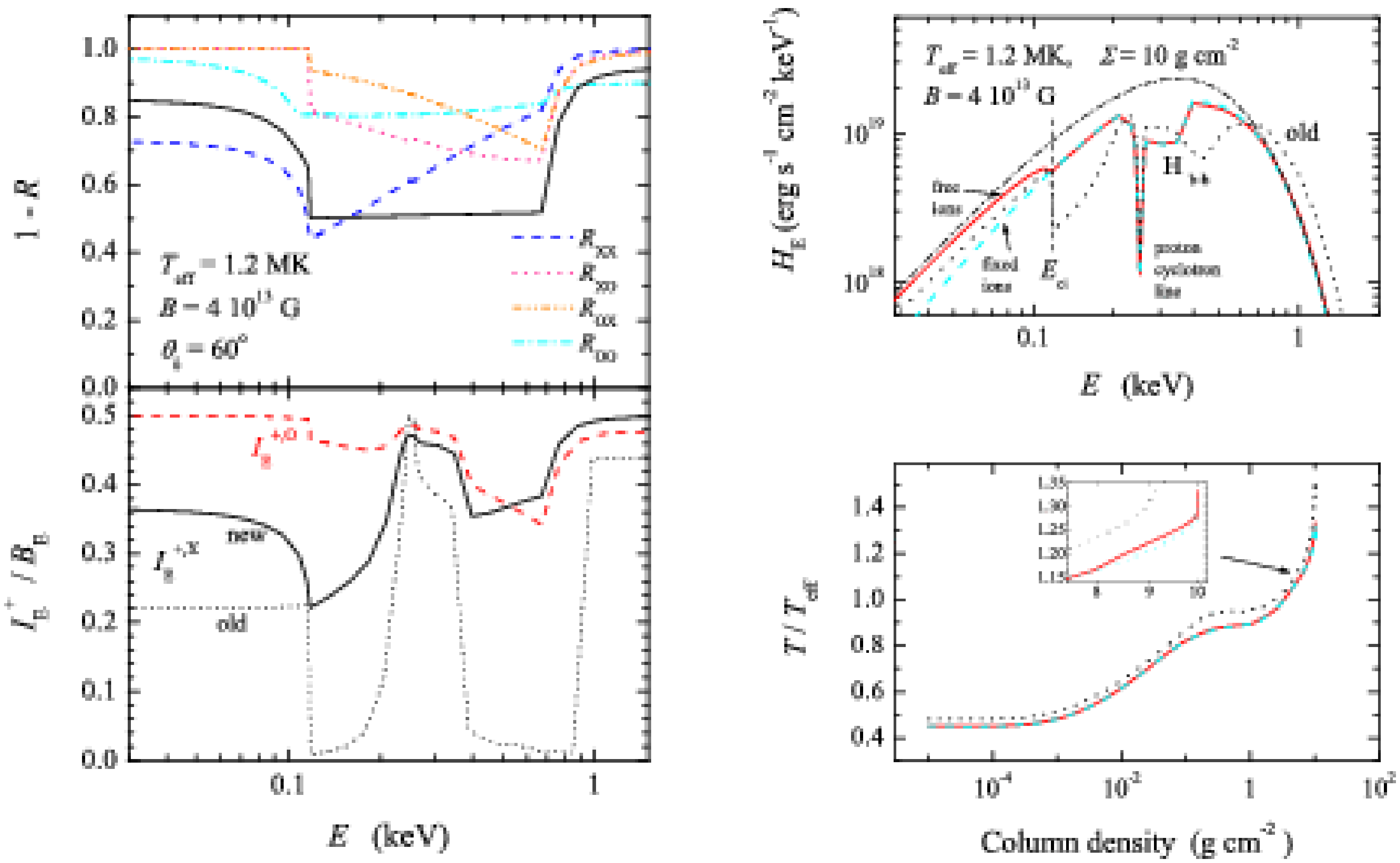


Figure: Wynn Ho (2007)

Thin atmospheres:

improved treatment of the condensed surface



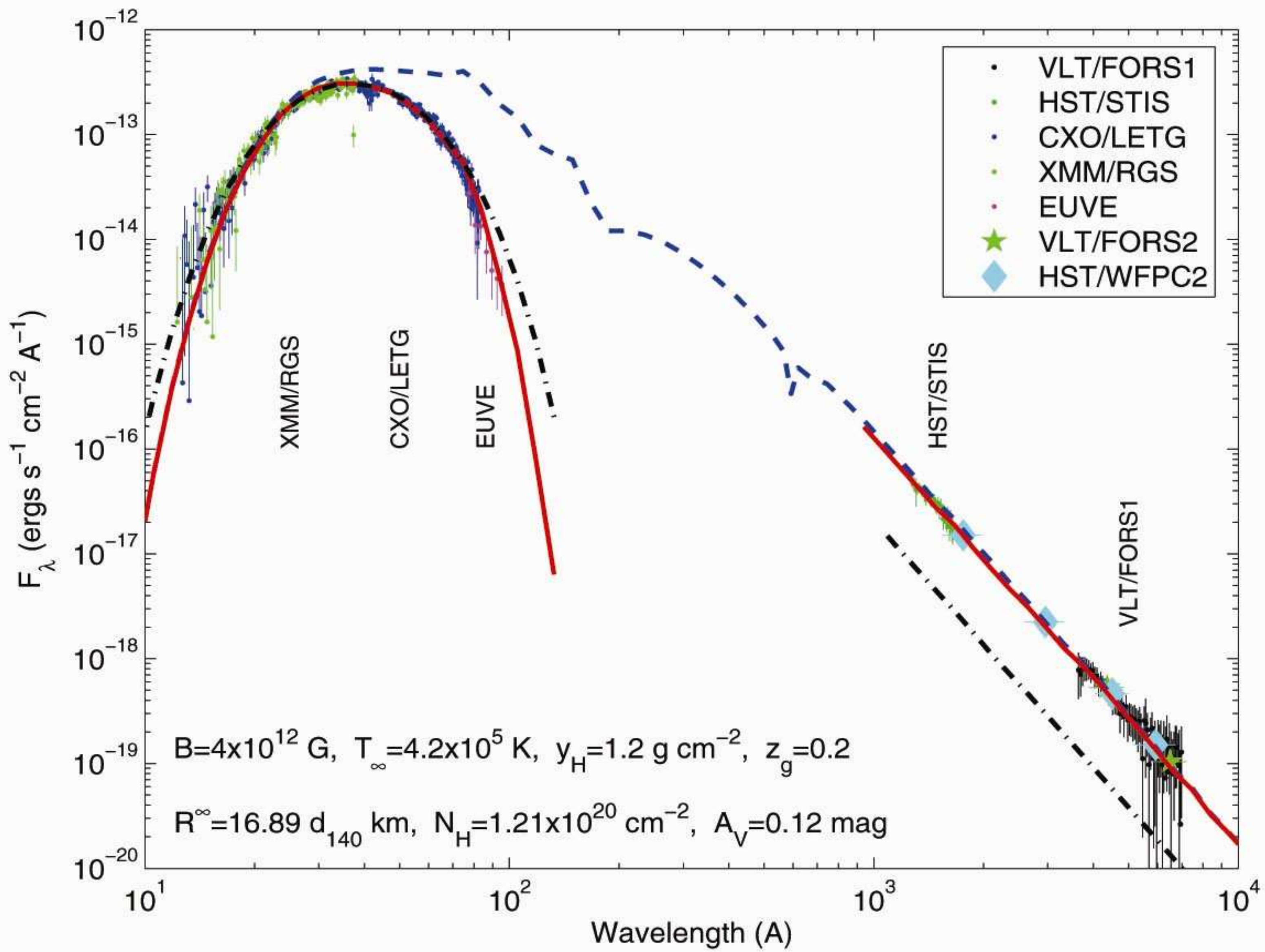
Normalized emissivity, thermal structure, and spectra of an iron surface and thin H atmosphere (old and new results)

AYP *et al.* (2012) *A&A* **546**, A121

Link of the theory with observations

Case of RX J1856.4-3754

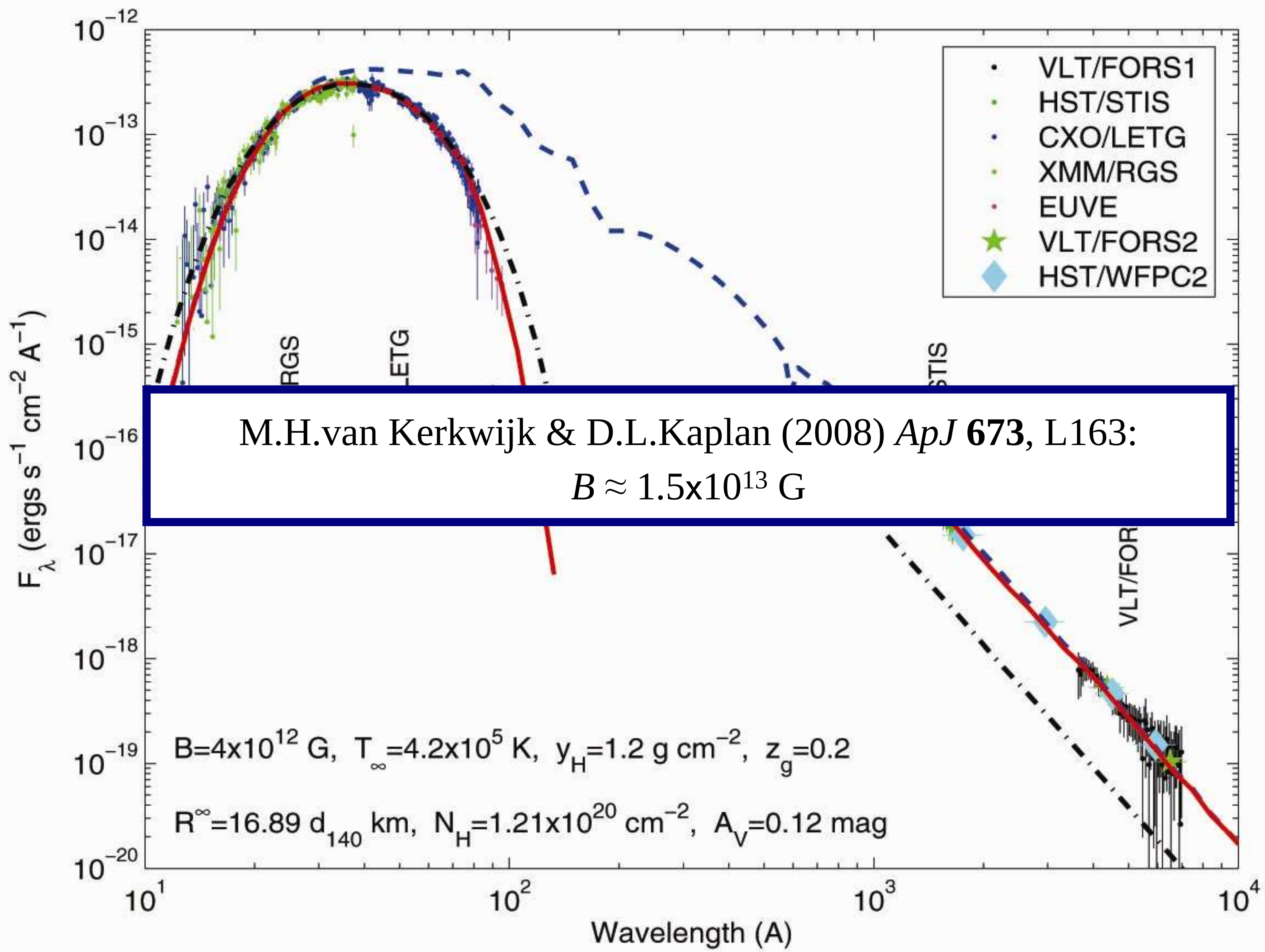
Ho *et al*. (2007) *MNRAS*, **375**, 821



Theory vs. observations

Case of RX J1856.4-3754

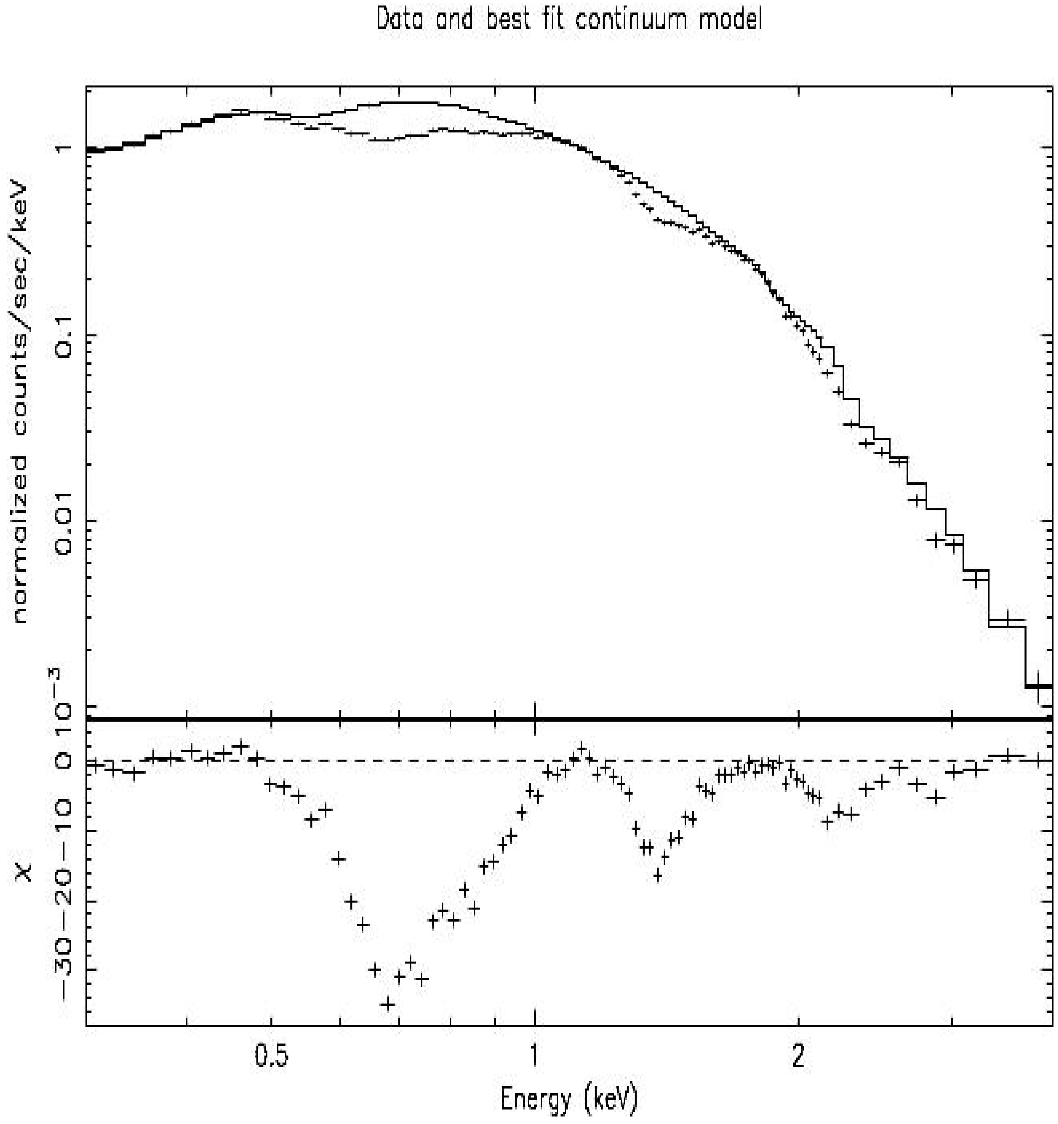
W.C.G.Ho *et al*. (2007) *MNRAS*, **375**, 821



M.H.van Kerkwijk & D.L.Kaplan (2008) *ApJ* **673**, L163:
$B \approx 1.5\mathrm{x}10^{13}$ G

Theory vs. observations

Case of 1E 1207.4−5209



[Figure: Bignami *et al*. (2004) *Mem.S.A.It.* **75**, 448]

$$\hbar\omega_{\rm c} = \hbar eB/mc = 11.577\ B_{12}\ {\rm keV}$$

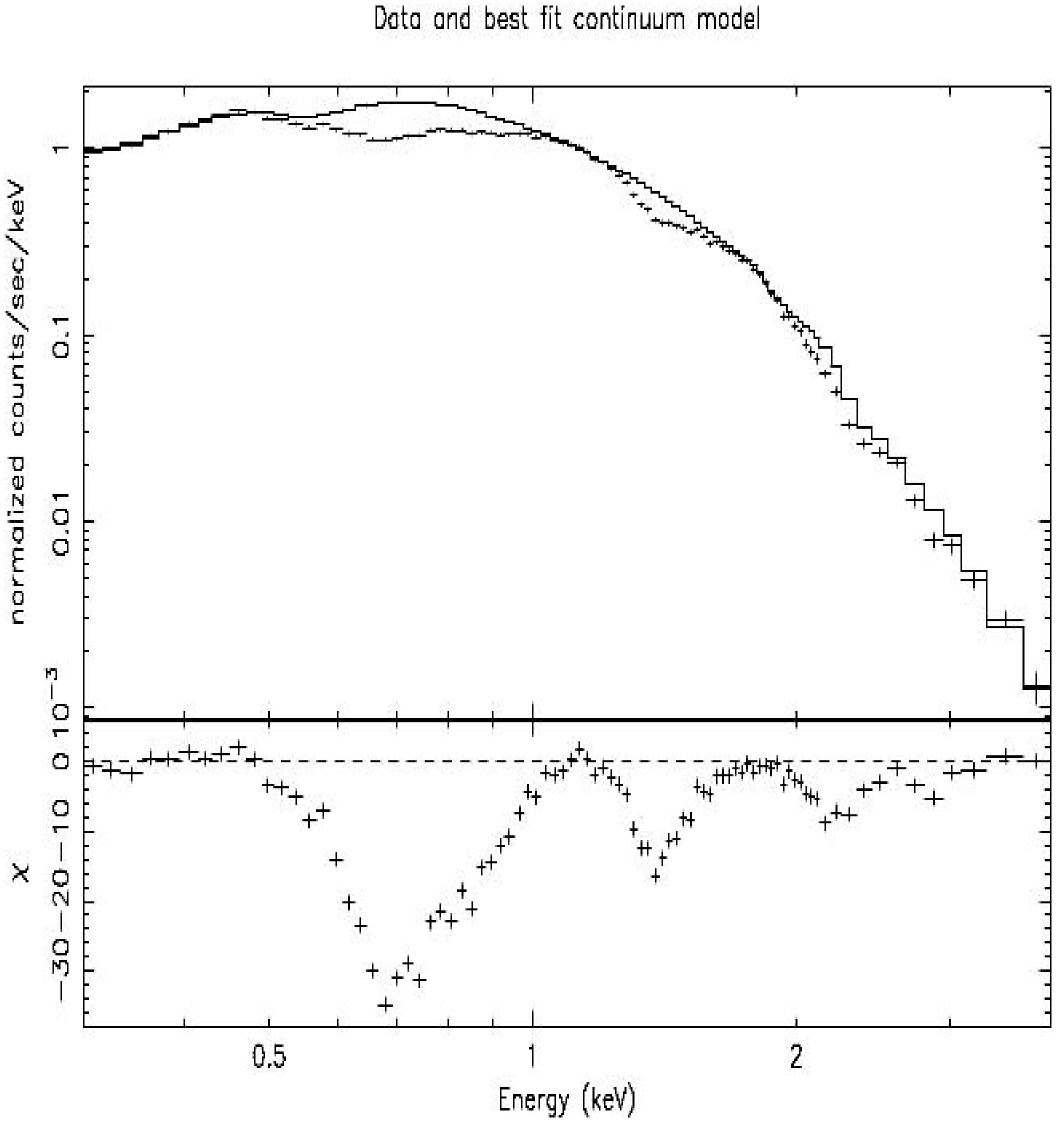
$$\hbar\omega_{\rm ci} = \hbar ZeB/m_{\rm i}c = 6.35\,(Z/A)B_{12}\ {\rm eV}$$

$$\max(T_{\rm eff}, E_{\rm a})/mc^2 \sim 10^{-3}$$

Mori, Chonko, & Hailey (2005) *ApJ* **631**, 1082:
only 2 features are real.

Theory vs. observations

Case of 1E 1207.4−5209



$$\hbar\omega_c = \hbar eB/mc = 11.577\ B_{12}\ \mathrm{keV}$$

$$\hbar\omega_{ci} = \hbar ZeB/m_i c = 6.35\,(Z/A)B_{12}\ \mathrm{eV}$$

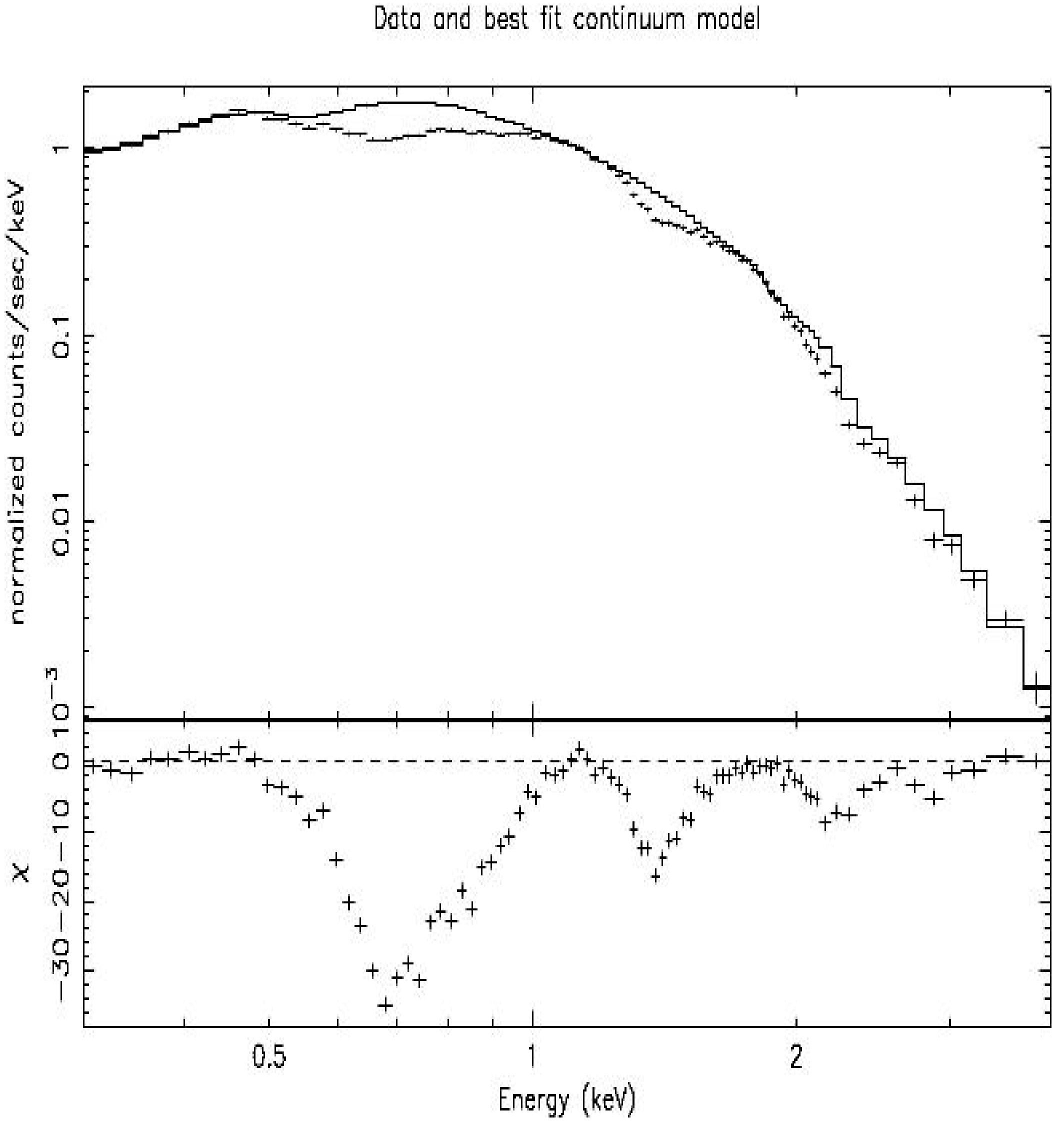
$$\max(T_{\rm eff}, E_a)/mc^2 \sim 10^{-3}$$

Pavlov & Shibanov (1978) *SvA* **22**, 214;
Zane *et al*. (2001) *ApJ* **560**, 384:
electron or proton (ion) free-free
cyclotron harmonics?
Electron cyclotron → $B \approx 8\mathrm{x}10^{10}$ G.

Suleimanov, Pavlov, & Werner (2010)
ApJ **714**, 630
("quantum" cyclotron harmonics)

Theory vs. observations

Case of 1E 1207.4−5209



$$\hbar\omega_{\rm c} = \hbar eB/mc = 11.577\ B_{12}\ {\rm keV}$$

$$\hbar\omega_{\rm ci} = \hbar ZeB/m_{\rm i}c = 6.35\,(Z/A)B_{12}\ {\rm eV}$$

$$\max(T_{\rm eff}, E_{\rm a})/mc^2 \sim 10^{-3}$$

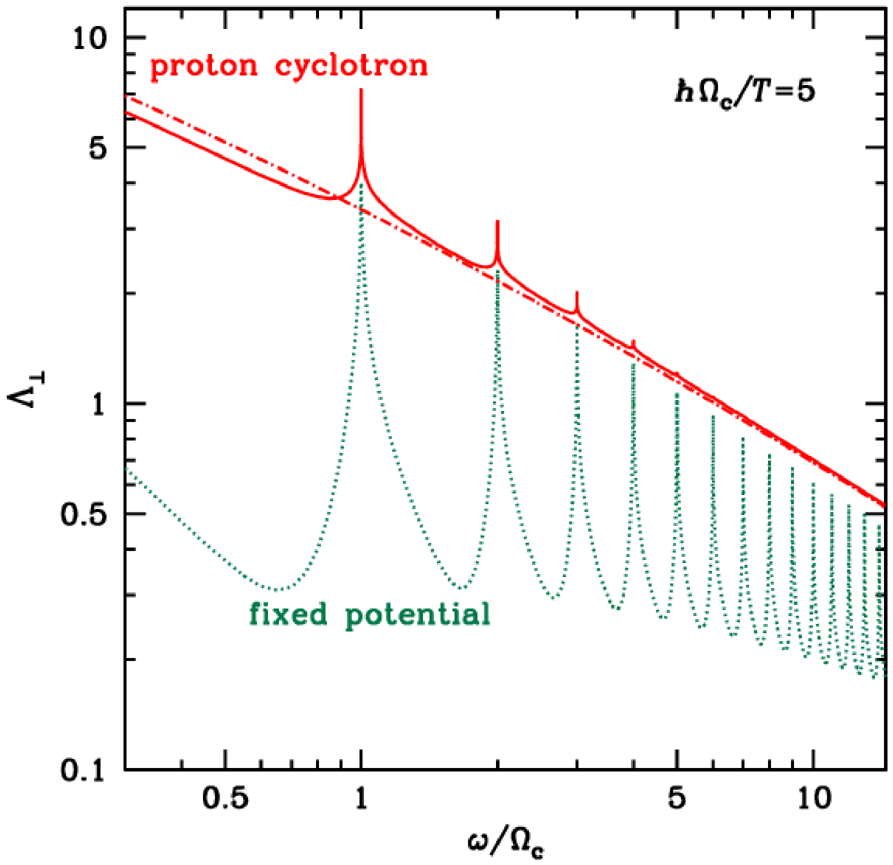
Pavlov & Shibanov (1978) *SvA* **22**, 214;
Zane *et al*. (2001) *ApJ* **560**, 384:
electron or proton (ion) free-free
cyclotron harmonics?
Electron cyclotron → $B \approx 8\text{x}10^{10}$ G.

Suleimanov, Pavlov, & Werner (2010)
ApJ **714**, 630
("quantum" cyclotron harmonics)

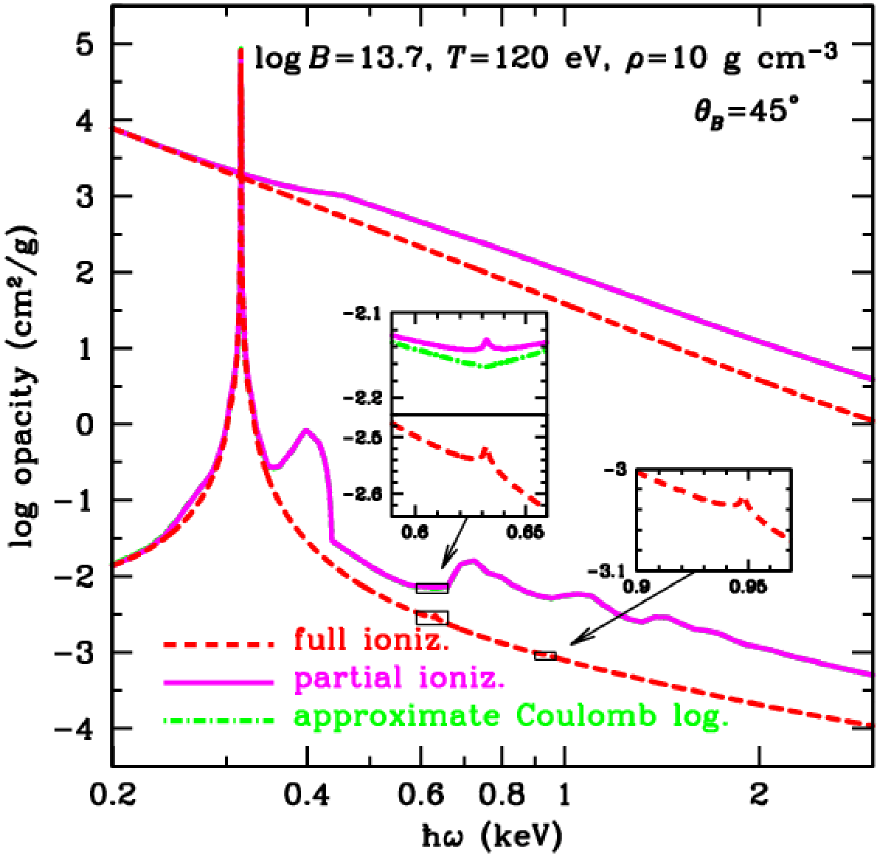
Halpern & Gotthelf (2011) *ApJ* **733**, L28:
$B \approx 2.4\text{x}10^{11}$ G or $9.9\text{x}10^{10}$ G (!)

Absence of ion cyclotron harmonics in spectra of isolated neutron stars

AYP (2010) *Aston. Astrophys.* **518**, A24



Coulomb logarithm in the cross section of the free-free photoabsorption in a H plasma with a strong magnetic field as a function of the ratio of photon frequency ω to the cyclotron frequency Ω_c. Dotted line – approximation of a fixed scattering potential Isuitable for electron cyclotron harmonics)Solid line – an accurate calculation. Dash-dotted line – neglecting Landau quantization for protons.

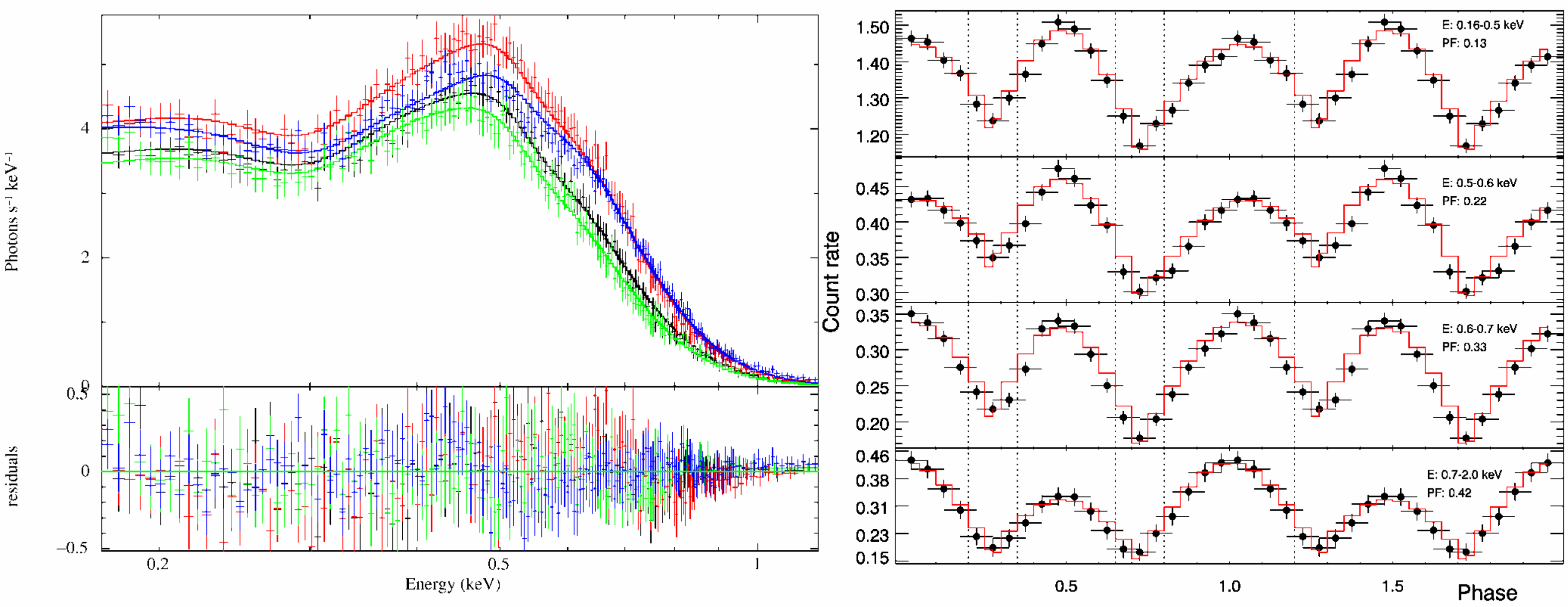


Opacities for O- (upper curves of each type) and X-modes of radiation in the H atmosphere of a NS with B=5x10^{13} G. Dashes – fully ionized plasma model, solid lines – partially ionized, dot-dashed – partially ionized without free-free cyclotron harmonics.

The features caused by incomplete ionization (atomic resonances) are much stronger than proton cyclotron harmonics.

Theory vs. observations

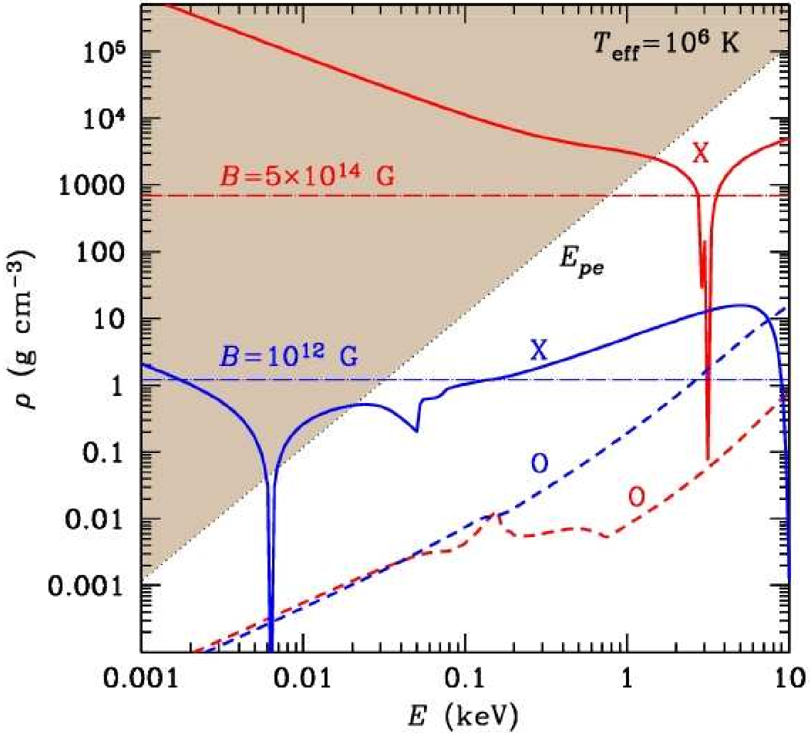
Case of RBS 1223



Hambaryan et al. (2011) *Astron. Astrophys.* **534**, A74

Challenges from **superstrong** fields

1. ***Surface layers: molecules, chains, and magnetic condensation***
2. ***Nonperturbative finite-mass effects for bound species***
3. ***Radiative transfer: vacuum polarization and mode conversion***
4. ***Energy transport below the plasma frequency***
5. ***Condensed surface: uncertainty at $\omega < \omega_{ci}$***



Conclusions

- Models of neutron-star thermal spectra with account of ***strong magnetic fields***, ***partial ionization***, and ***magnetic condensation*** are becoming practical for interpretation of observations.
- ***For chemical elements other than H***, magnetic atmosphere opacities are known at crude approximations and need further studies.
- ***Superstrong*** magnetic fields (1) induce new effects which can reveal themselves in the spectra and (2) lead to theoretical uncertainties, which require further studies.