Theory of thermal radiation from isolated neutron stars

Alexander Y. Potekhin[1,2]

in collaboration with:
Gilles Chabrier[2]
Andrey Chugunov[1]
Paweł Haensel[3]
Wynn Ho[4]
Alexander Kaminker[1]
Dong Lai[5]
Zach Medin[6]
Forrest Rogers[7]
Peter Shternin[1]
Valery Suleimanov[8,9]
Vadim Urpin[1]
Matt van Adelsberg[10]
Dmitry Yakovlev[1]

affiliations:
[1]*Ioffe Physical-Technical Institute, St.Petersburg (Russia)*
[2]*CRAL, Ecole Normale Supérieure de Lyon (France)*
[3]*CAMK, Warsaw (Poland)*
[4]*University of Southampton (UK)*
[5]*Cornell University (USA)*
[6]*Los Alamos National laboratory (USA)*
[7]*Lawrence Livermore National Laboratory (USA)*
[8]*Universität Tübingen (Germany)*
[9]*Kazan Federal University (Russia)*
[10]*Georgia Institute of Technology (USA)*

and also: Denis Baiko, Victor Bezchastnov, George Pavlov, Chris Pethick, Yuri Shibanov, Joseph Ventura, ...

Theory of thermal radiation from isolated neutron stars

Alexander Y. Potekhin

Outline:

1. Introduction
2. Envelopes: EOS, conductivities, thermal structure, and cooling
3. Atmospheres: EOS, opacities, spectra
4. Radiation from condensed surface and symbiotic models

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Outline:

1. Introduction
2. Atmospheres
3. Radiation from condensed surface and symbiotic models

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Outline:

1. Introduction
2. Atmospheres with strong magnetic fields
3. Radiation from condensed surface and symbiotic models

Theory of thermal radiation from isolated neutron stars

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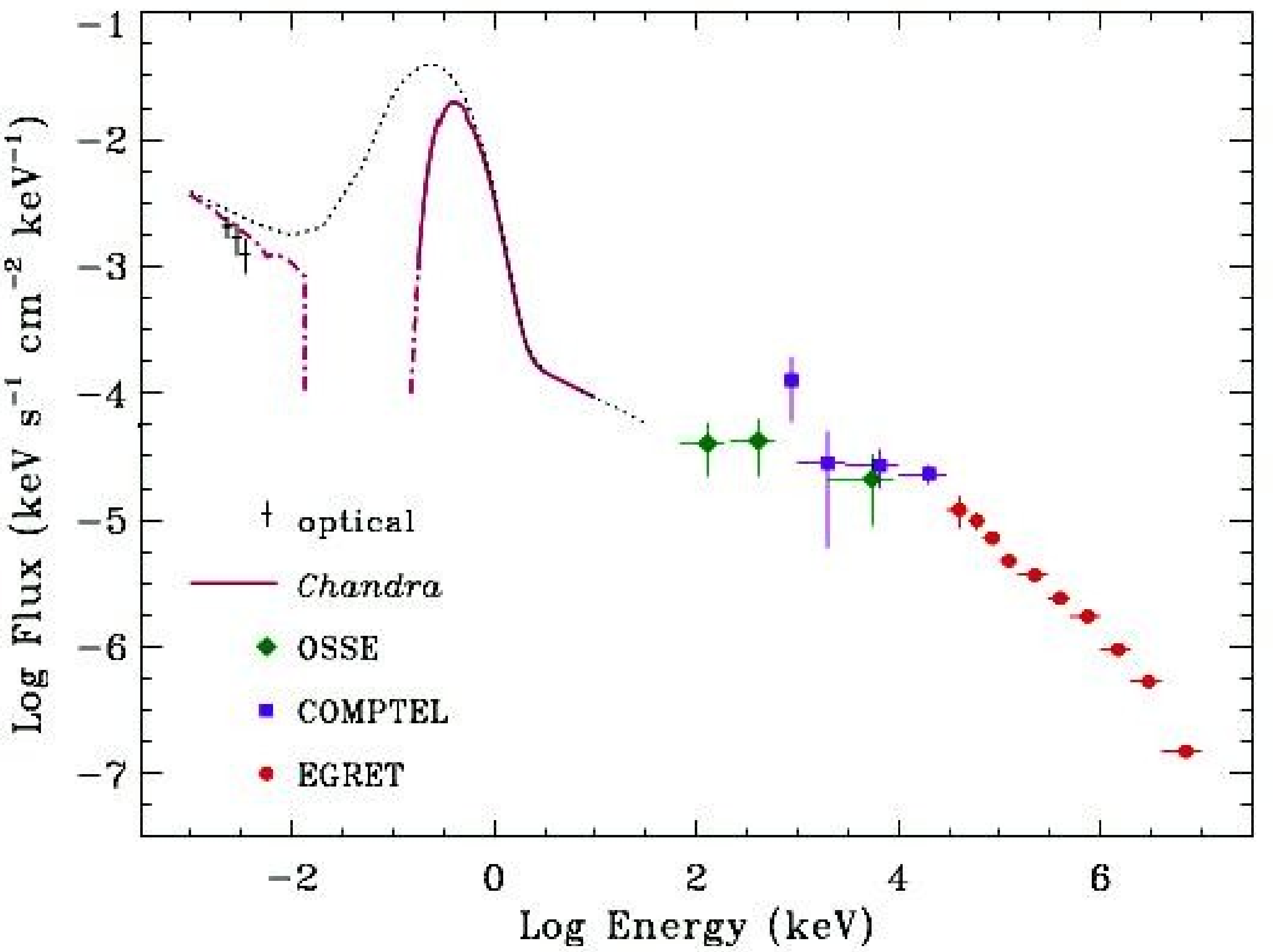
Plan:

1. Introduction
2. Fully ionized magnetic atmospheres
3. Partially ionized magnetic H atmospheres
4. Radiation from condensed surface
5. Integral spectra, thin and layered atmospheres
6. Heavier-element magnetic atmospheres
7. Challenges from superstrong fields
8. Link with observations. Cyclotron harmonics & the case of 1E 1207.4–5209.

Typical multiwavelength spectrum of an isolated neutron star

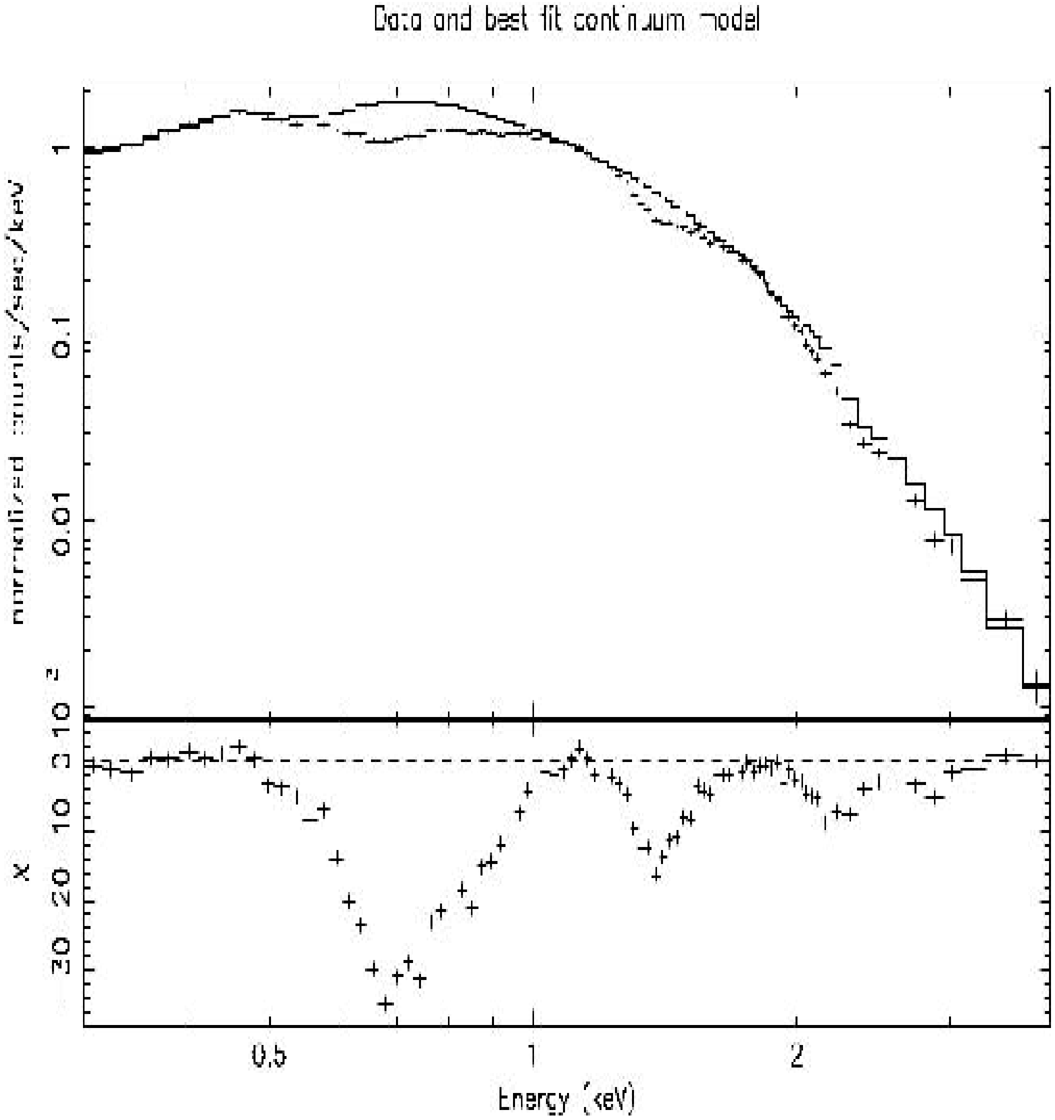


Multiwavelength spectrum of the Vela pulsar

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 lines in spectra of thermally emitting neutron stars

CCO 1E 1207.4–5209

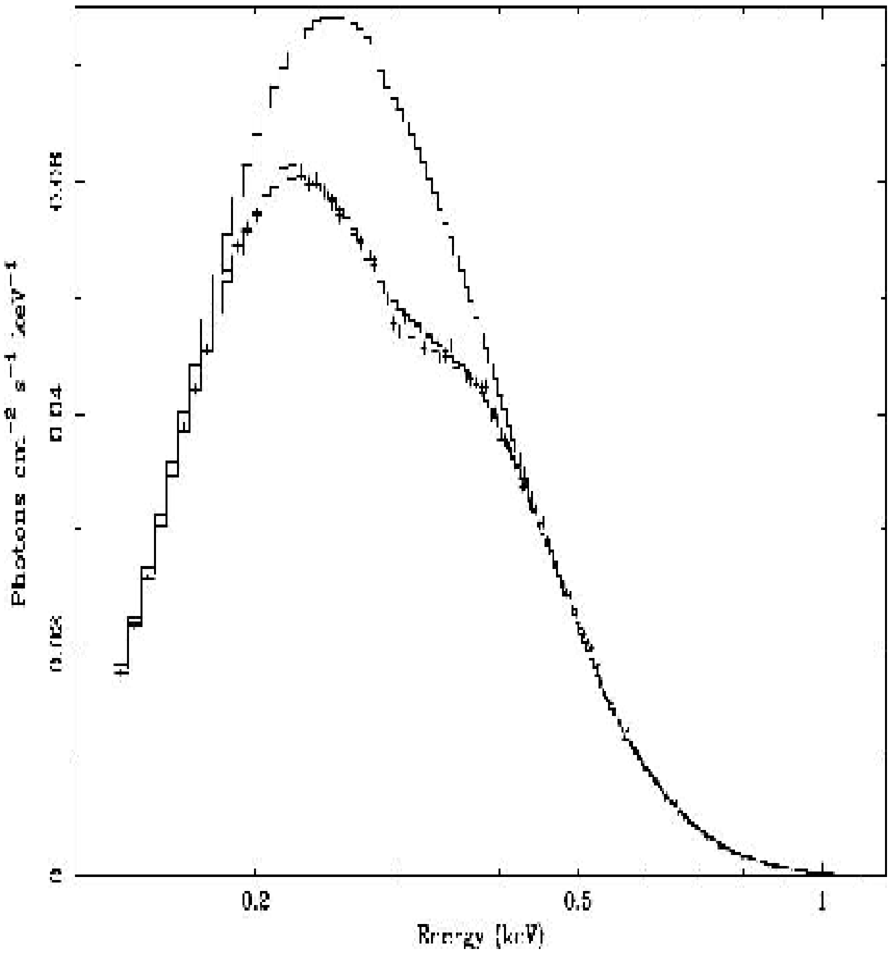


D.Sanwal *et al*. (2002);
S.Mereghetti *et al*. (2002);
G.Bignami *et al*. (2003):
2 (3? 4?) lines in 1E1207.4–5209.

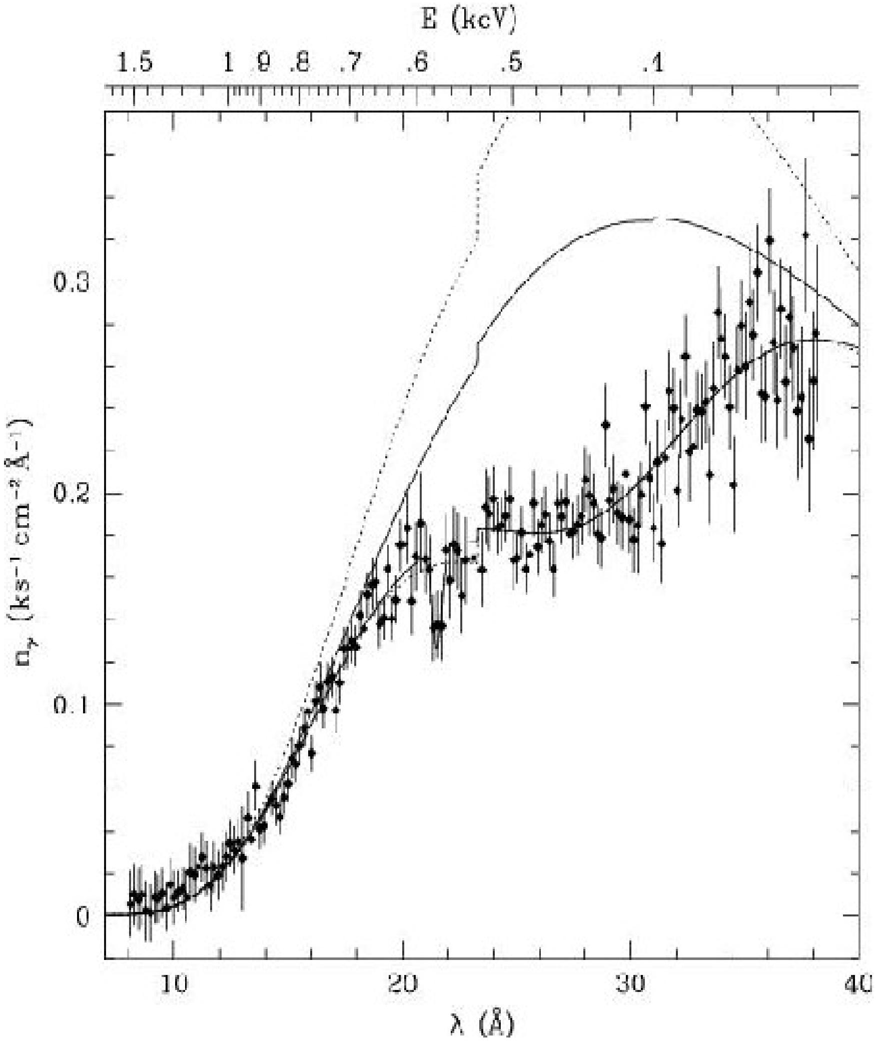
[Figure from Bignami *et al*. (2004) *Mem.S.A.It*. **75**, 448]

Absorption lines in spectra of thermally emitting neutron stars

XDINSs



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



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

XDINS – X-ray dim isolated neutron star

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Magnificent Seven

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NTEINS – nearby thermally emitting isolated neutron star (*David Kaplan*)

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NTEINS – nearby thermally emitting isolated neutron star (*David Kaplan*)

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RQINS – radio quiet isolated neutron star

INS – isolated neutron star (*Vicky Kaspi*)

XDINS – X-ray dim isolated neutron star

Magnificent Seven

NTEINS – nearby thermally emitting isolated neutron star (*David Kaplan*)

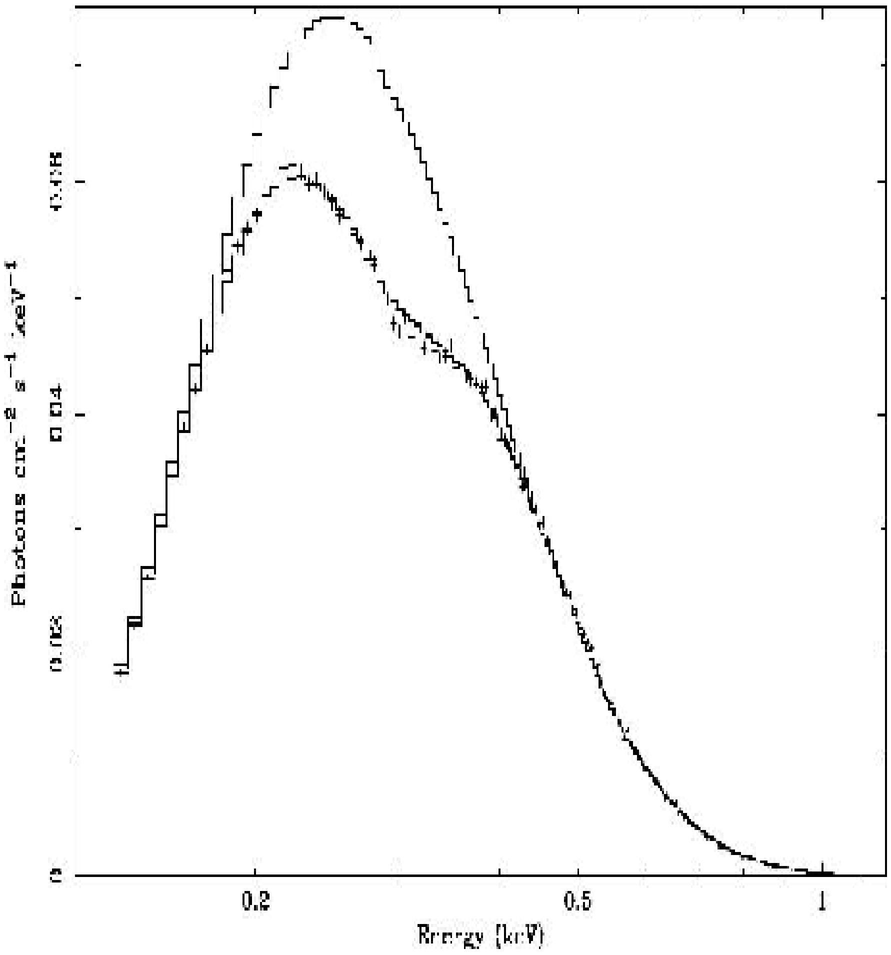
RQINS – radio quiet isolated neutron star

INS – isolated neutron star (*Vicky Kaspi*)

HMTERQINS – highly magnetized thermally emitting radio quiet isolated neutron star

Absorption lines in spectra of isolated neutron stars

XDINSs



F.Haberl *et al*. (2004) *A&A* **419**, 1077:
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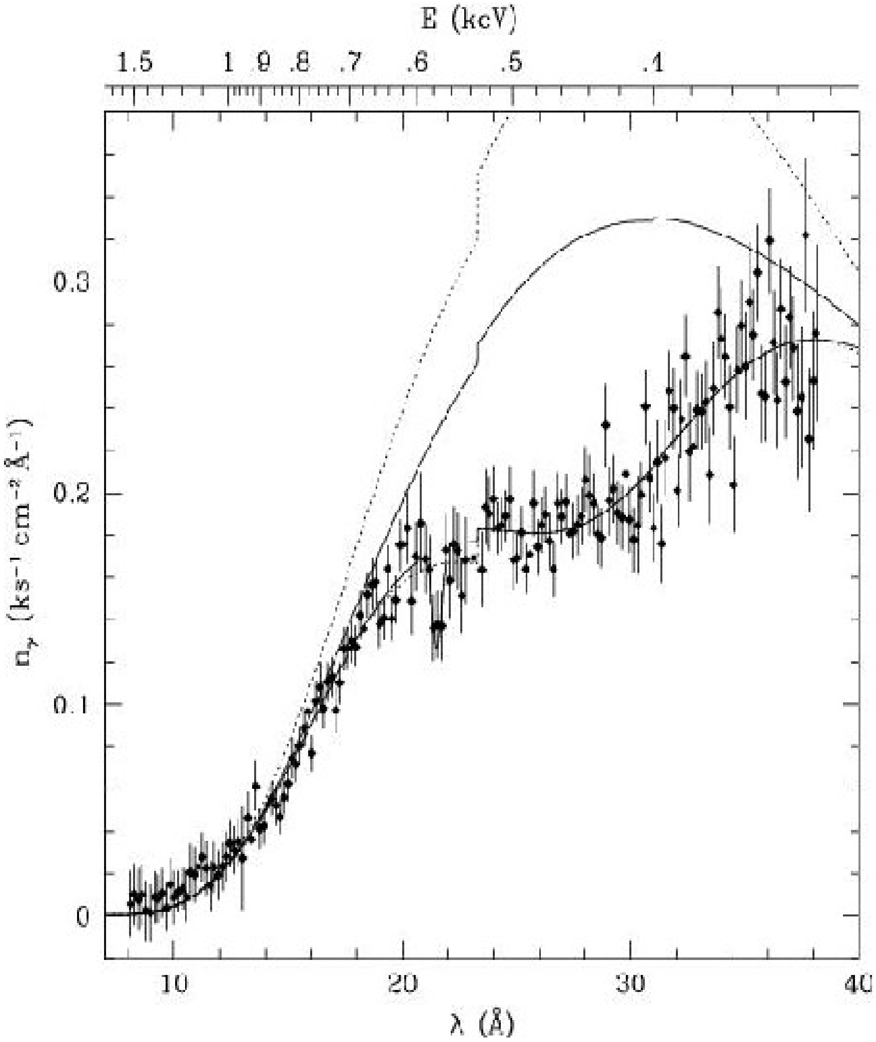
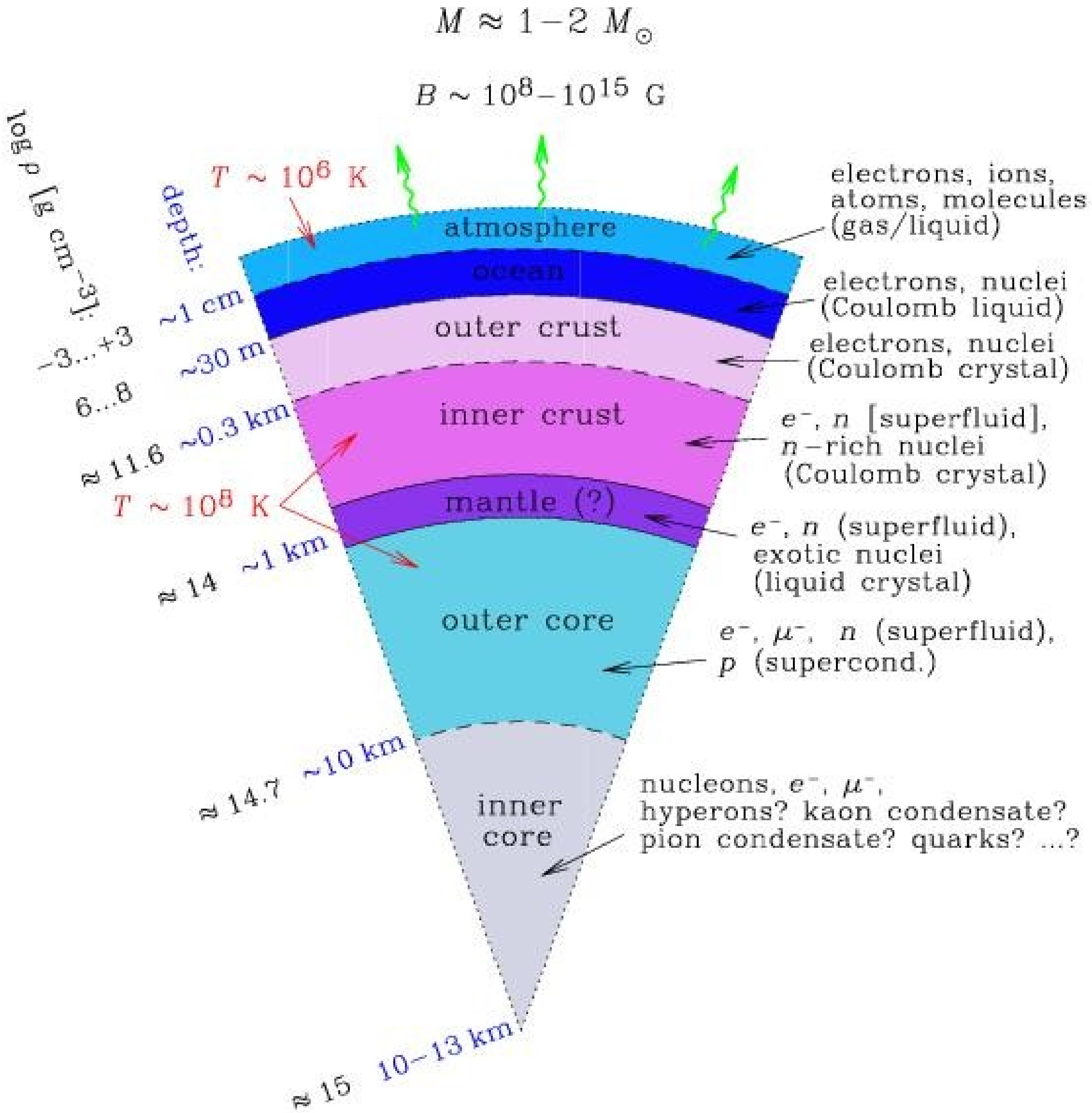
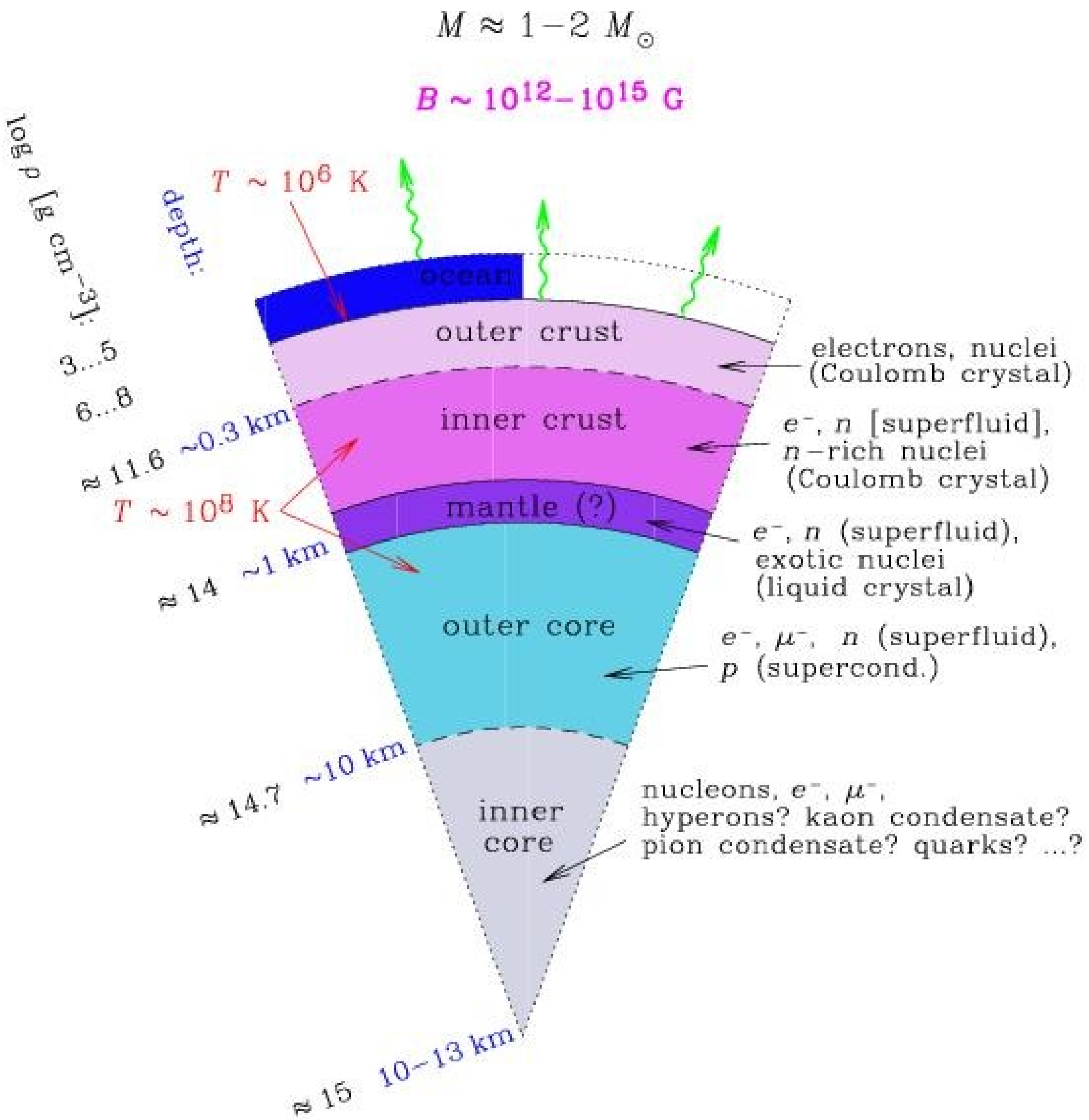


M. van Kerkwijk *et al*. (2004) *ApJ* **608**, 432:
absorption in RX J1605.3+3249

Neutron star structure



Neutron star without atmosphere: possible result of a phase transition



Characteristic values of the magnetic field

- Strong magnetic field *B* :

$$\hbar\omega_c = \hbar eB/m_e c > 1 \text{ a.u.}$$

$$B > m_e^2 ce^3/\hbar^3 = 2.35 \times 10^9 \text{ G}$$

- Superstrong field :

$$\hbar\omega_c > m_e c^2$$

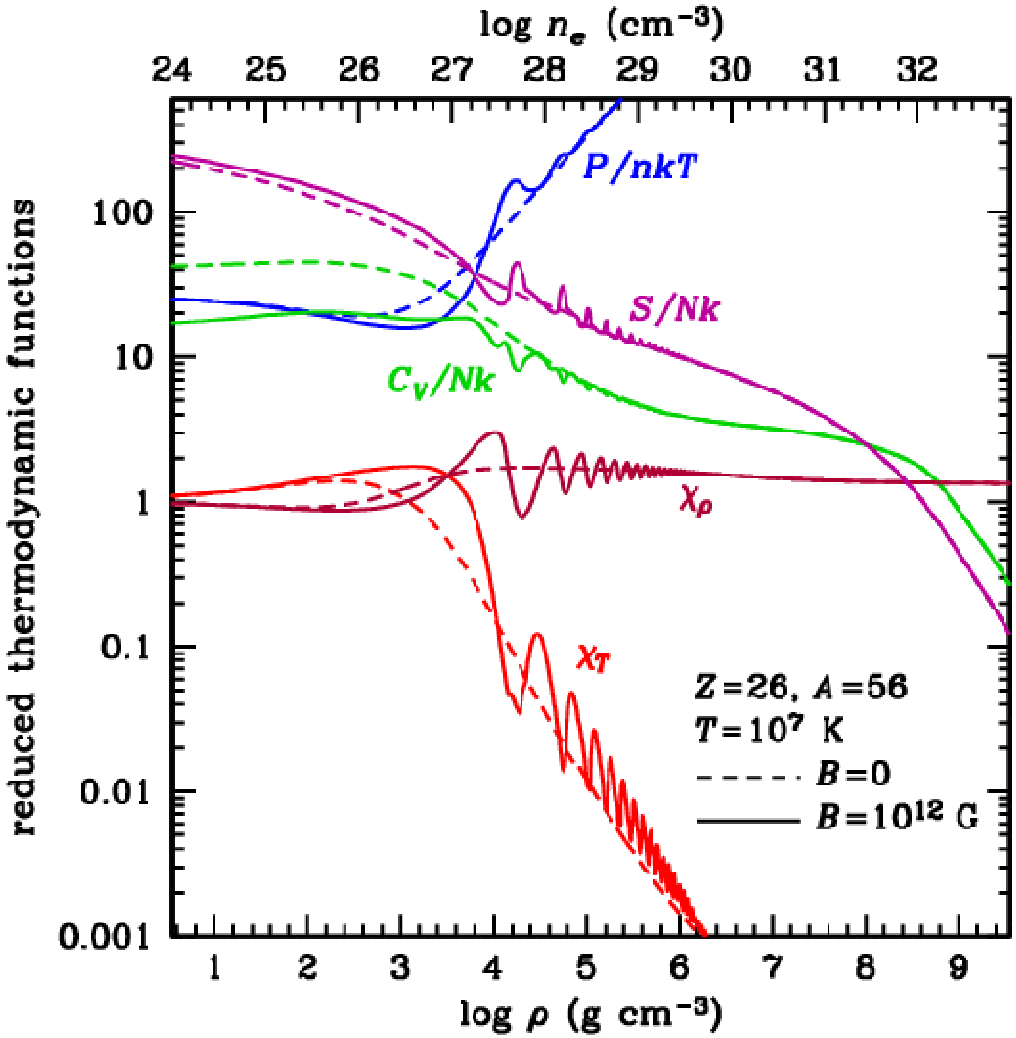
$$B > m_e^2 c^3/e\hbar = 4.4 \times 10^{13} \text{ G}$$

- Strongly quantizing magnetic field :

$$\rho < \rho_B = m_{\text{ion}} n_B \langle A\rangle/\langle Z\rangle \approx 7 \times 10^3 B_{12}^{3/2} (\langle A\rangle/\langle Z\rangle) \text{ g cm}^{-3}$$

$$T \ll T_B = \hbar\omega_c / k_B \approx 1.3 \times 10^8 B_{12} \text{ K}$$

Equation of state of magnetic neutron star envelopes

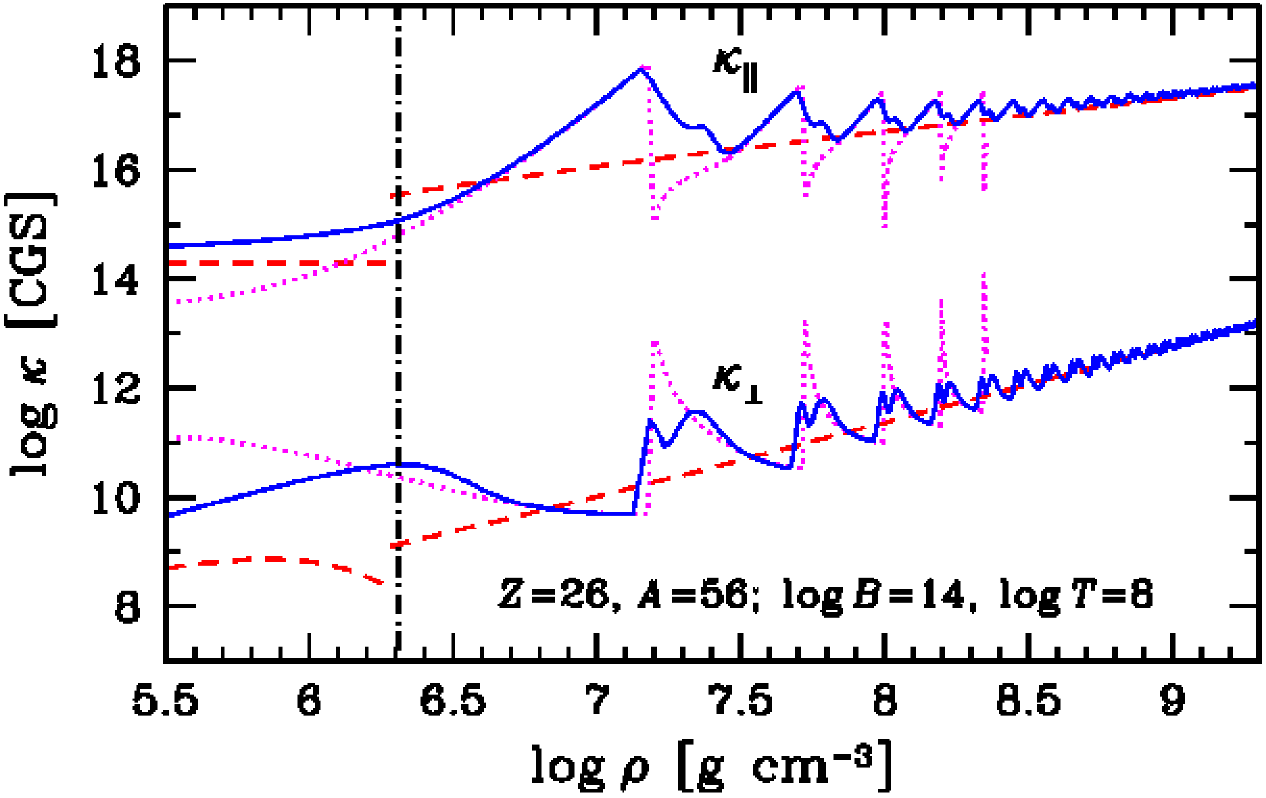


Normalized thermodynamic functions of fully ionized iron without magnetic field (dashed lines) and in a strong magnetic field (solid lines)

[**Haensel et al.,** ***Neutron Stars. 1. Equation of State and Structure*** (Springer, New York, 2007), Chap.4, + refs. therein]

Thermal conductivities in a strongly magnetized envelope

http://www.ioffe.ru/astro/conduct/



Solid – exact, dots – without T-integration, dashes – magnetically non-quantized

Ventura & Potekhin (2001), in *The Neutron Star – Black Hole Connection*, ed. Kouveliotou *et al*. (Dordrecht: Kluwer) 393

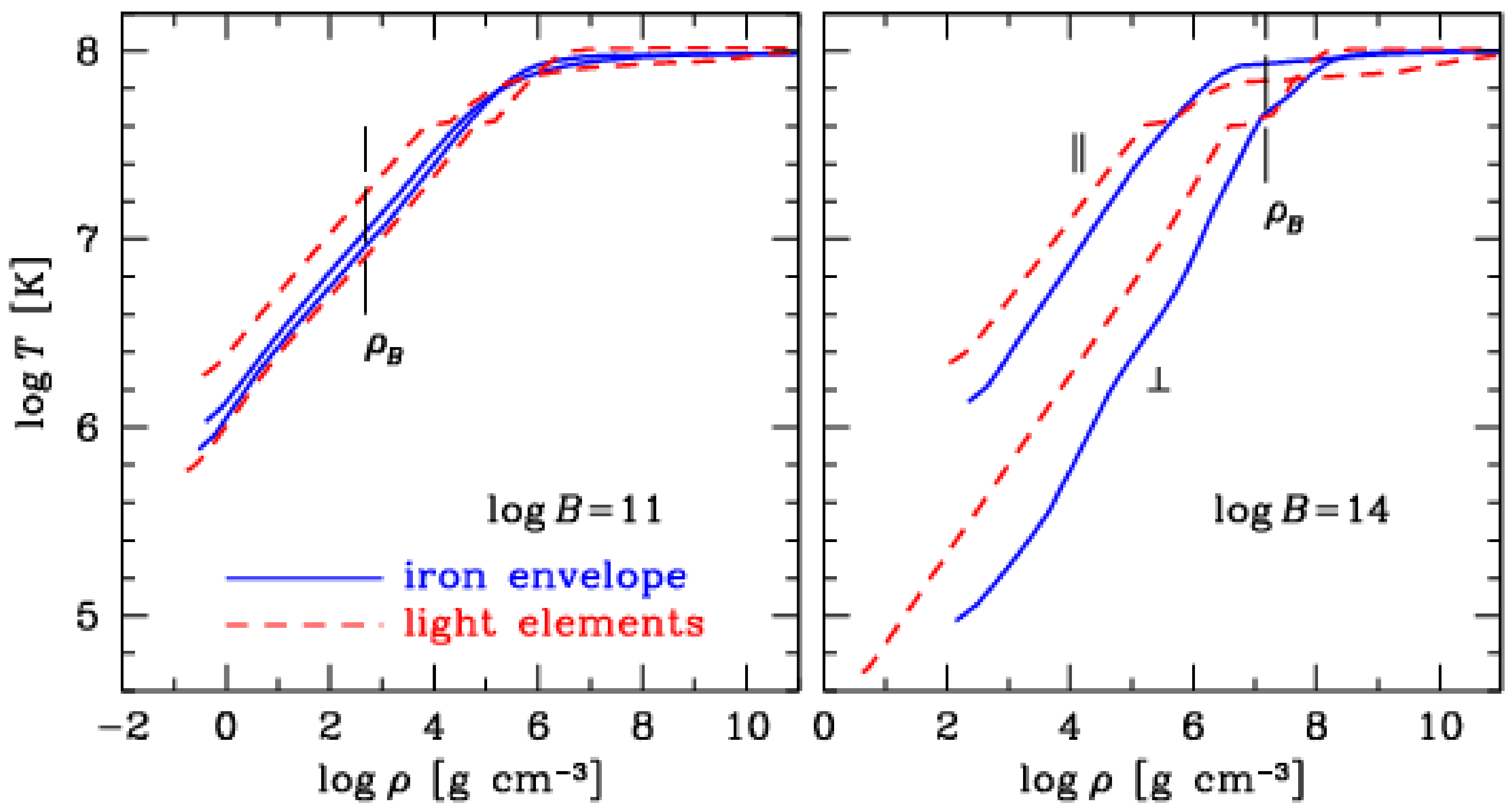
***Summary and update*:** Cassisi, Potekhin, Pietrinferni, Catelan, & Salaris (2007) *Astrophys.J.* **661**, 1094 **[+ references!]**

***Heat conduction by ions*:** Chugunov & Haensel (2009) *MNRAS* **381**, 1143

***Heat conduction by neutrons*:** Aguilera et al. (2009) *Phys. Rev. Lett.* **102**, 091109

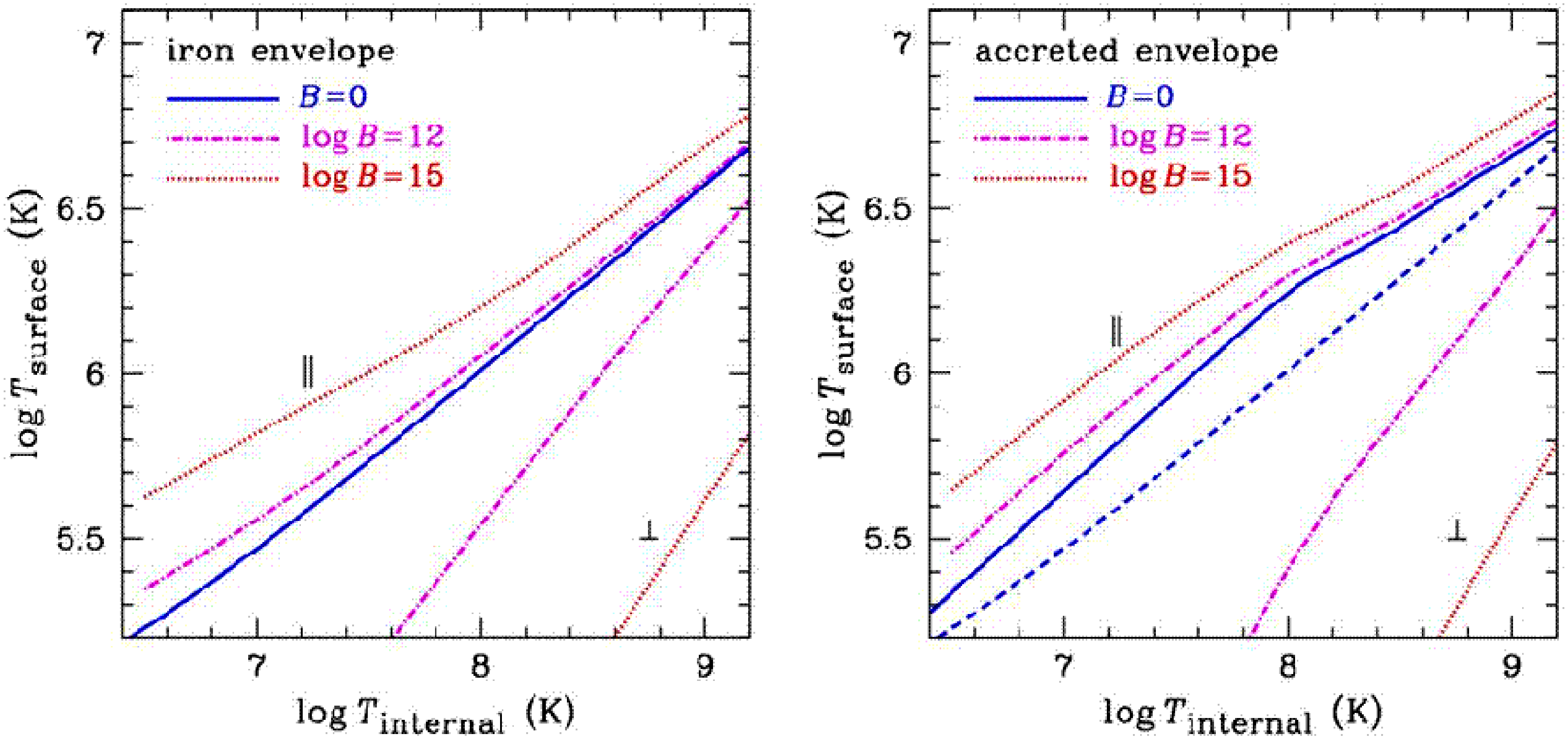
***Electron conduction at very low temperatures*:** Chugunov (2011), to be published

Temperature profiles in envelopes of neutron stars with strong magnetic fields



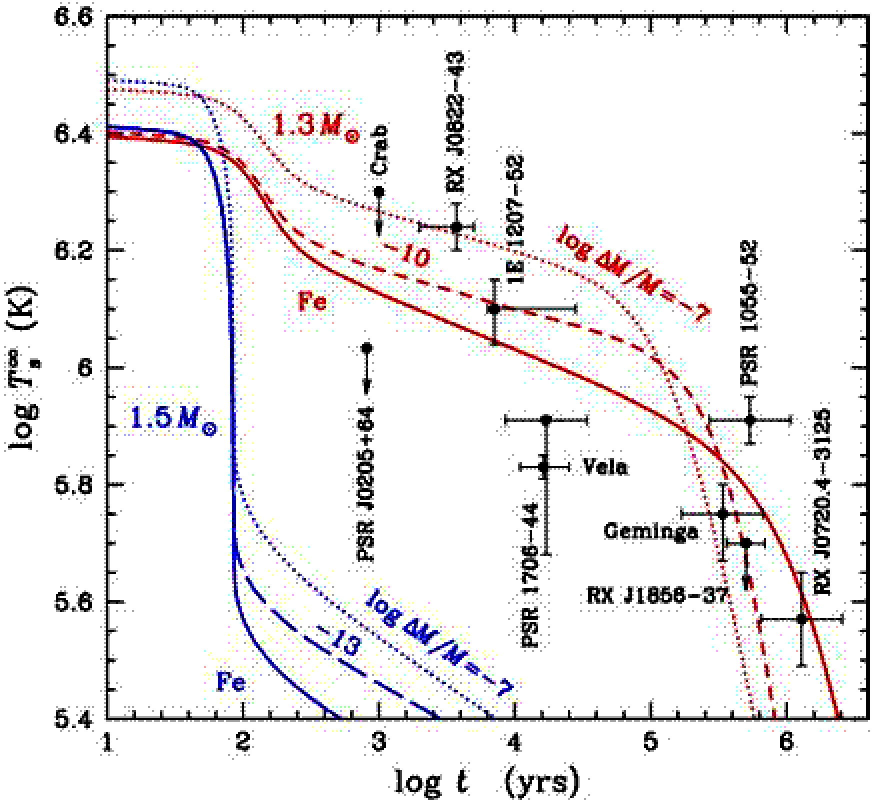
$T_s - T_b$

Temperature drops in magnetized envelopes of neutron stars

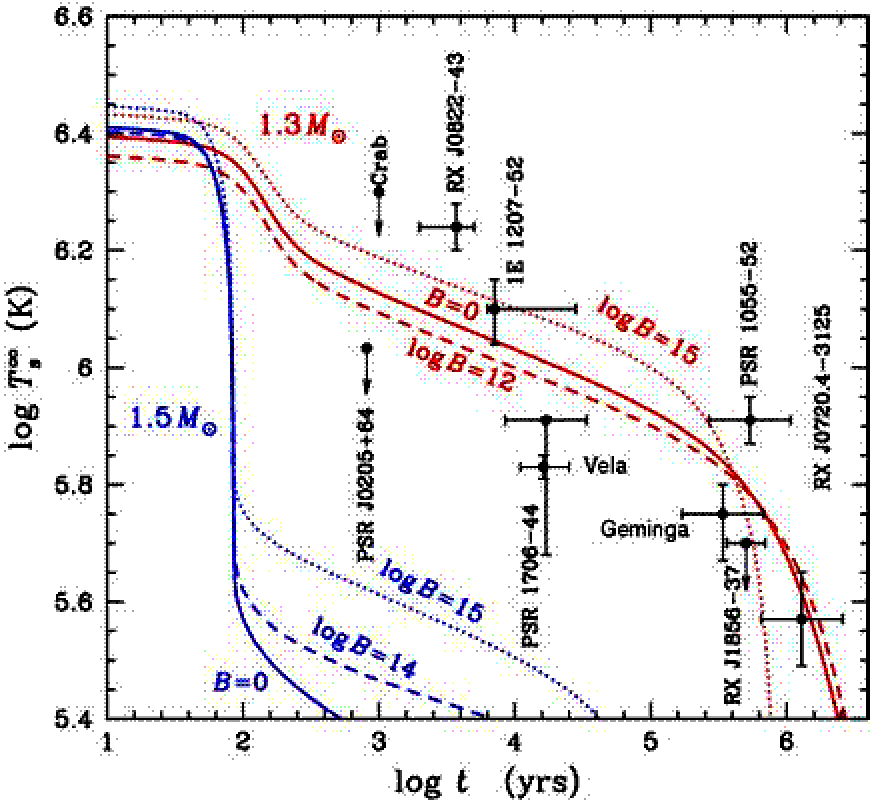


Potekhin, Yakovlev, Chabrier, & Gnedin (2003) *Astrophys.J.* **594**, 404

Cooling of neutron stars with ***accreted envelopes***



Cooling of neutron stars with ***magnetized envelopes***



Chabrier, Saumon, & Potekhin (2006) *J.Phys.A: Math. Gen.* **39**, 4411

Atmospheres: general

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

General algorithm - solution of coupled equations:
- Hydrostatic equilibrium
- Energy balance
- Radiative transfer

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Basic ingredients:
- Equation of state
- Radiative opacities

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Basic ingredients:

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This generally requires:

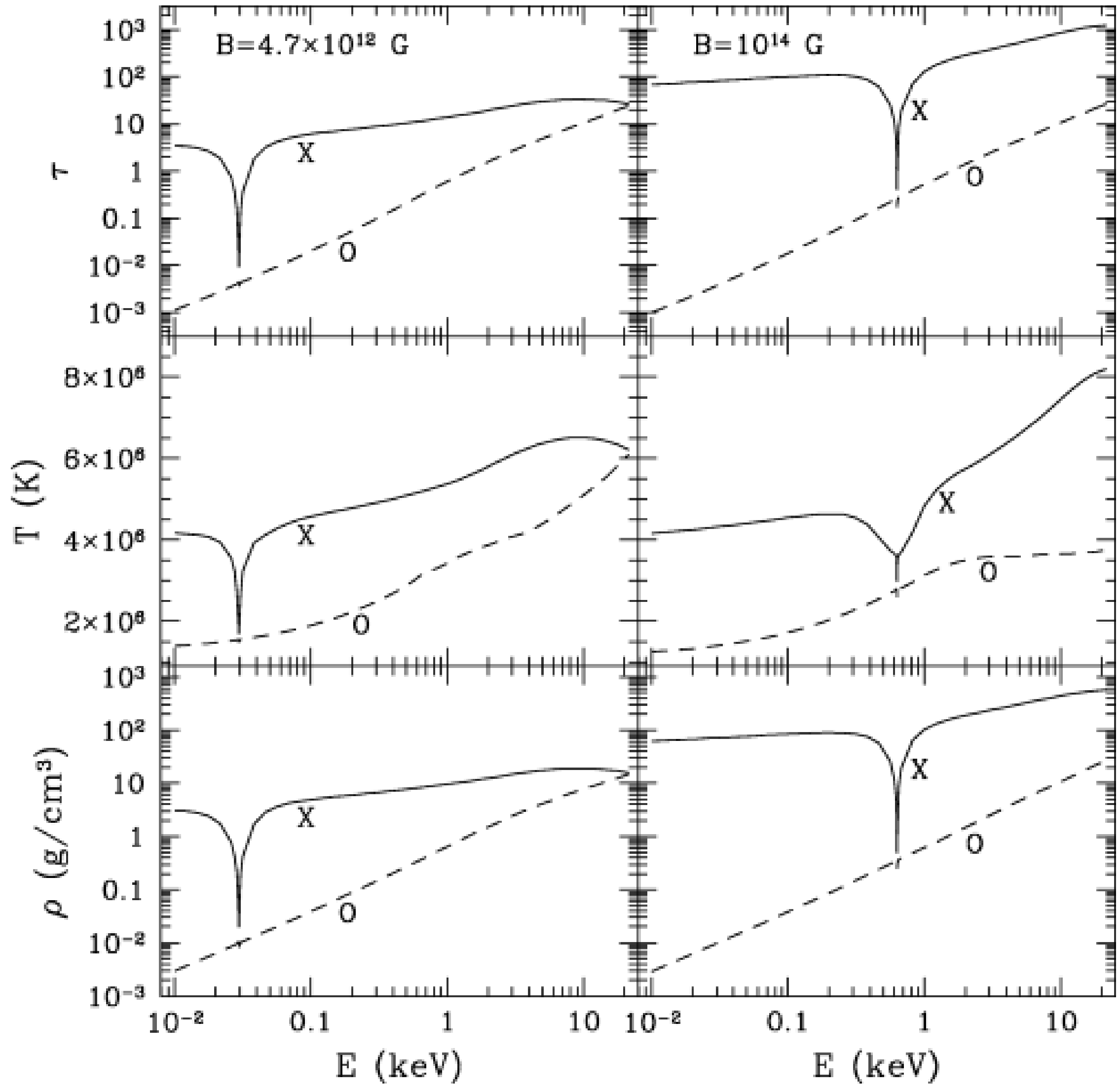
- Atomic and molecular data (binding energies, cross sections)
- Ionization and dissociation equilibrium
- Thermodynamic quantities
- Treatment of plasma effects (line broadening, pressure ionization, etc.)

Fully ionized neutron star atmospheres with strong magnetic fields

Yu.N.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)

W.C.G.Ho & D.Lai
(2000s)



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

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

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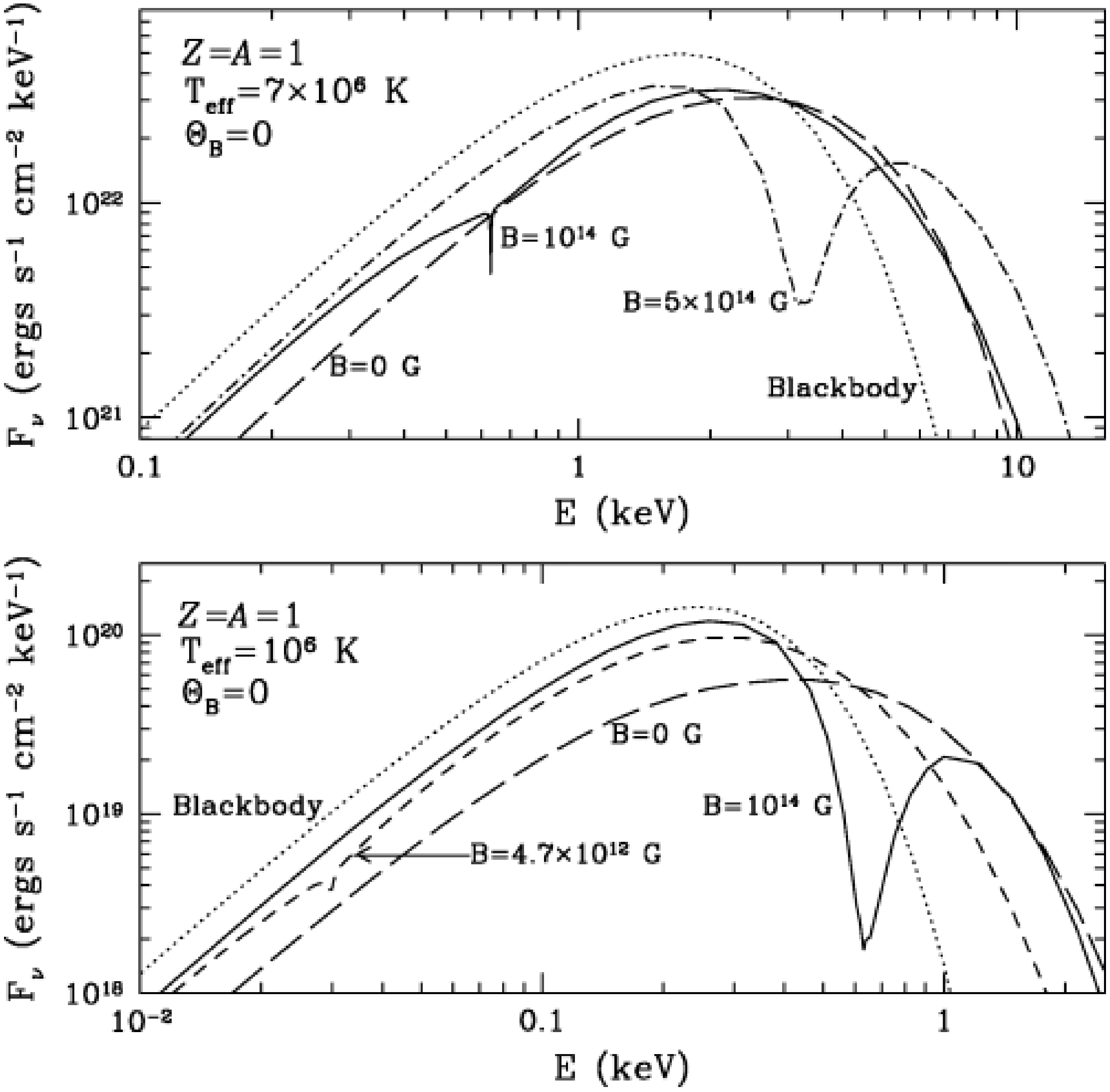


Comparison of spectra for non-magnetic and magnetic H atmospheres

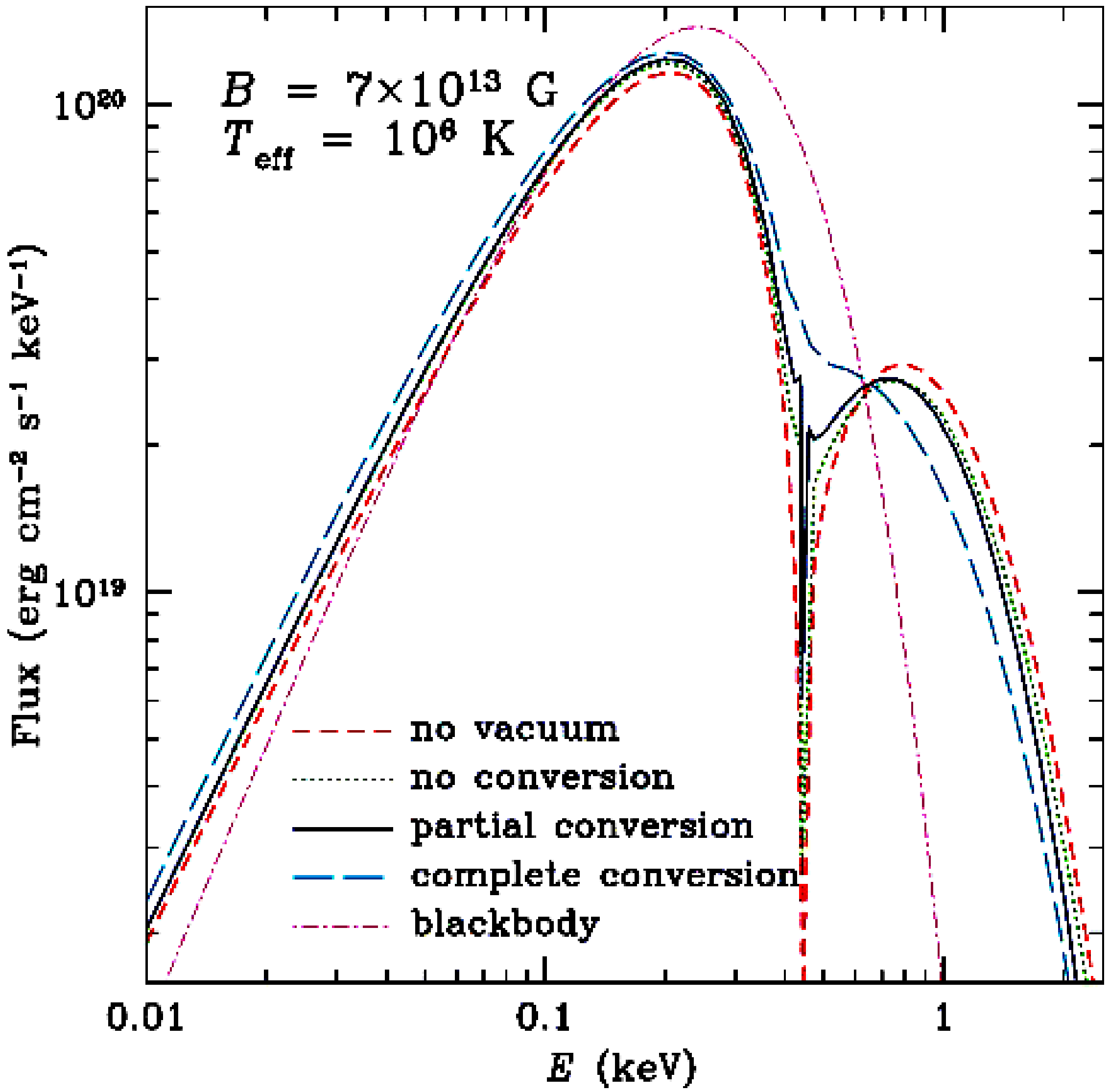
W.C.G.Ho & D.Lai (2001) *MNRAS* **327**, 1081

The effect of vacuum polarization

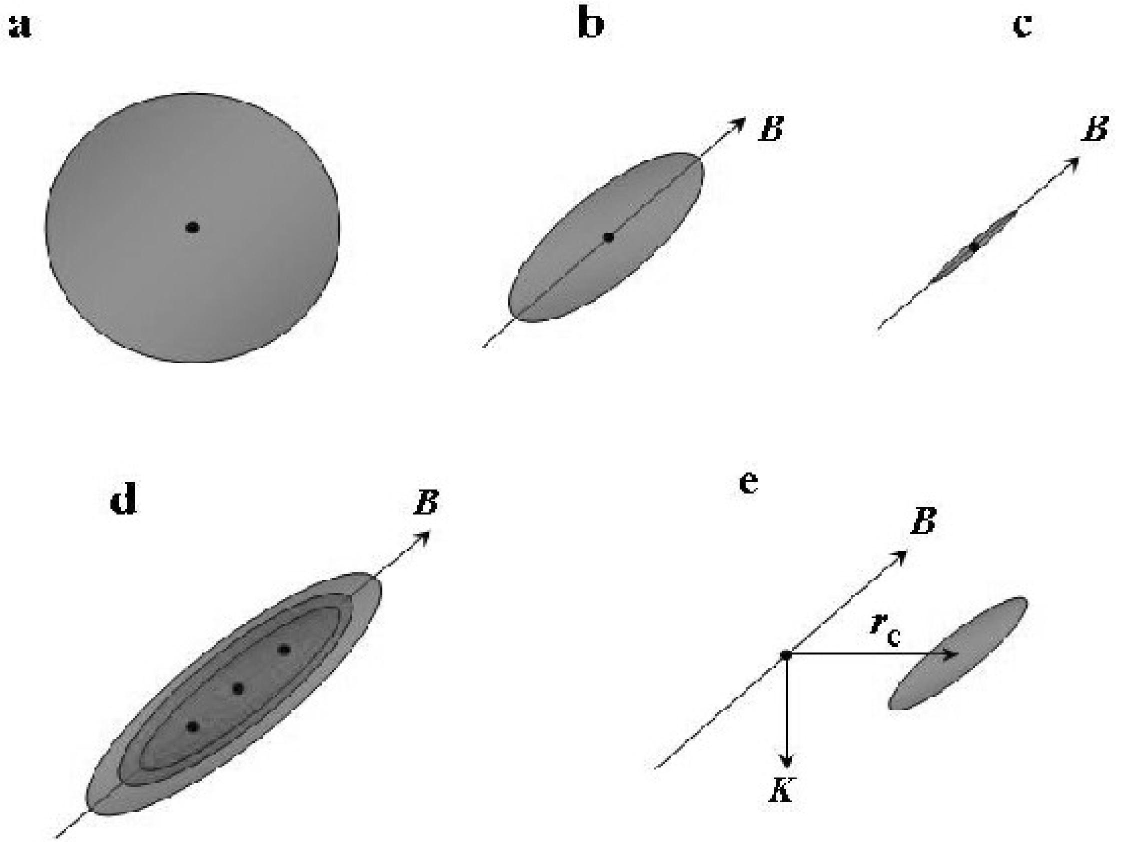
Yu.N.Gnedin & G.G.Pavlov
(1970s – 1984)

W.C.G.Ho & D.Lai (2003)
MRNAS **338**, 233

M.van Adelsberg & D.Lai
(2007) *MRNAS* **373**, 495

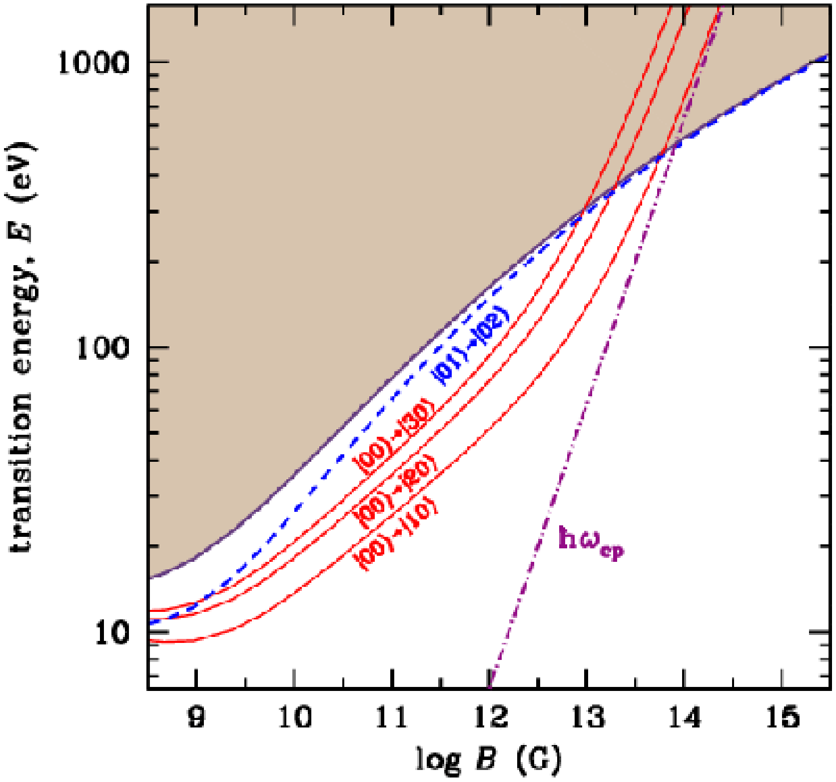


Bound species in a strong magnetic field

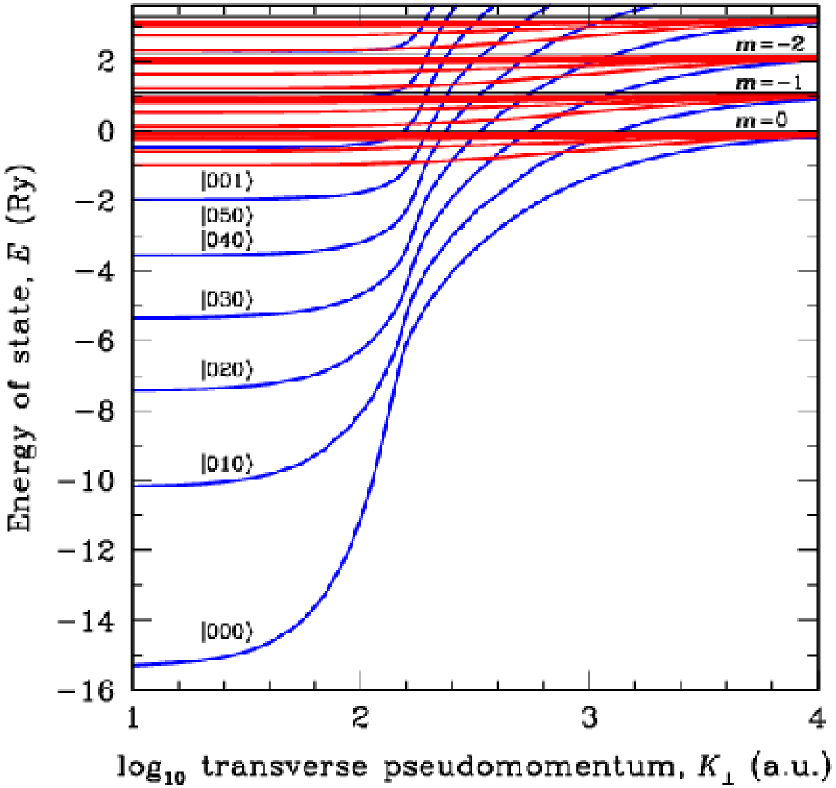


The effects of a strong magnetic field on the atoms and molecules.
a–c: H atom in the ground state (**a**: $B \ll 10^9$ G, **b**: $B \sim 10^{10}$ G, **c**: $B \sim 10^{12}$ G).
d: The field stabilizes the molecular chains (H_3 is shown).
e: H atom moving across the field becomes decentered.

Bound species in a strong magnetic field

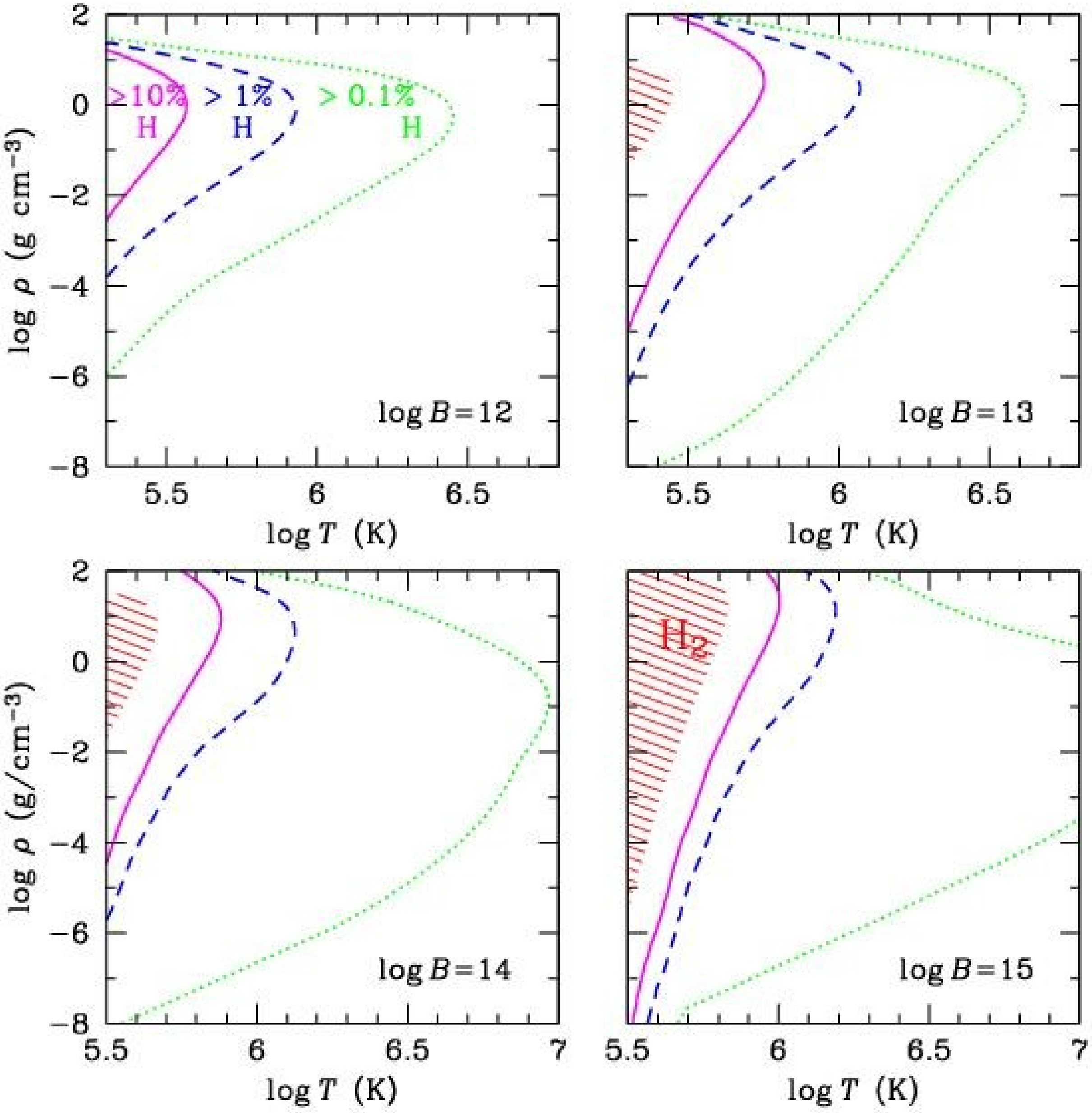


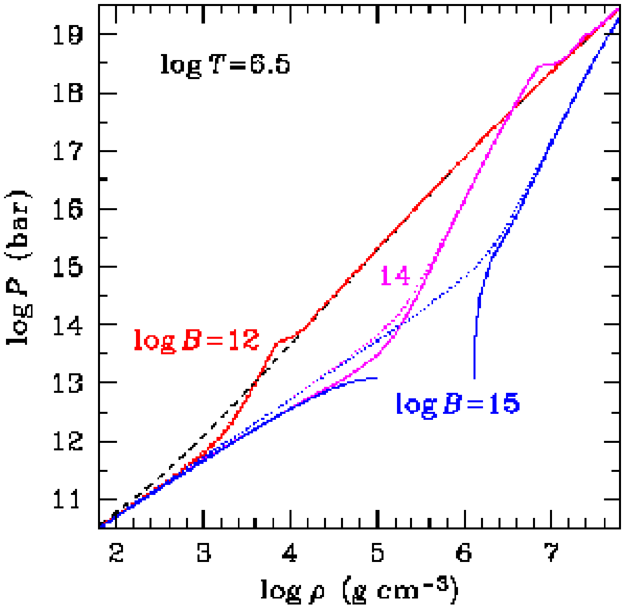
Main transition energies of the hydrogen atom in a magnetic field
[Potekhin & Chabrier (2004) *ApJ*, **600**, 317]



Binding energies of the hydrogen atom in the magnetic field B=2.35x10^{12} G as functions of its state of motion across the field
[Potekhin (1994) *J.Phys.B: At. Mol. Opt. Phys.* **27**, 1073]

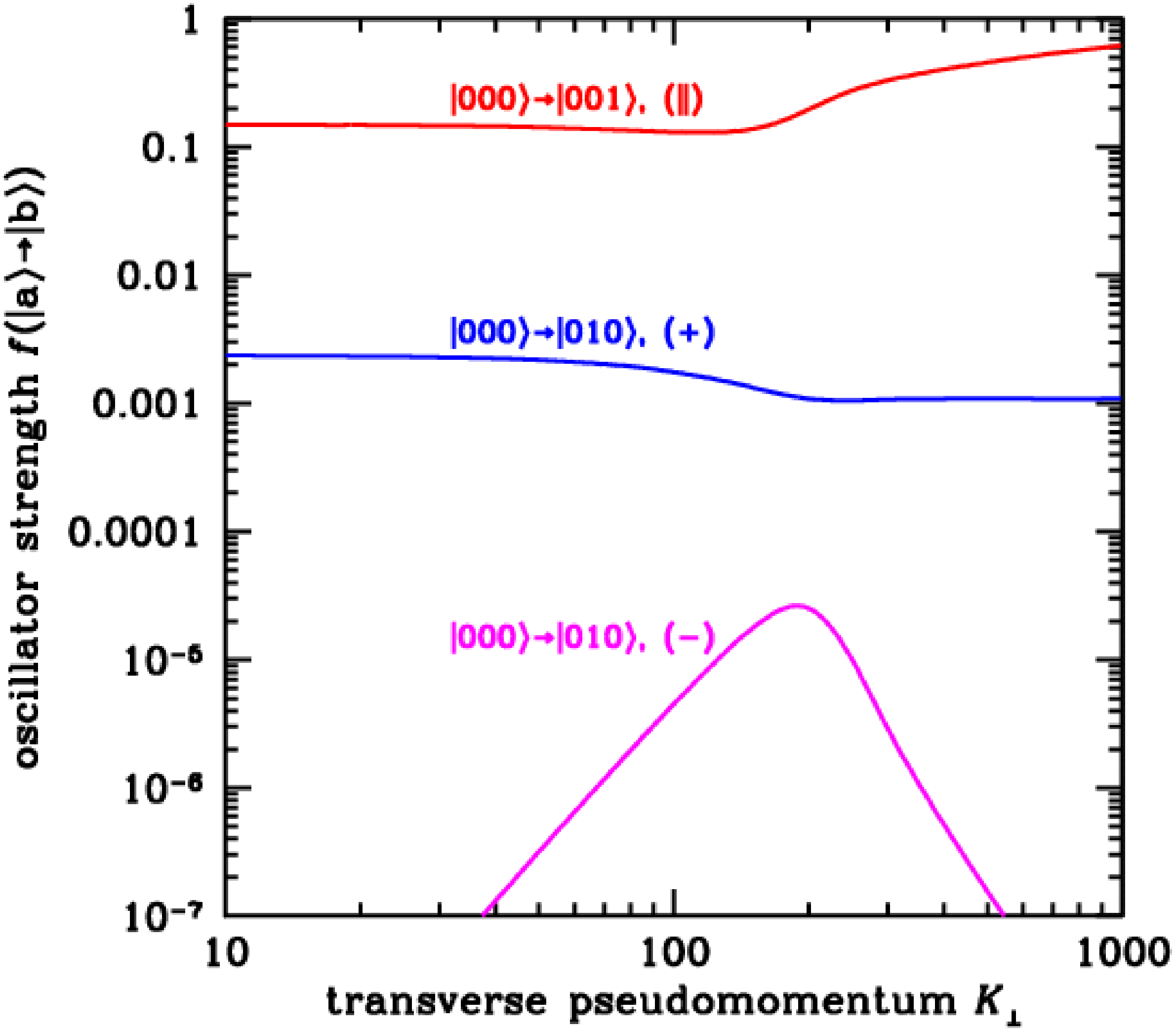
Ionization equilibrium and the equation of state of hydrogen in strong magnetic fields: the effects of nonideality and partial ionization





EOS of ideal (dotted lines) and nonideal (solid lines) H plasmas at various field strengths
[Potekhin & Chabrier (2004) *Astrophys.J.* **600**, 317]

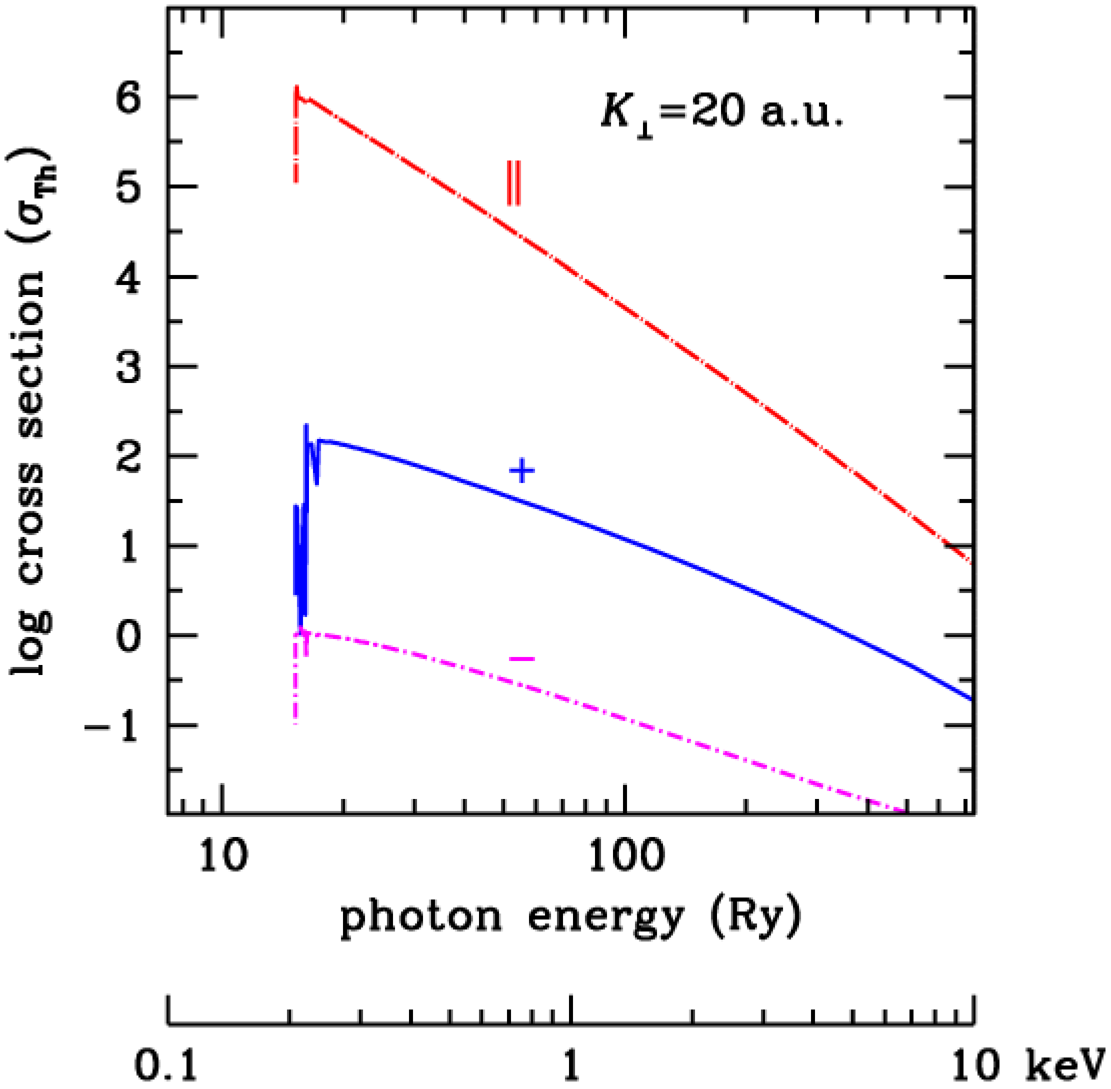
Bound-bound transitions in strong magnetic field



Oscillator strengths for transitions between 2 levels of the hydrogen atom at B=2.35x10^{12} G, as functions of pseudomomentum

[Potekhin (1994) *J.Phys.B: At. Mol. Opt. Phys.* **27**, 1073]

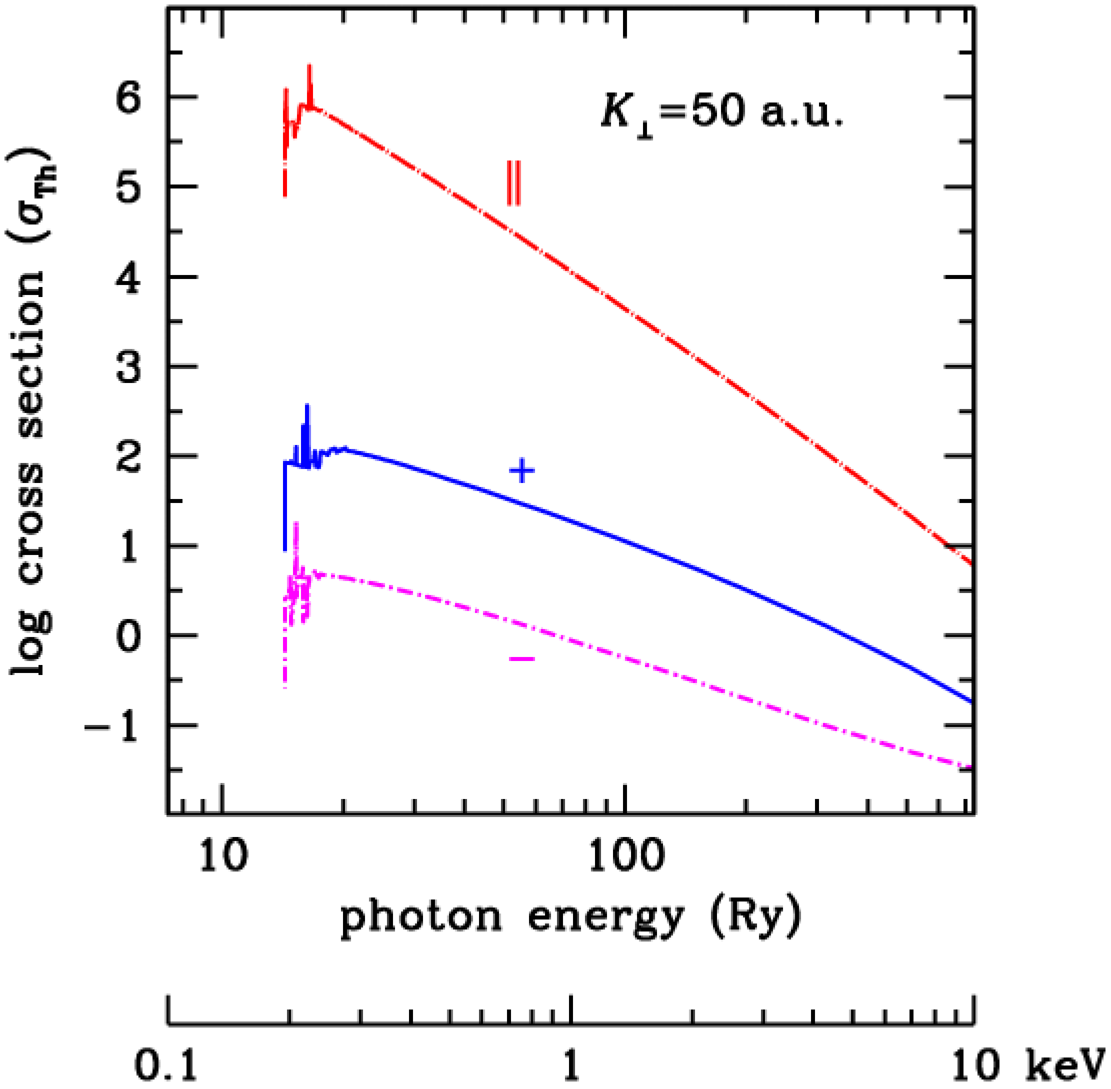
Bound-free transitions in strong magnetic field



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

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

Bound-free transitions in strong magnetic field



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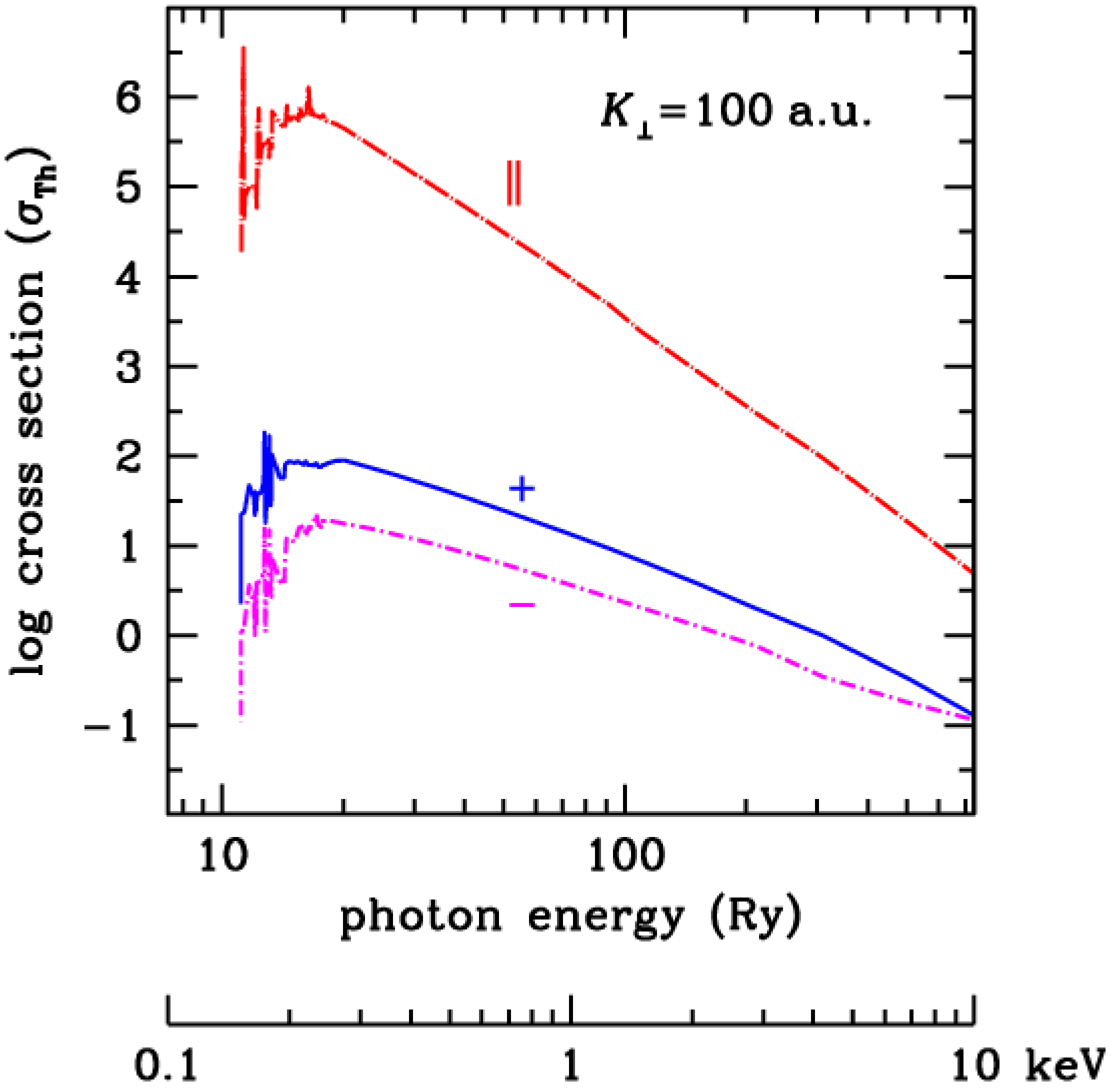

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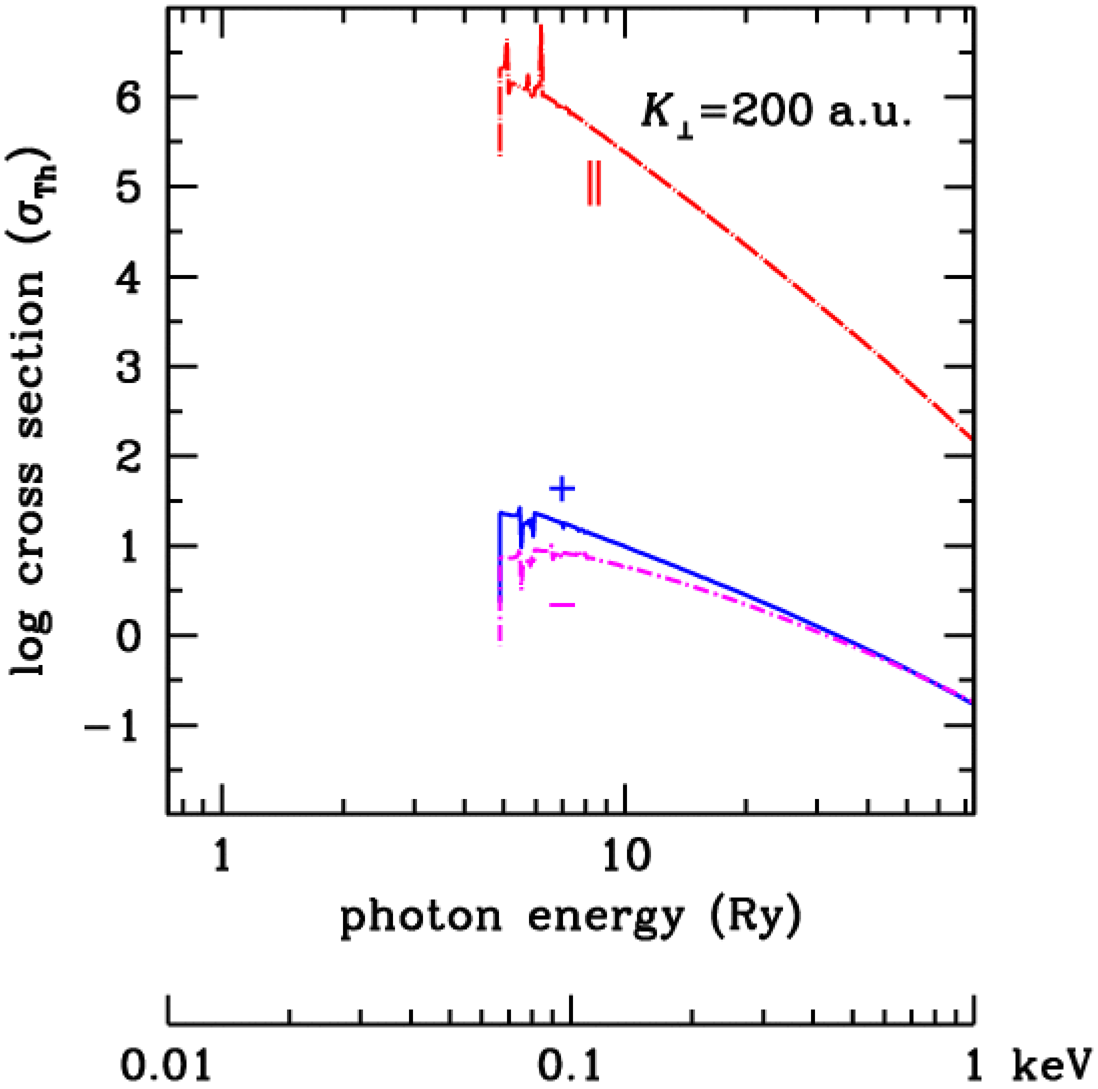

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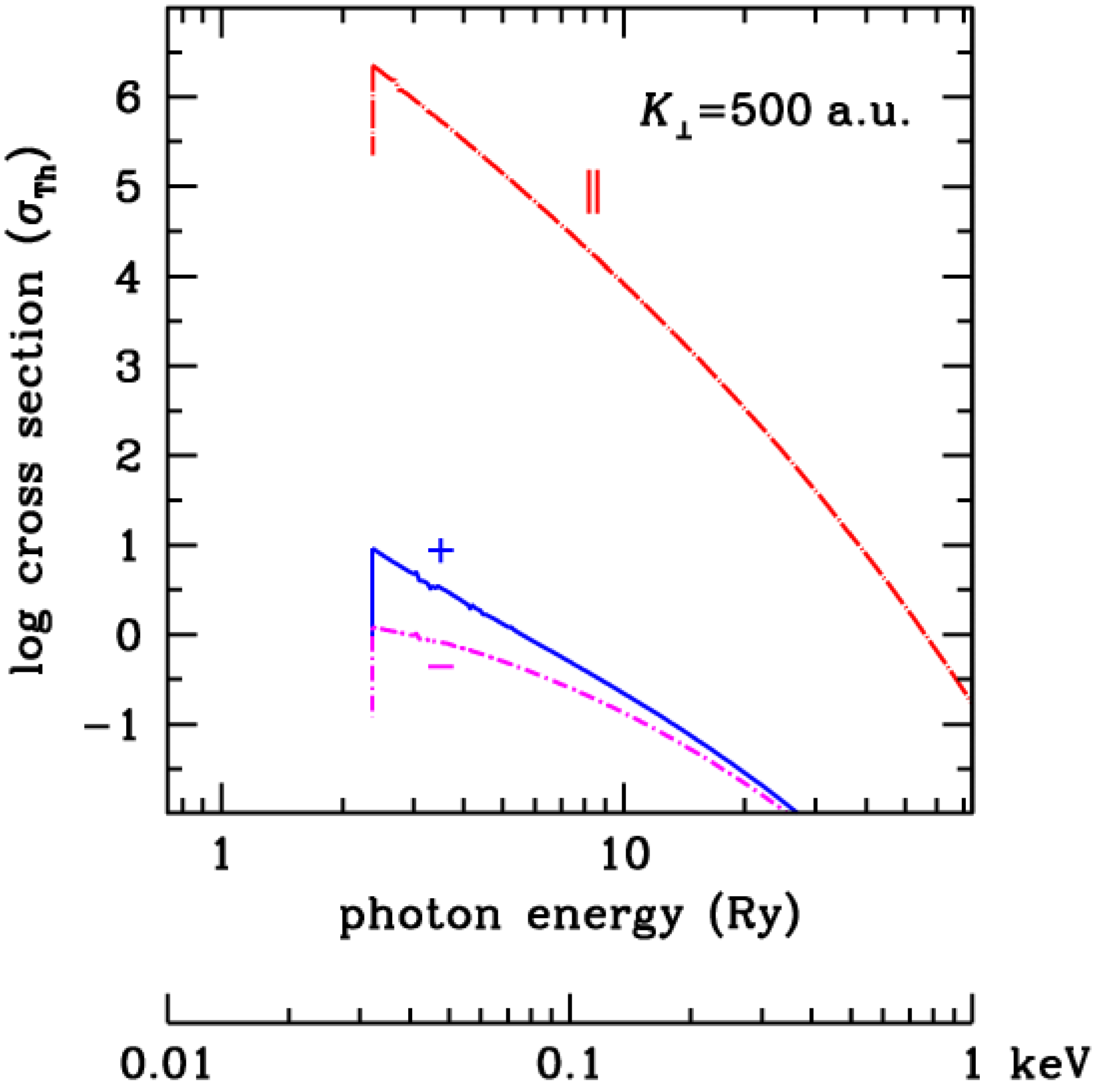
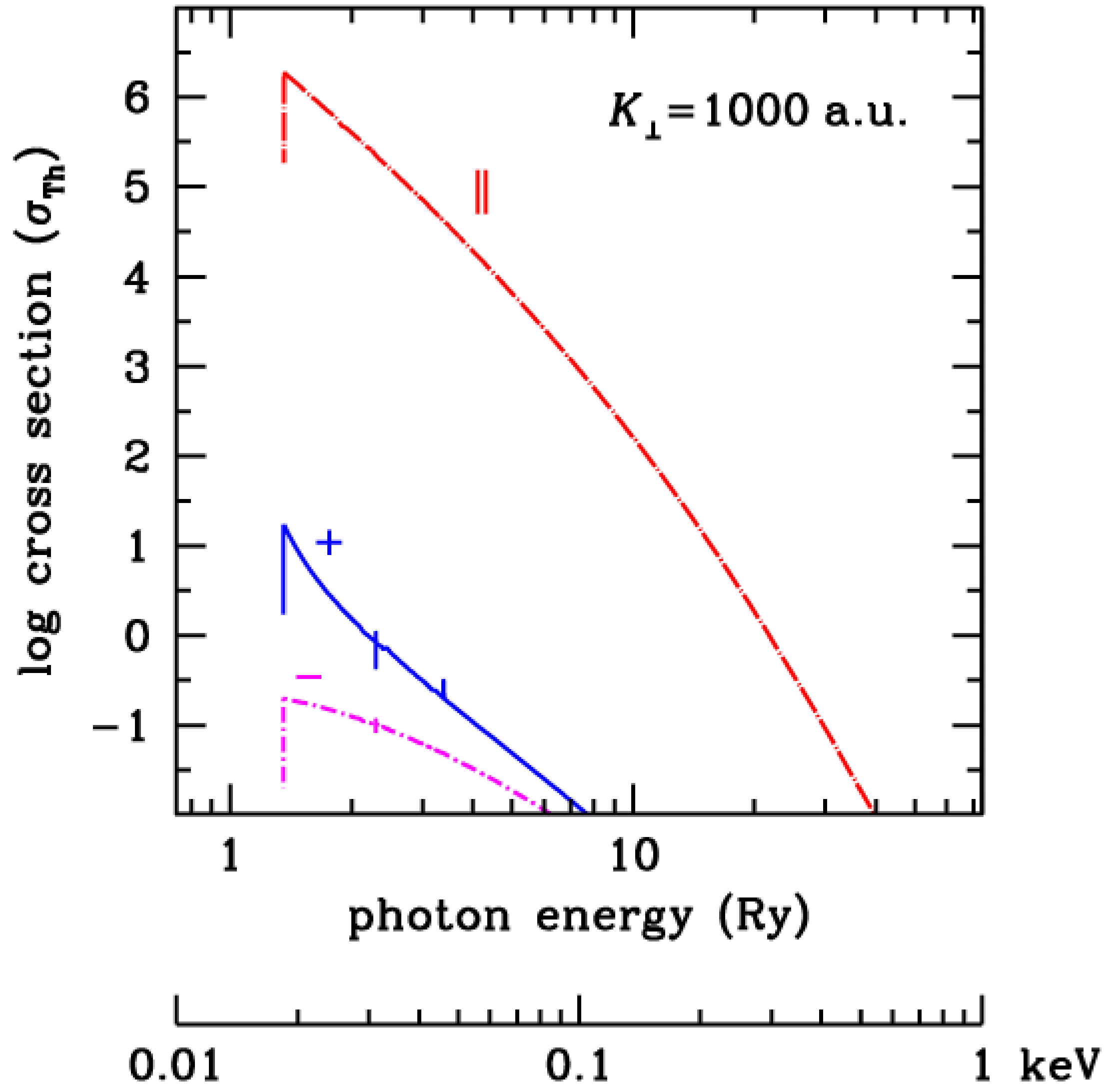


Photoionization cross sections for the ground-state H atom at $B=2.35\times10^{12}$ G

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

Bound-free transitions in strong magnetic field



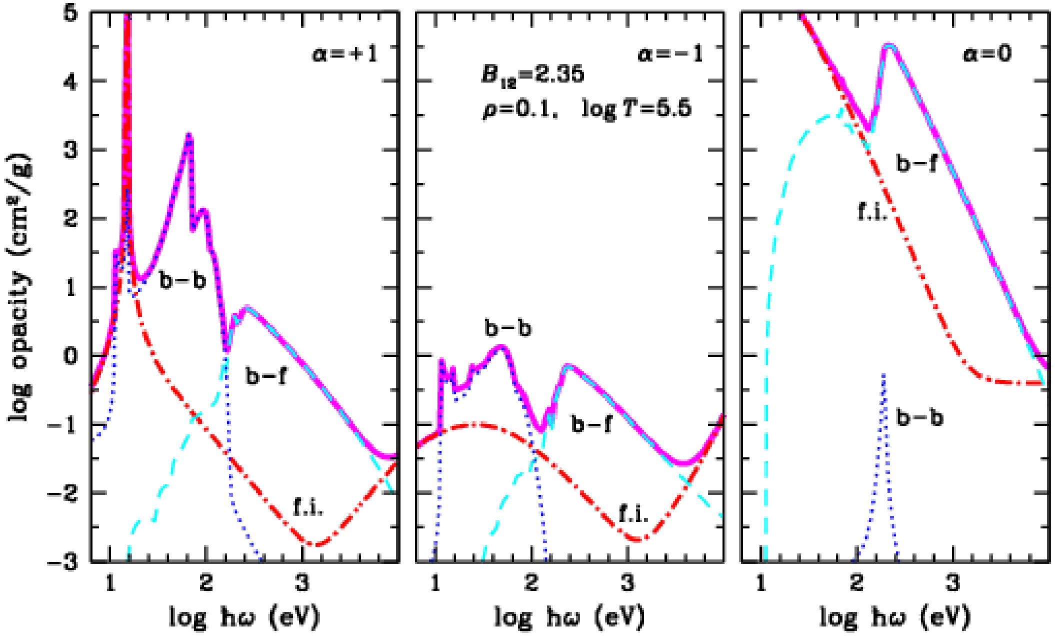
Photoionization cross sections for the ground-state H atom at B=2.35×10^{12} G

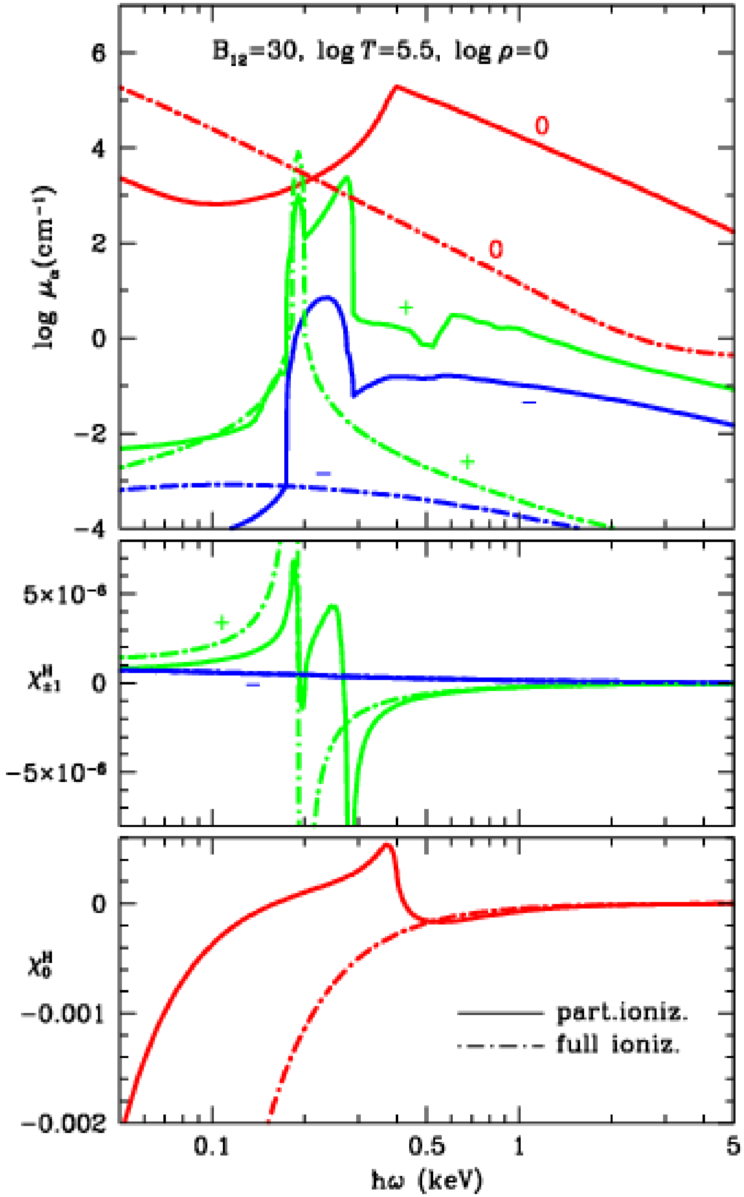
[Potekhin & Pavlov (1997) *Astrophys. J.* **483**, 414]

Plasma absorption and polarizabilities in strong magnetic fields:

The effects of nonideality and partial ionization

$$\kappa_j(\omega,\theta_B) = \sum_{\alpha=-1}^{1} |e_\alpha^j(\omega,\theta_B)|^2\, \hat{\kappa}_\alpha(\omega), \qquad j = 1, 2\ (\mathrm{X,O})$$





Spectral opacities for 3 basic polarizations.

Solid lines – taking into account bound states,

dot-dashes –full ionization

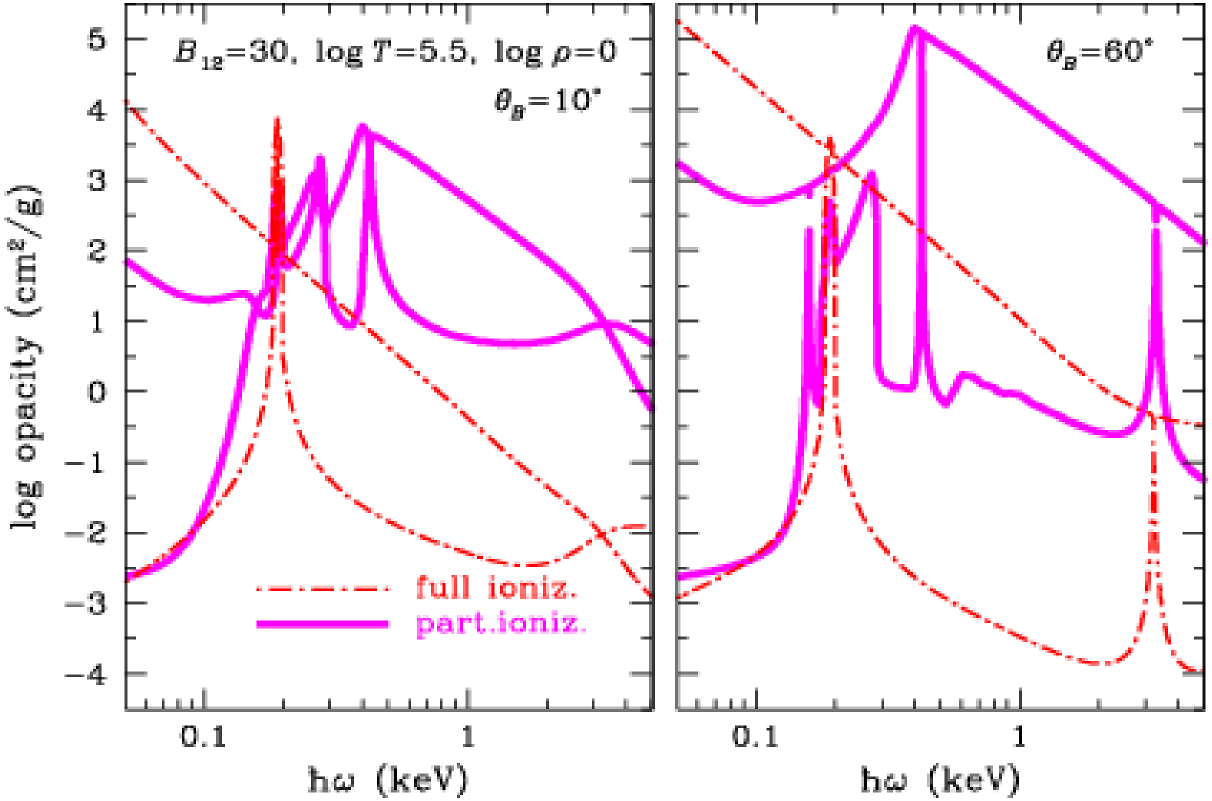
[Potekhin & Chabrier (2003) *ApJ* **585**, 955]

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

[Potekhin, Lai, Chabrier, & Ho (2004) *ApJ* **612**, 1034]

Opacities for normal modes in a strongly magnetized plasma:

The effects of nonideality and partial ionization



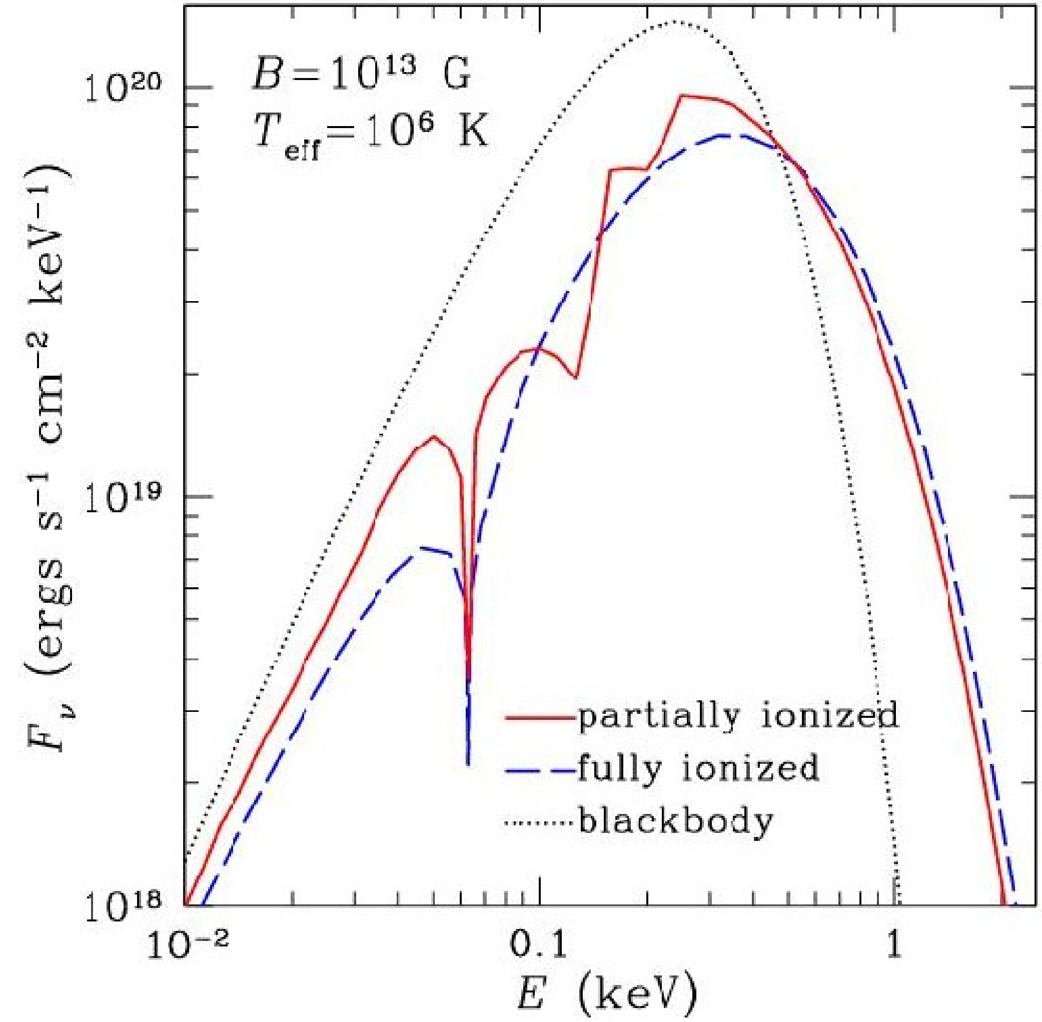
Opacities for two normal modes of electromagnetic radiation in models of an ideal fully ionized (dash-dot) and nonideal partially ionized (solid lines) plasma

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
[Potekhin, Lai, Chabrier, & Ho (2004) *ApJ* **612**, 1034]

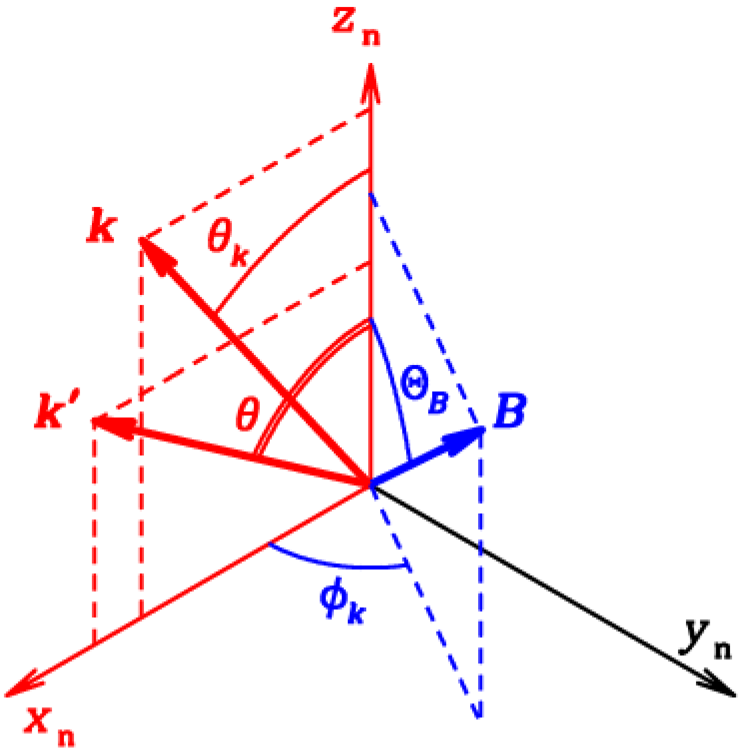
Result: the spectrum

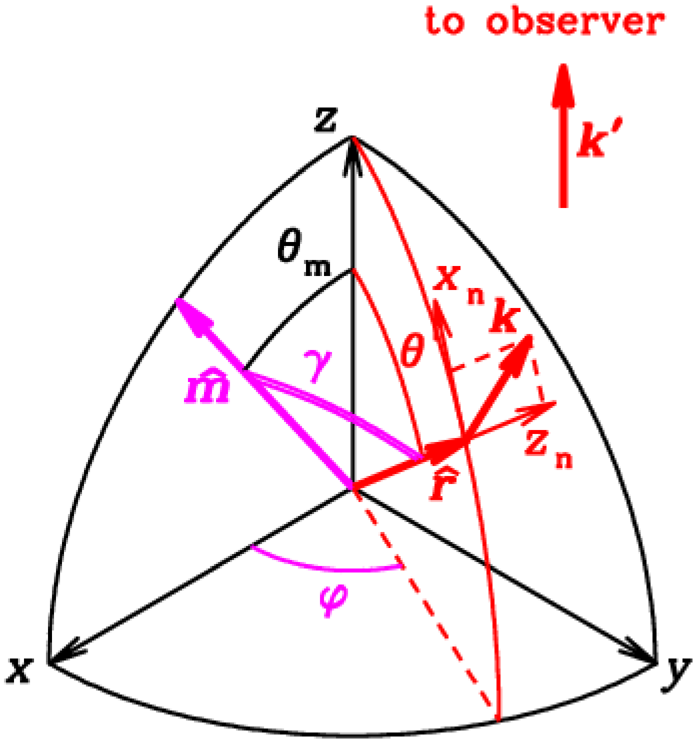
Potekhin, Lai, Chabrier, Ho,
& van Adelsberg (2006)
J.Phys.A: Math. Gen **39**, 4453



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)





Parameters: $T_{\rm eff}$, B, g, θ_k ϕ_k Θ_B

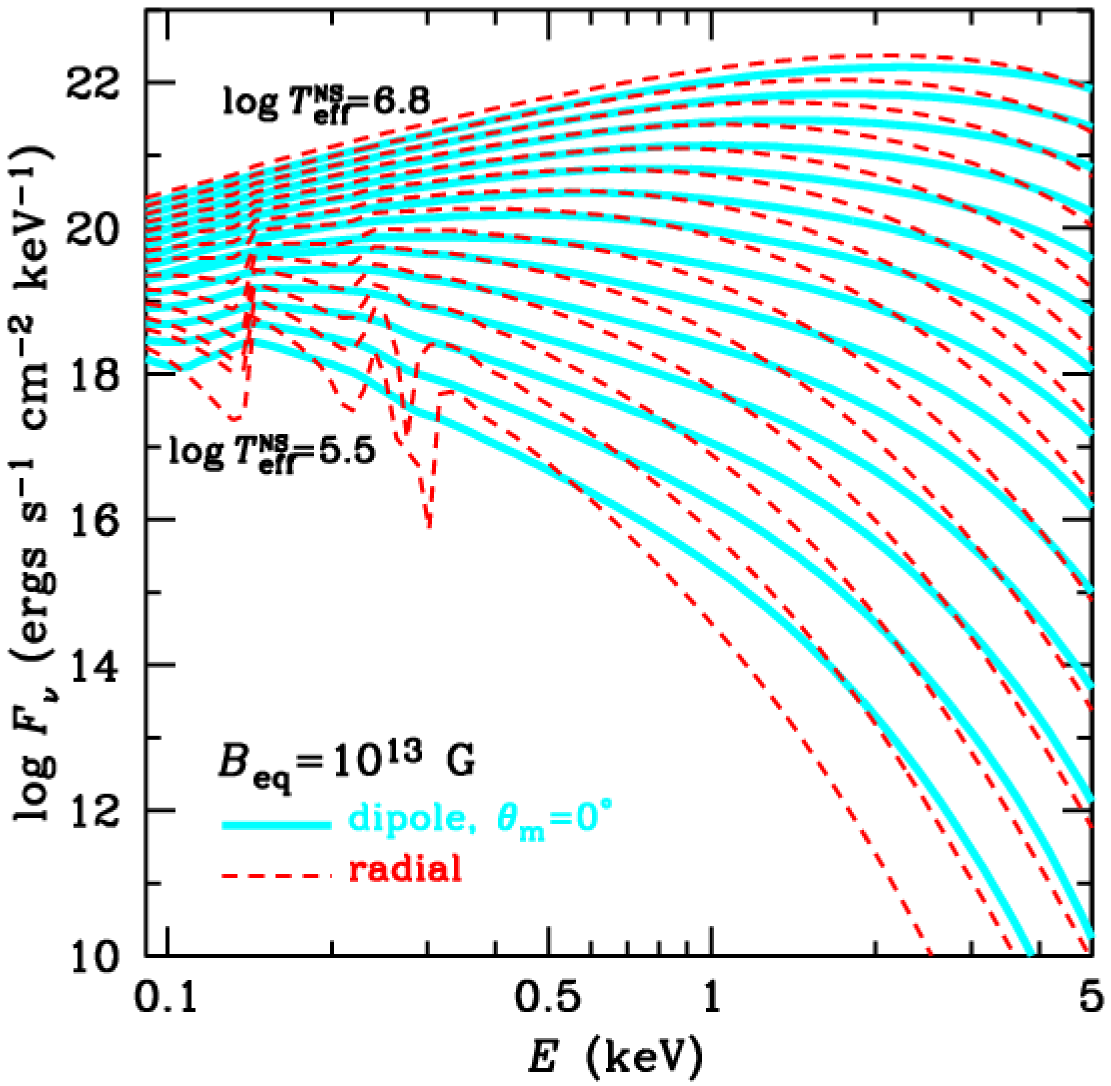
Pavlov & Zavlin (2000):

$$\theta = a \int_0^u \frac{\mathrm{d}x}{\sqrt{1 - a^2(1-x)x^2}} \quad \text{for } \theta \le \pi \ (z_{\rm g} \le 0.54)$$

$$a = u(1 + z_{\rm g}) \sin\theta_k \qquad u \equiv \frac{r_{\rm g}}{R}$$

Beloborodov (2002): $1 - \cos\theta \approx \dfrac{1 - \cos\theta_k}{1 - u}$

Result of modelling: spectra, dipole model



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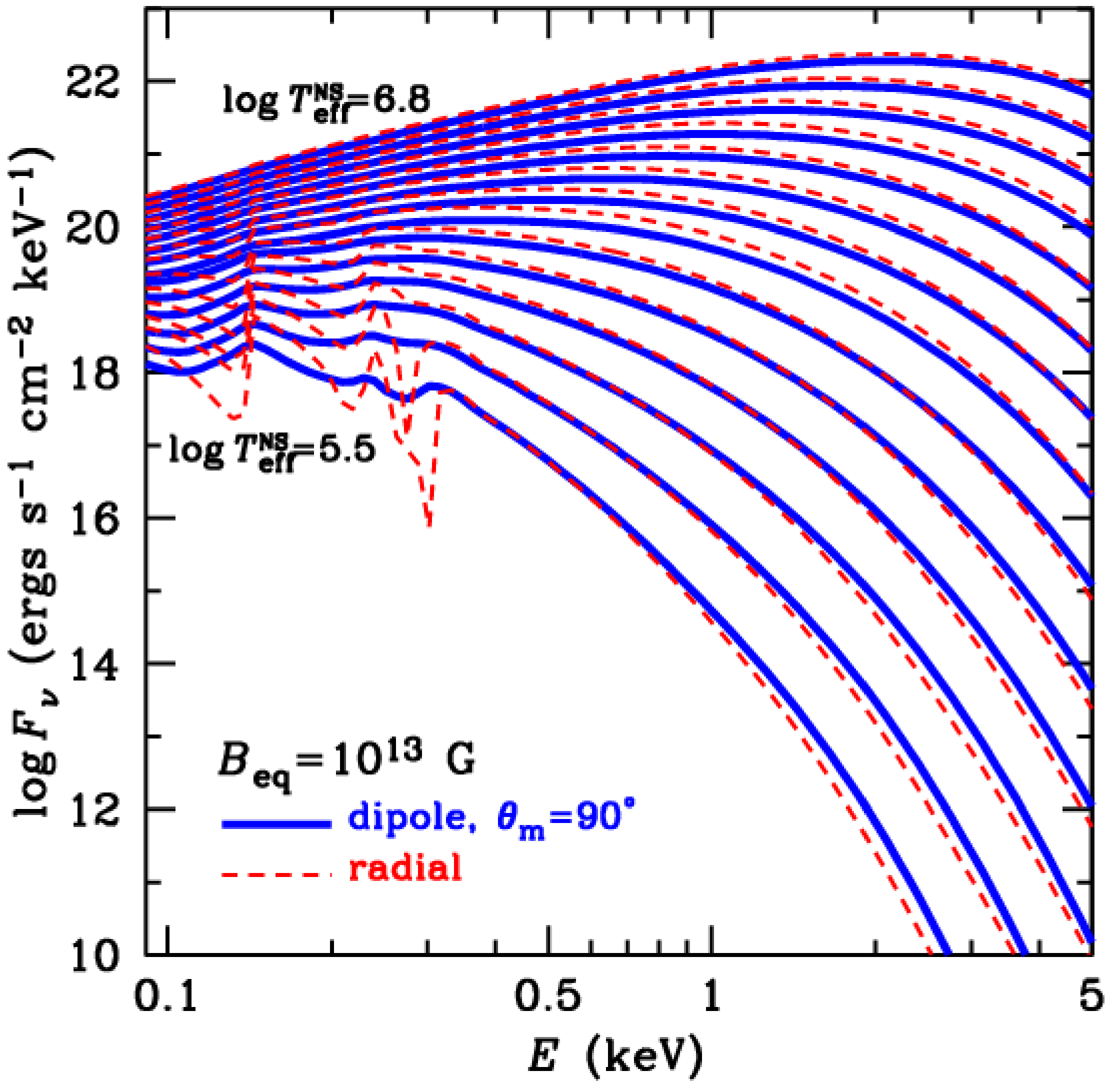
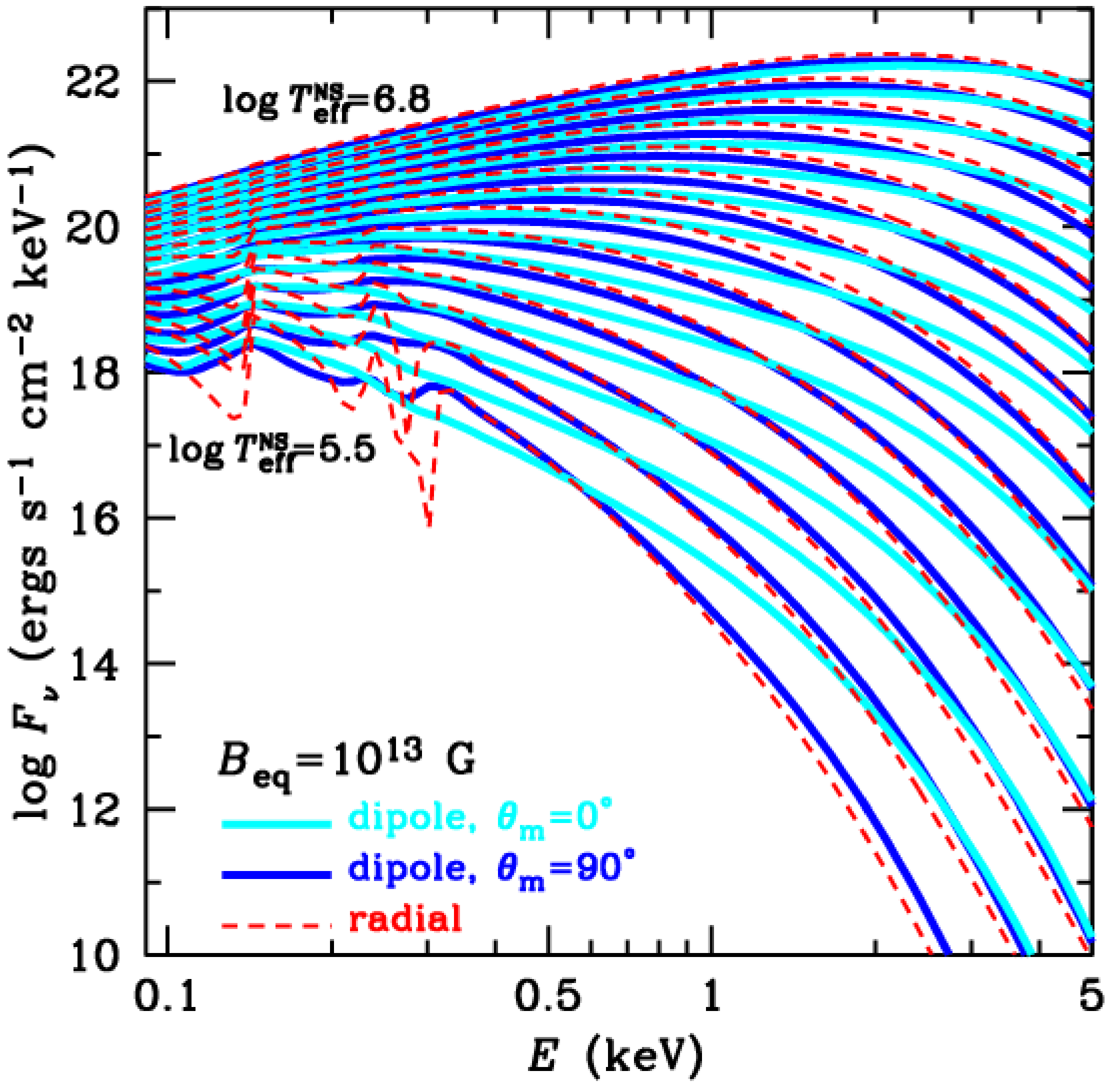


Result of modelling: spectra, dipole model

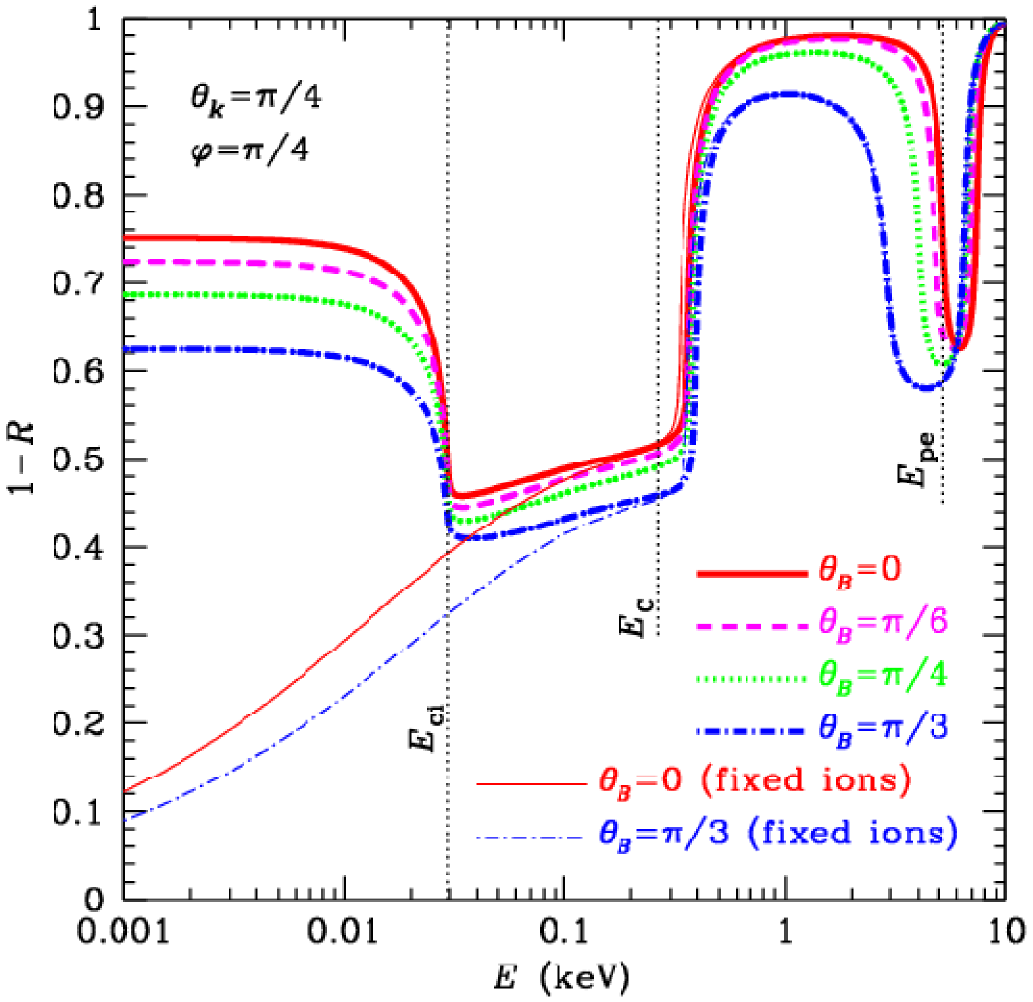
Ho, Potekhin, & Chabrier
(2008) *ApJS* **178**, 102



Spectral features are smoothed by surface field distribution.

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

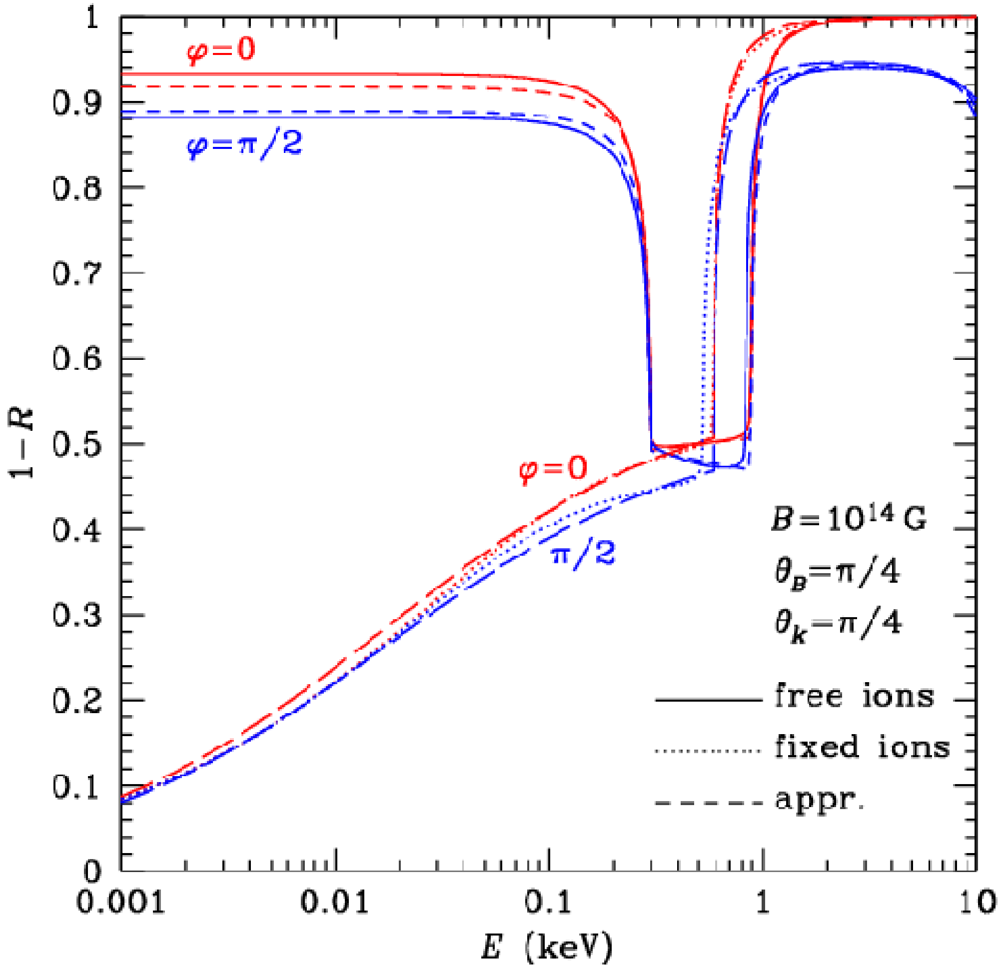
Radiation from condensed surface



Dimensionless emissivity of iron surface as function of photon energy at $B=10^{13}$ G.

Method of M. van Adelsberg, D. Lai, et al. (2005) *ApJ* **628**, 902; **improved in 2011**.

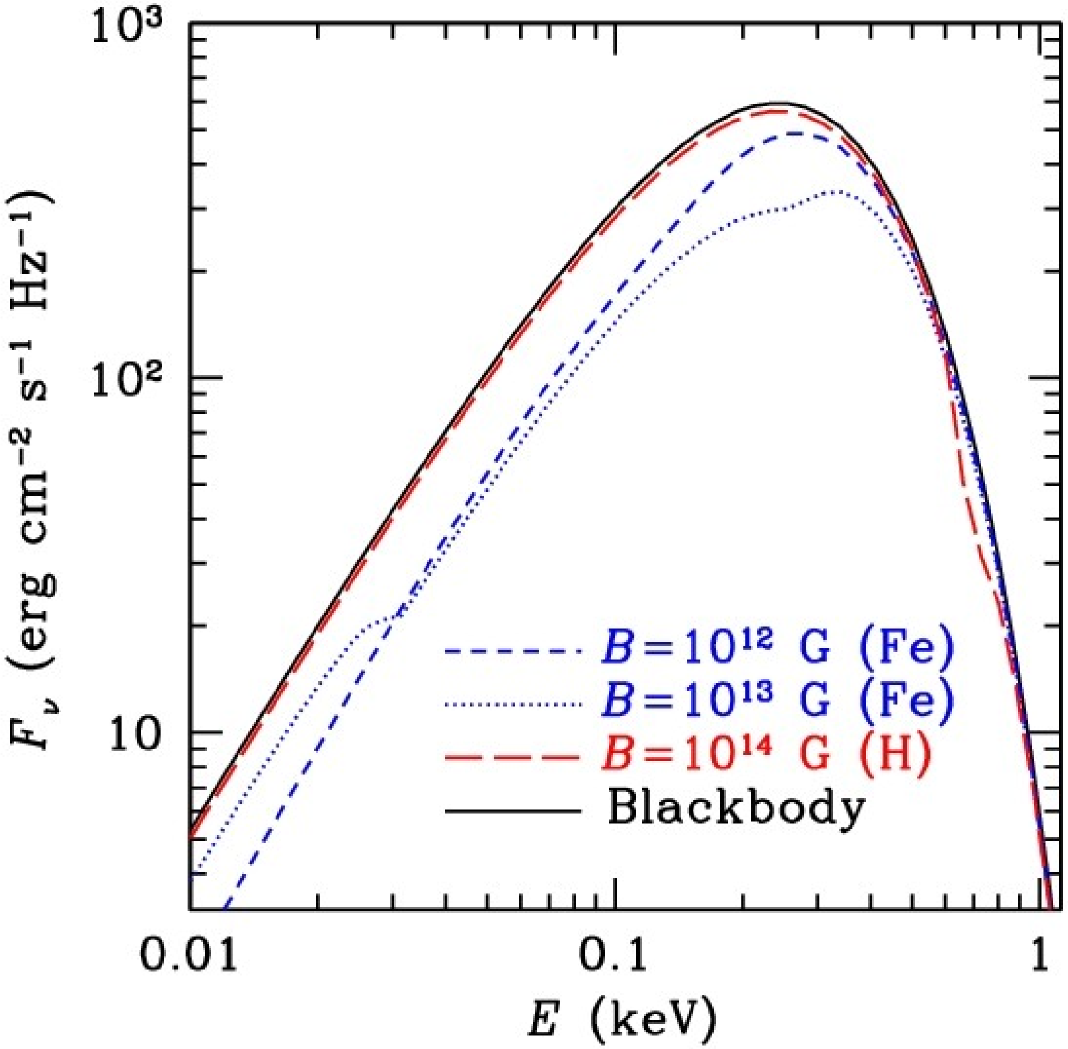
Radiation from condensed surface



Dimensionless emissivity of iron surface as function of photon energy at $B=10^{13}$ G.

Method of M. van Adelsberg, D. Lai, et al. (2005) *ApJ* **628**, 902; improved in 2011. Numerical results **and fit**.

Radiation from condensed surface



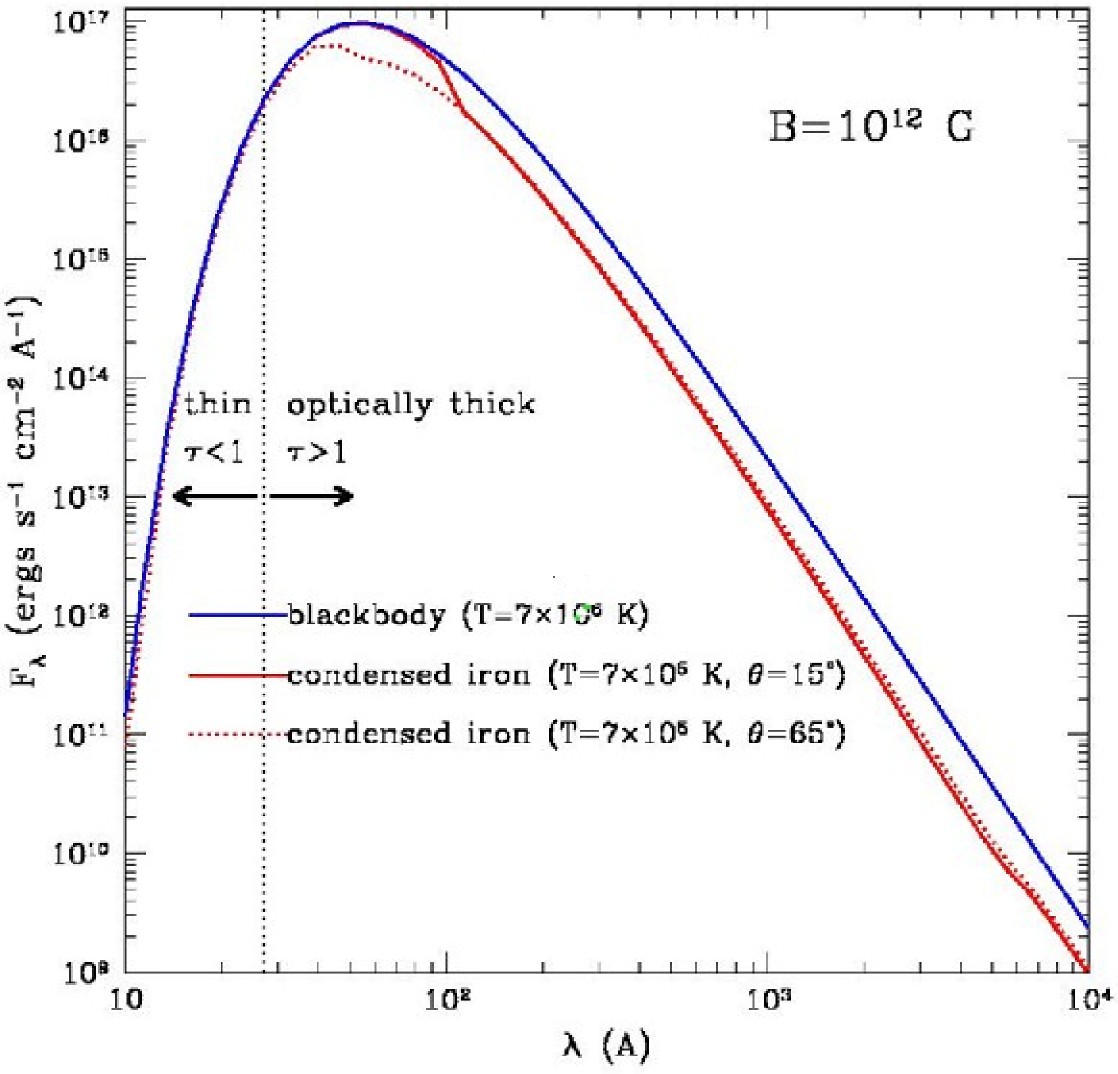
Monochromatic flux from the condensed surface in various cases

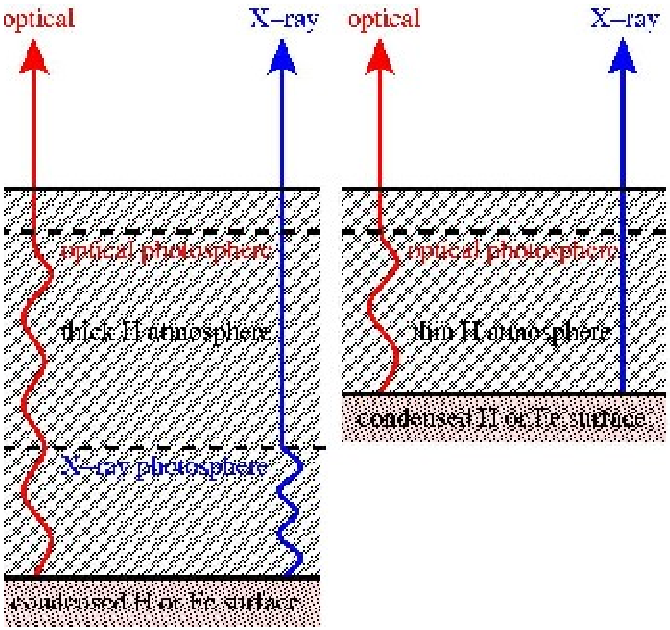
[Matt van Adelsberg, for Potekhin *et al*. (2006) *J.Phys.A: Math. Gen.* **39**, 4453]

“Thin atmospheres”

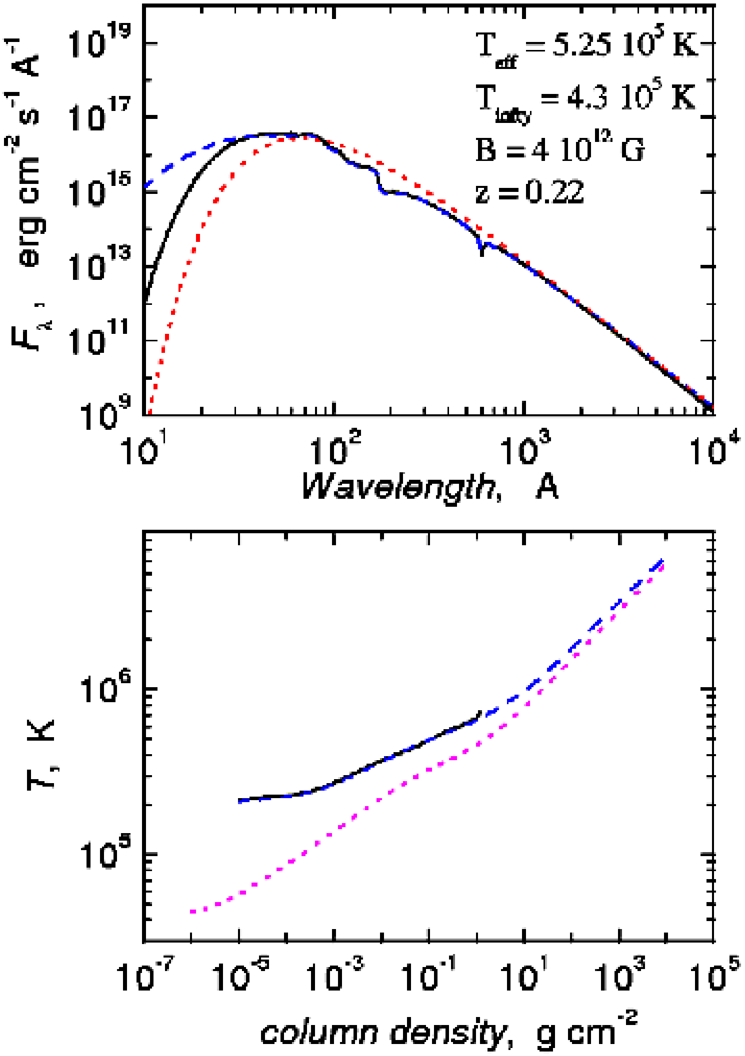
= condensed surface covered by an atmosphere, so that neither is negligible

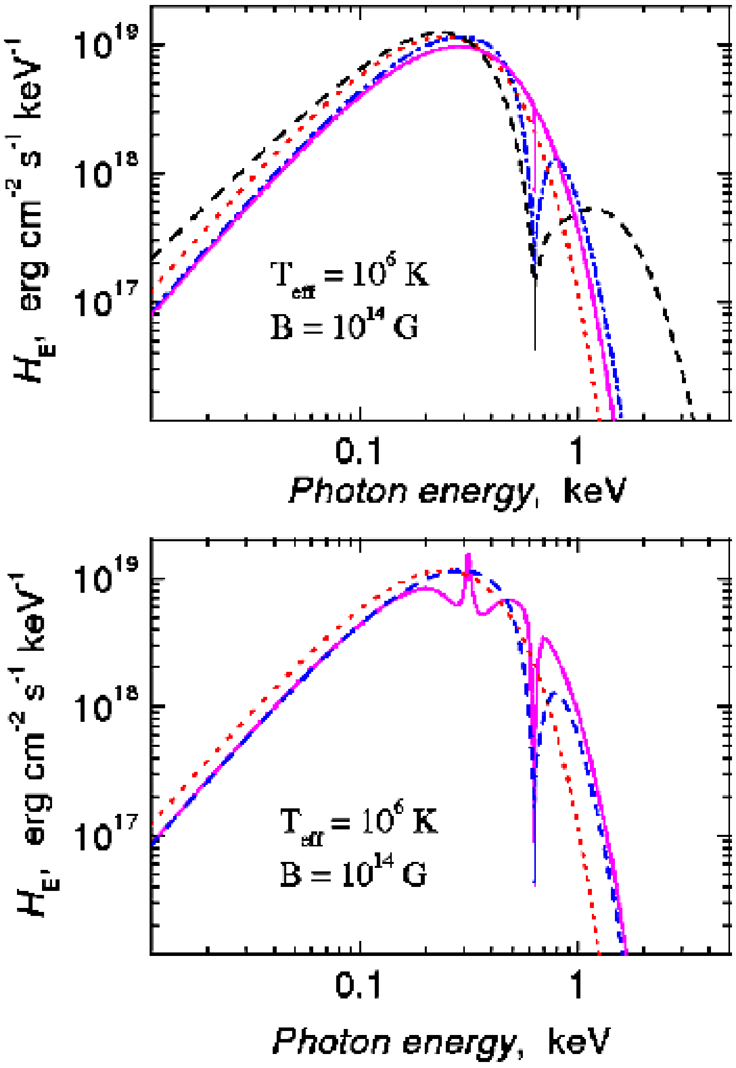
Idea by Motch, Zavlin, & Haberl (2003);
realized by Wynn Ho (2004 – 2007) and by Valery Suleimanov (2008 – 2011) with coauthors





Thin and layered atmospheres



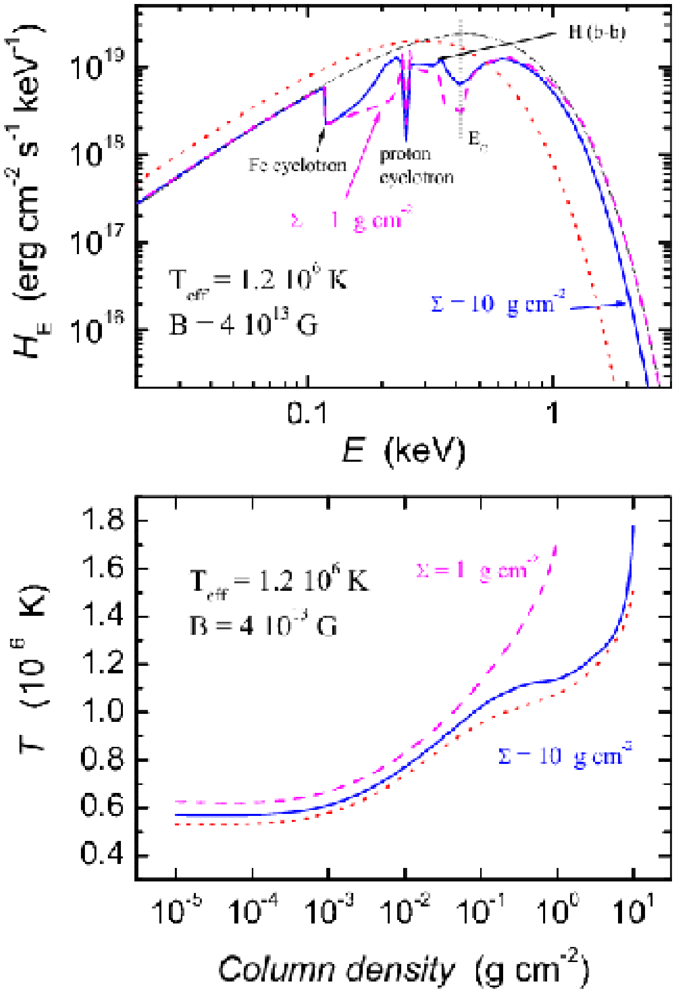


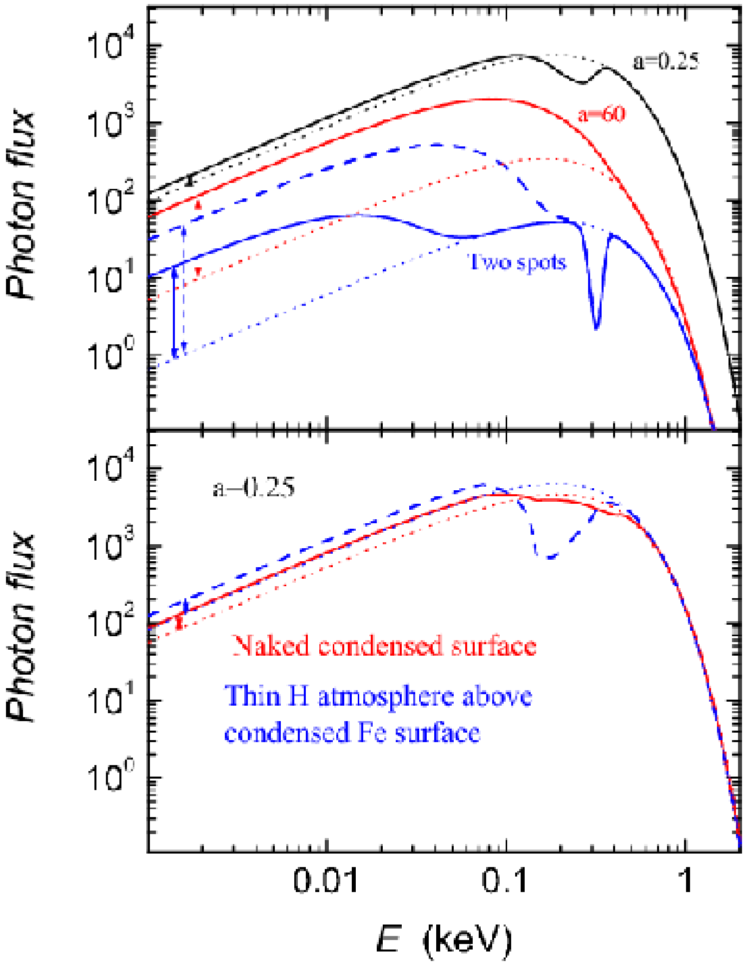
Emergent spectra (top) and temperature profiles (bottom) for partially ionized H atmospheres: semi-infinite (dashed line) or thin (column density 1.2 g cm^{-2}) atmospheres vs. fully ionized model (dotted)

Emergent spectra of fully ionized atmospheres. Top – H (semi-infinite – dashes, 100 g cm^{-2} – dot-dash, 1 g cm^{-2} – solid); bottom – H/He (25/75 g cm–2). Dottel lines – blackbody.

[V.Suleimanov, A.Y.Potekhin, K.Werner, *A&A* **500**, 891 (2009)]

Thin atmospheres: approximate formulae





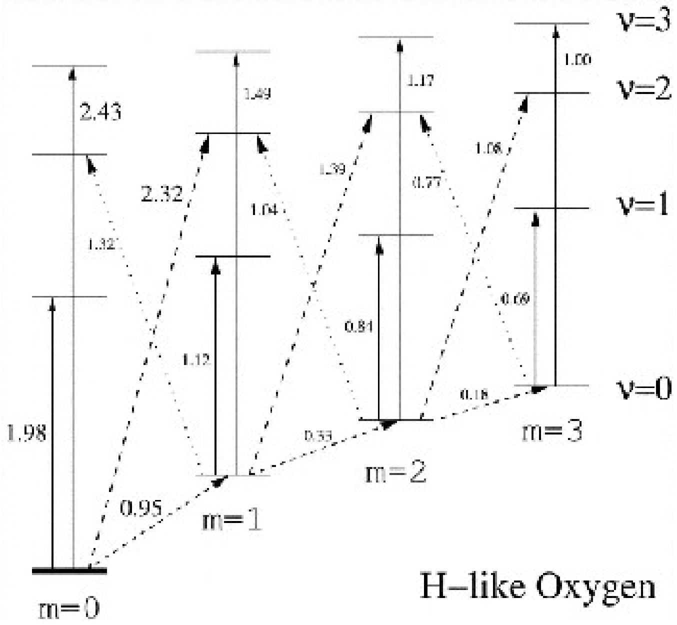
Emergent spectra (top) and temperature profiles (bottom) of thin partially ionized H atmospheres

Integral spectra for different models, compared with the BB spectra that fit the model at $E > 0.5$ keV

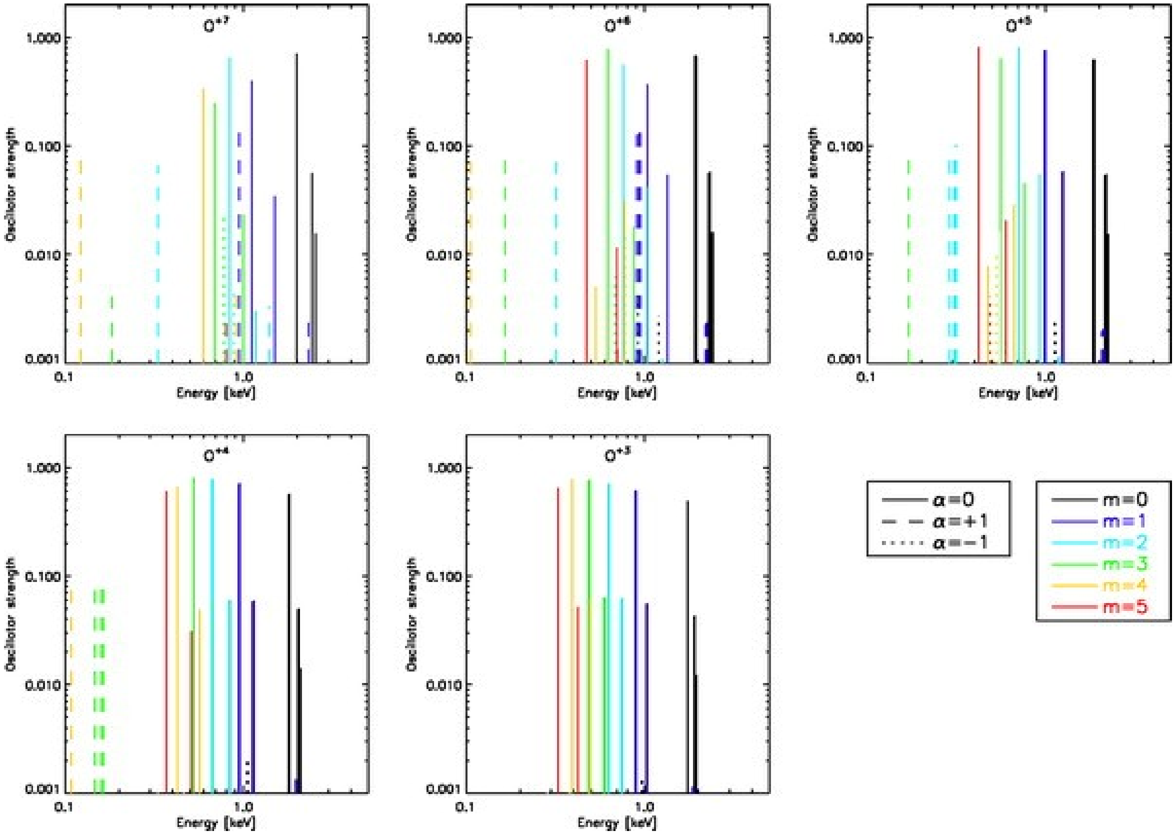
V.Suleimanov, V.Hambaryan, A.Y.Potekhin, R.Neuhäuser, K.Werner, *A&A* **522**, A111 (2010)

Atmosphere models for heavier elements

K.Mori, C.Hailey (2006) *ApJ* **648**, 1139



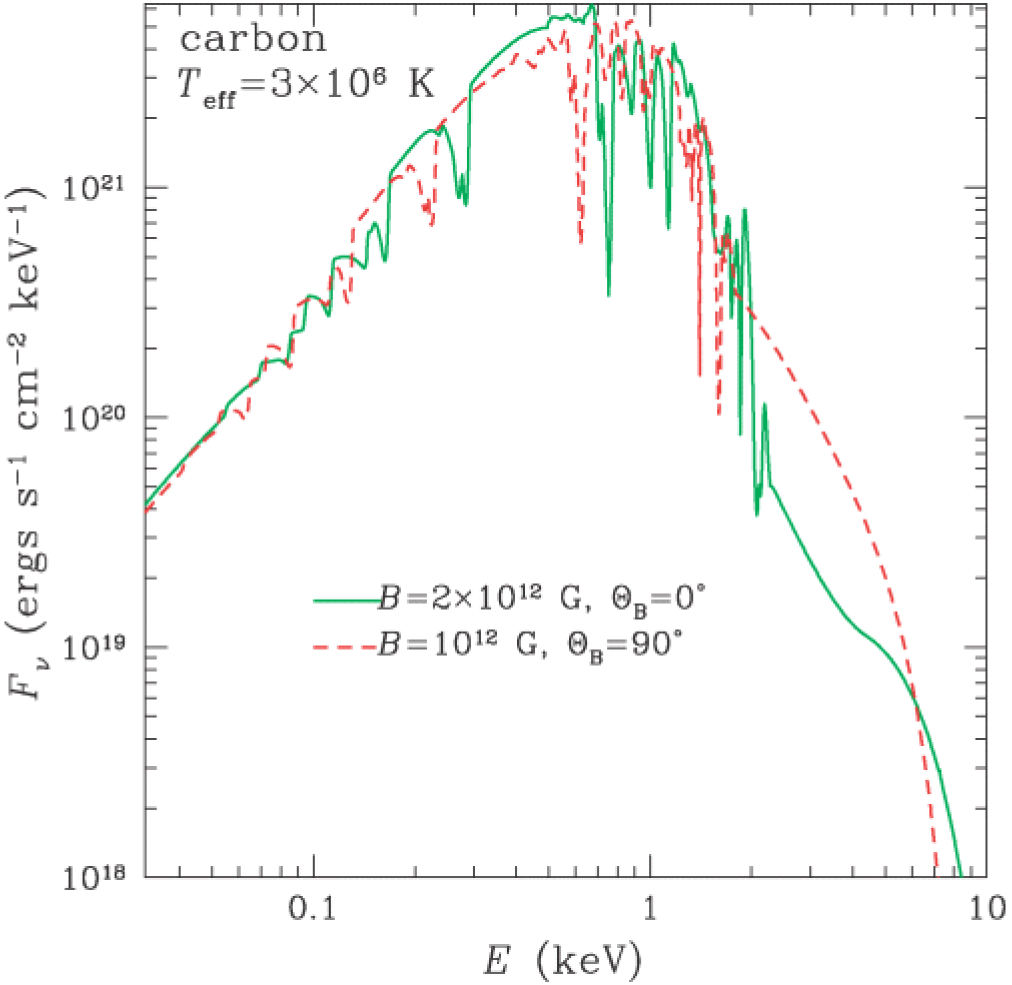
Energies of allowed transitions from the ground state, at $B=10^{12}$ G



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

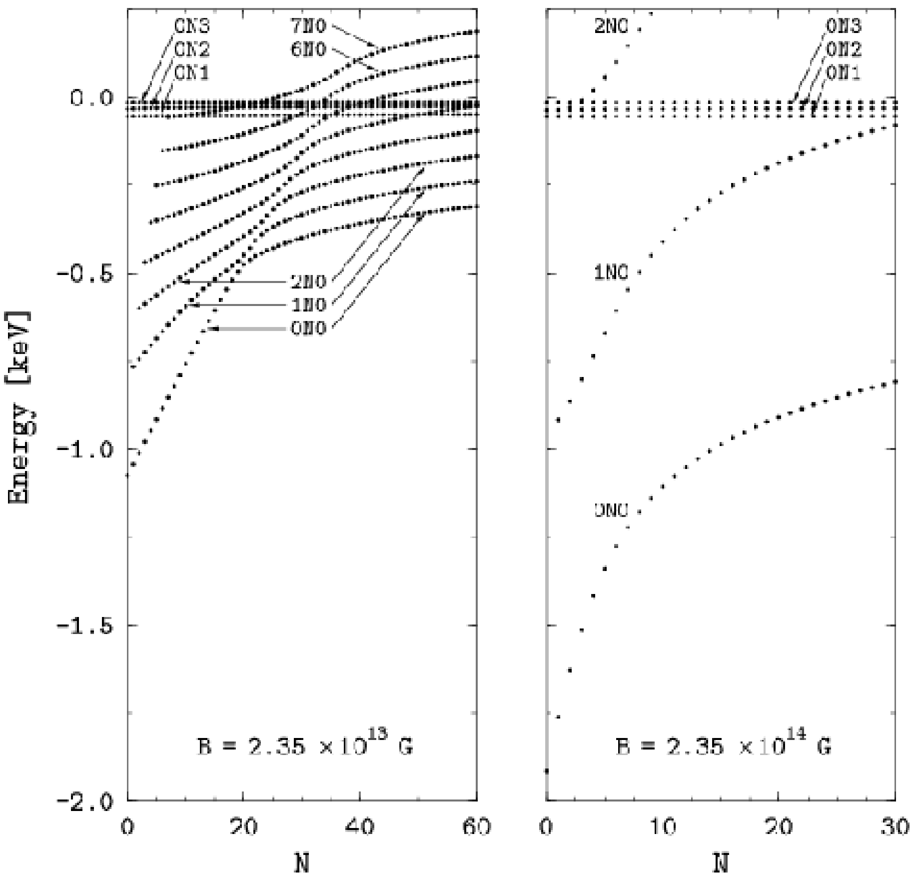
Atmosphere models for heavier elements

K.Mori & W.C.G.Ho (2007) *MNRAS* **377**, 905

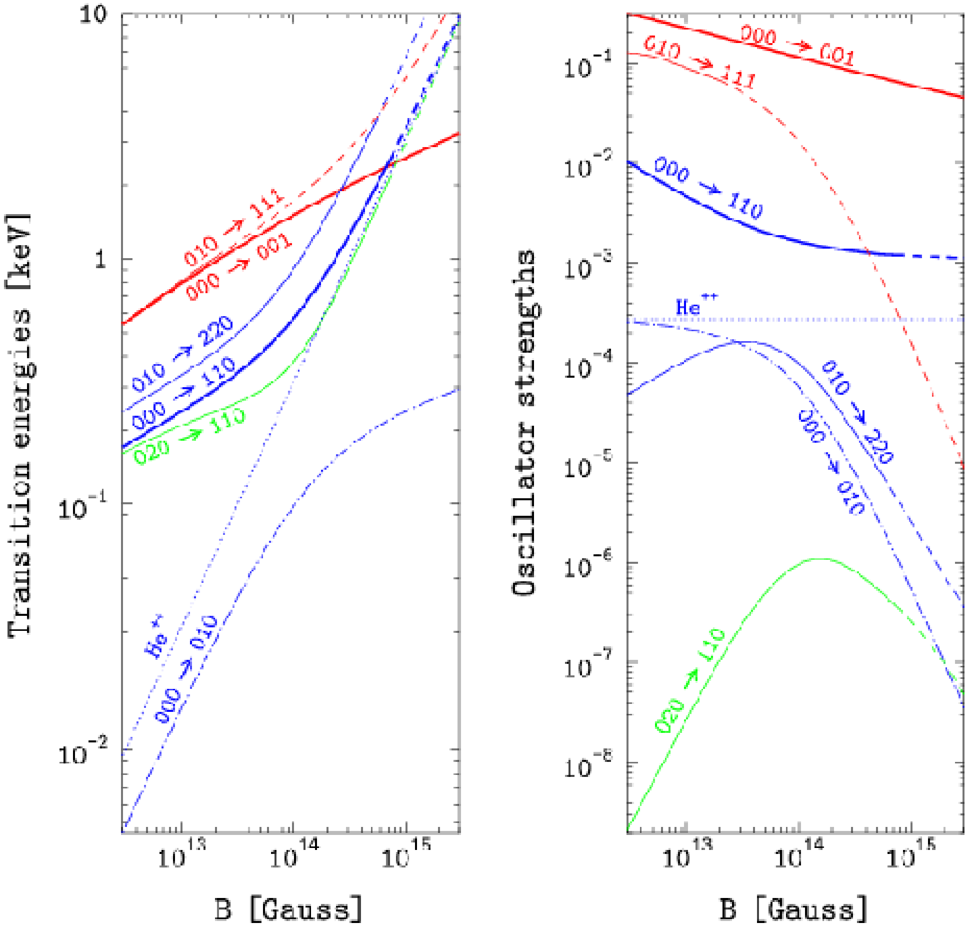


Helium ion moving in a strong magnetic field

G.G.Pavlov & V.G.Bezchastnov (2005) *ApJ* **635**, L61



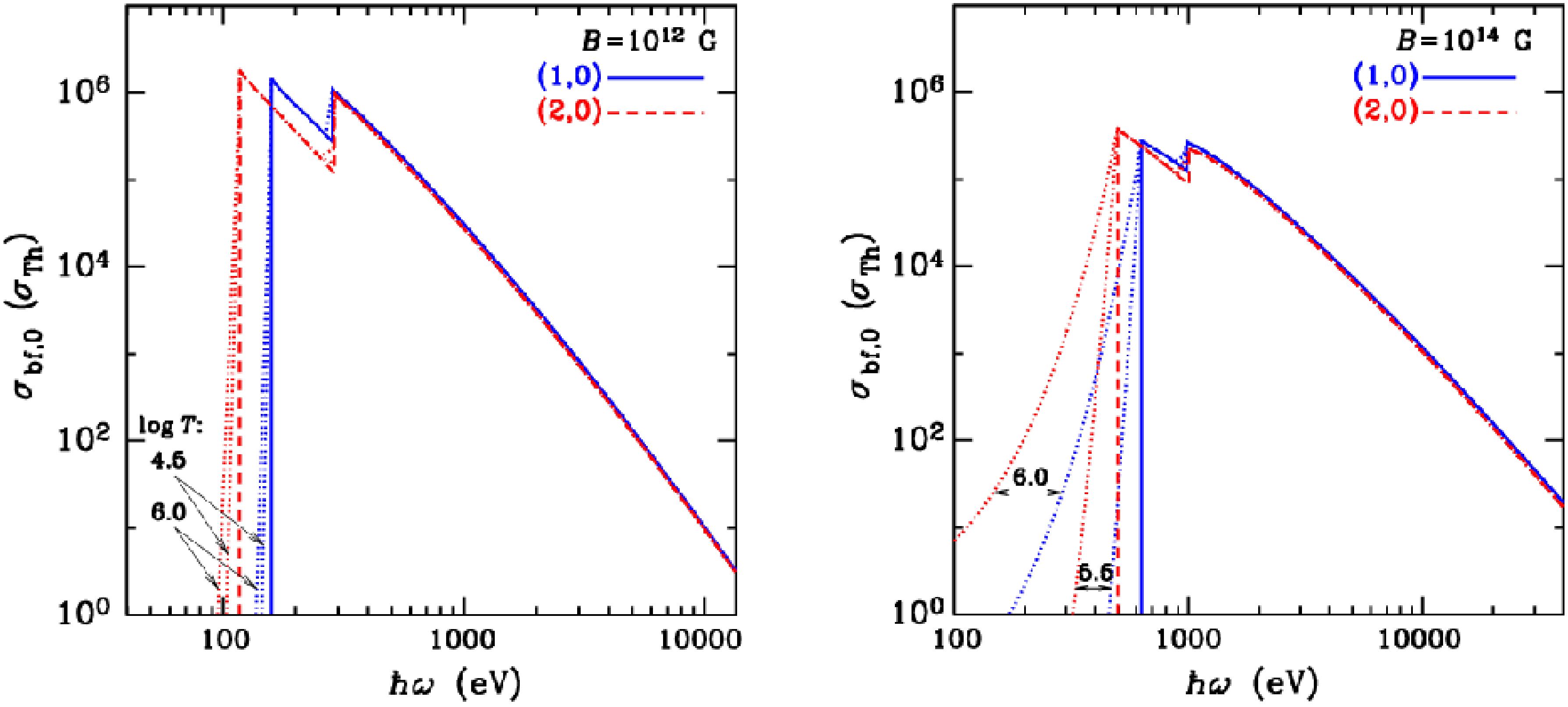
Energies of the ion as functions of N, which characterizes the state of motion across the magnetic field



Transition energies and oscillator strengths as functions of *B*

Helium atom: photoionization

Z.Medin, D.Lai, A.Y.Potekhin (2008) *MNRAS* **383**, 161



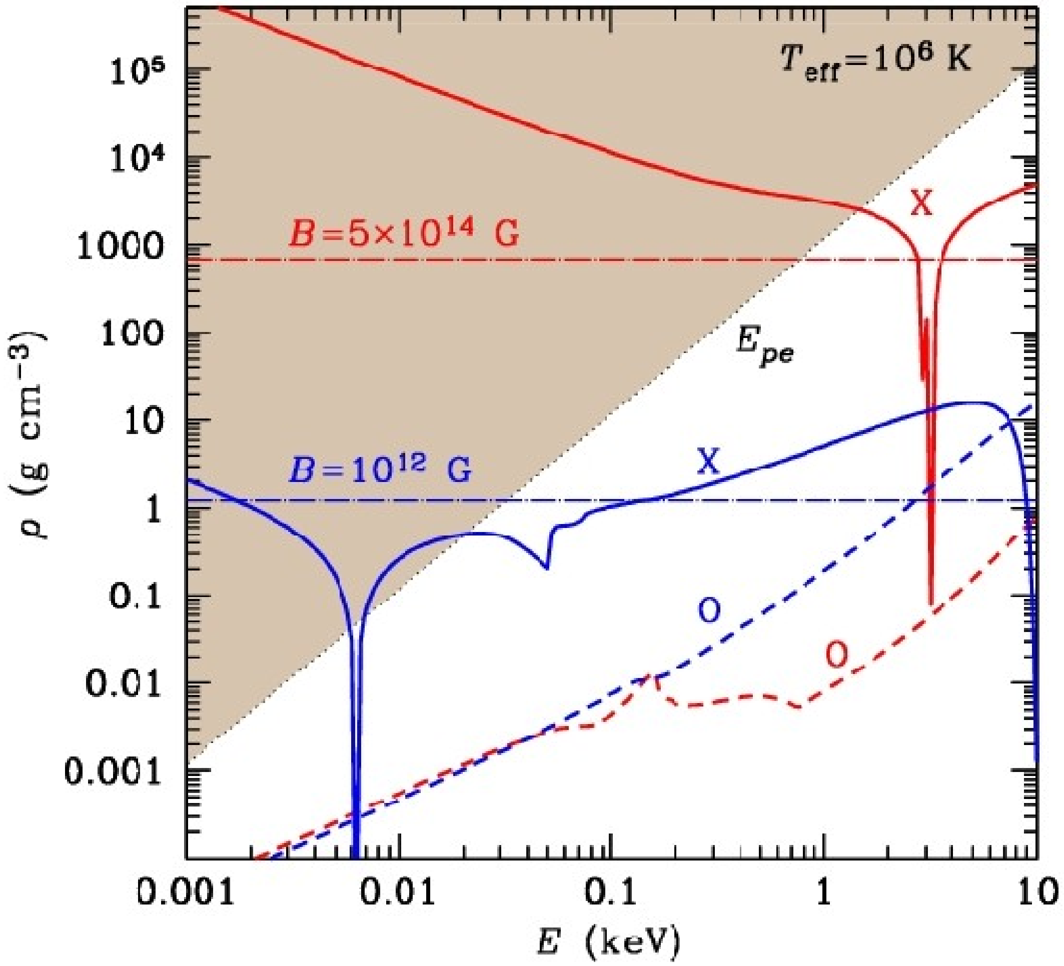
Photoionization cross sections for polarization along *B* without (solid and dashed lines) and with (dots) account of magnetic broadening.

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

Challenges from **superstrong** fields

1. ***Mechanical structure: field affects EOS***
2. ***Thermal structure: field affects luminosity***
3. ***Non-isotropic heat transport in the inner crust***
4. ***Surface layers: molecules, chains, and magnetic condensation***
5. ***Nonperturbative finite-mass effects for bound species***
6. ***Radiative transfer: vacuum polarization and mode conversion***
7. ***Energy transport below the plasma frequency***

Energy transport below the plasma frequency can be especially important for superstrong fields



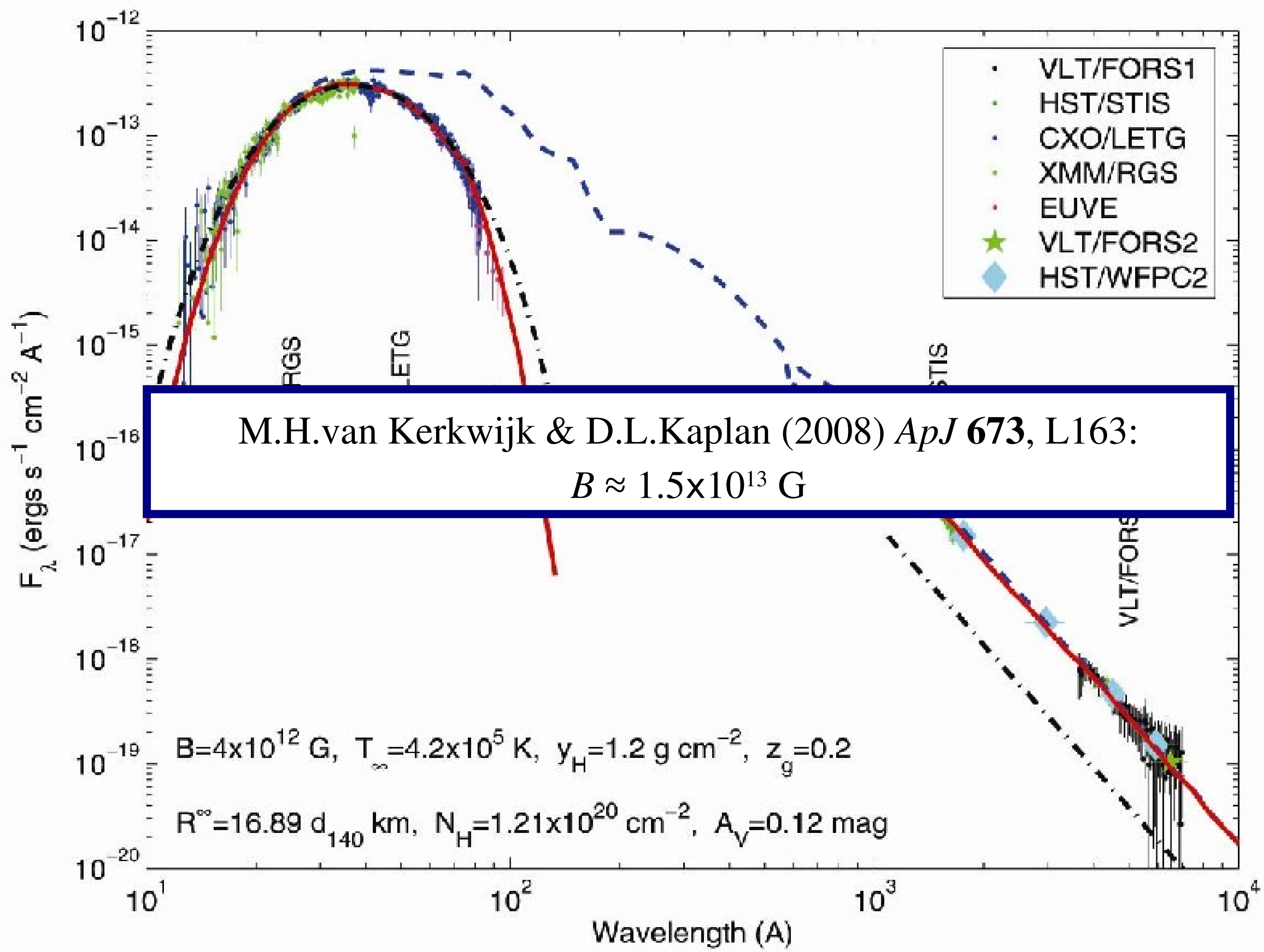
Photon-decoupling densities for X- and O-modes for a partially ionized H amosphere, for magnetic field strengths typical of pulsars (blue lines) and magnetars (red lines).

Dot-dashed lines correspond to the radiative surface, the shadowed region corresponds to $E < E_{pl}$.

Link of the theory with observations

Case of RX J1856.4-3754

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



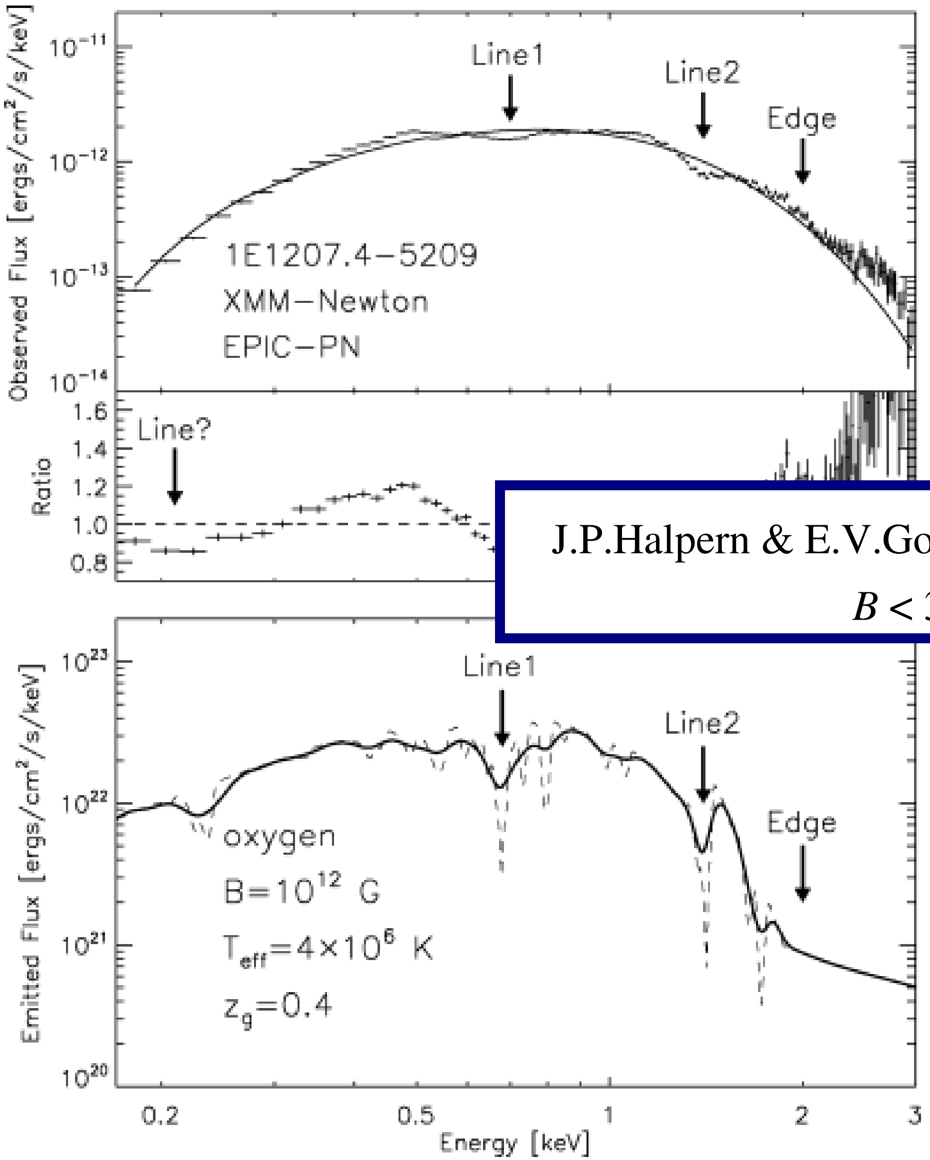
M.H.van Kerkwijk & D.L.Kaplan (2008) *ApJ* **673**, L163:
$B \approx 1.5\times10^{13}$ G

Link of the theory with observations

Case of 1E 1207.4−5209

Atmosphere models for heavier elements

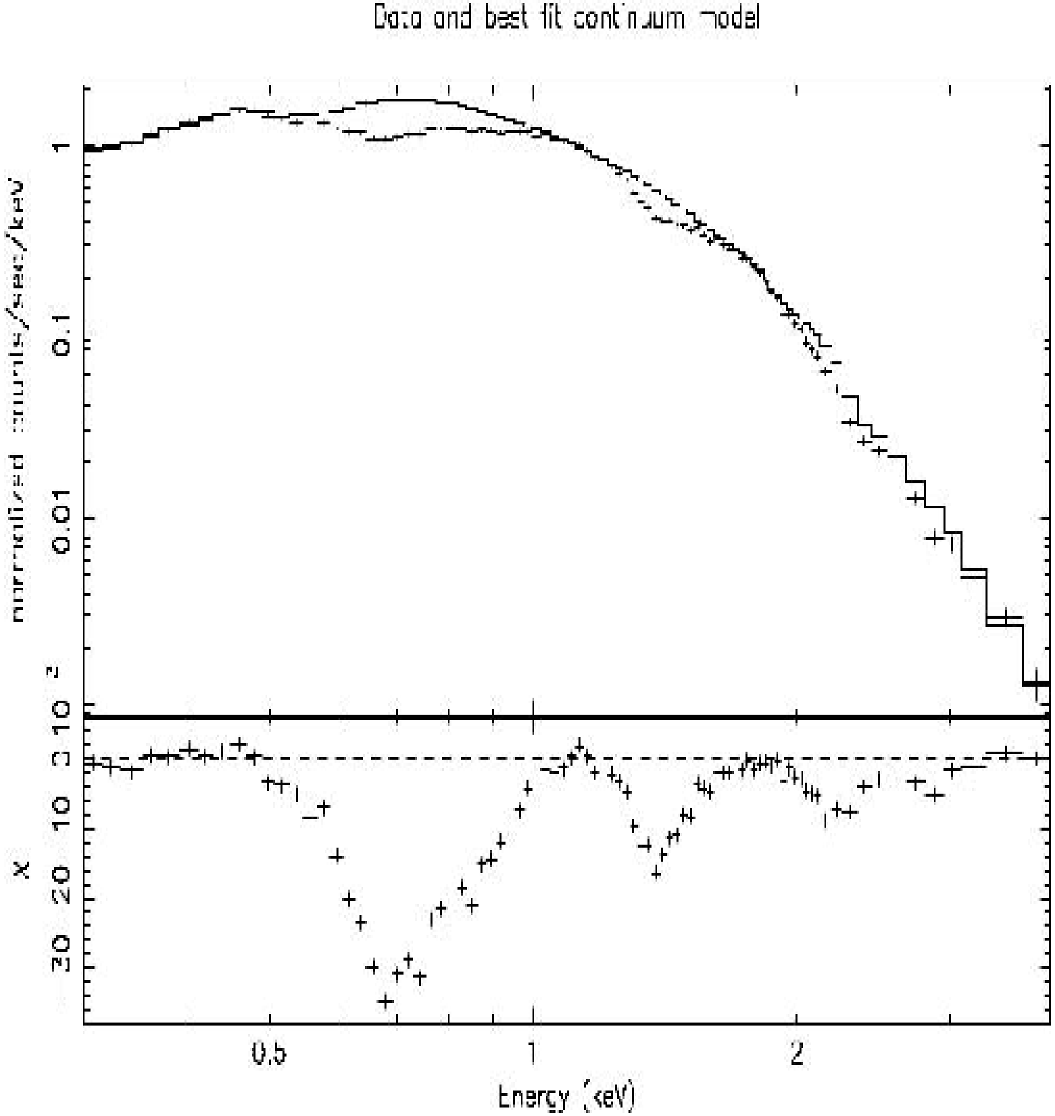
K.Mori & W.C.G.Ho (2007) *MNRAS* **377**, 905



J.P.Halpern & E.V.Gotthelf (2010) *ApJ* **709**, 436:

$B < 3.3\text{x}10^{11}$ G

Case of 1E 1207.4−5209



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

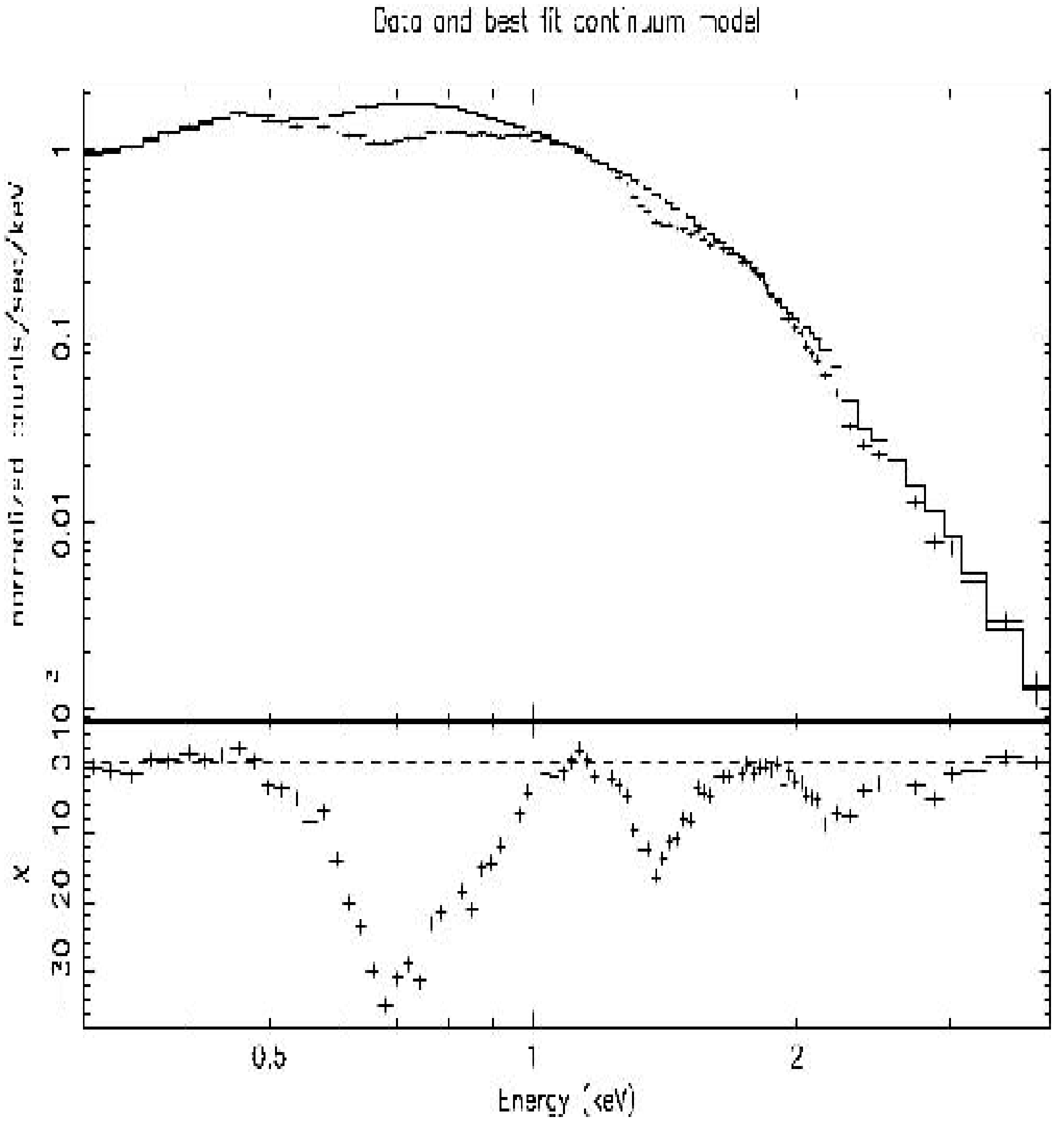
$$\hbar\omega_c = \hbar eB/mc = 11.577\ B_{12}\ \mathrm{keV}$$

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

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

K.Mori, J.C.Chonko, C.J.Hailey (2005): only 2 features are real.

Case of 1E 1207.4−5209



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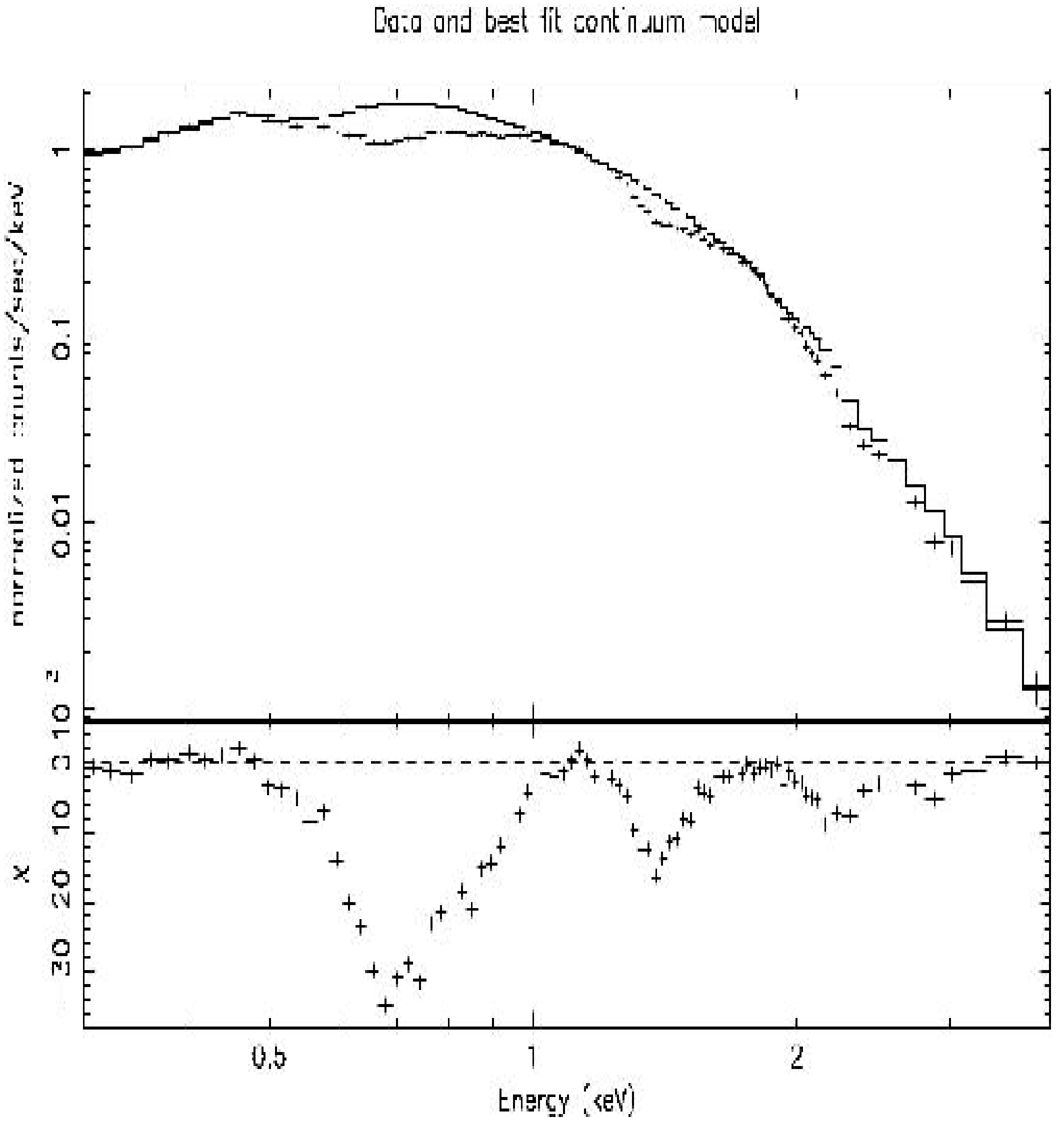
G.G.Pavlov & Yu.A.Shibanov (1978);
S.Zane, R.Turolla, A.Treves (2001):
electron or proton (ion) free-free cyclotron harmonics?
Electron cyclotron → $B \approx 8\times10^{10}$ G.

V.F.Suleimanov, G.G.Pavlov, K.Werner (2010) *ApJ* **714**, 630 (“quantum” cyclotron harmonics)

Case of 1E 1207.4−5209



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

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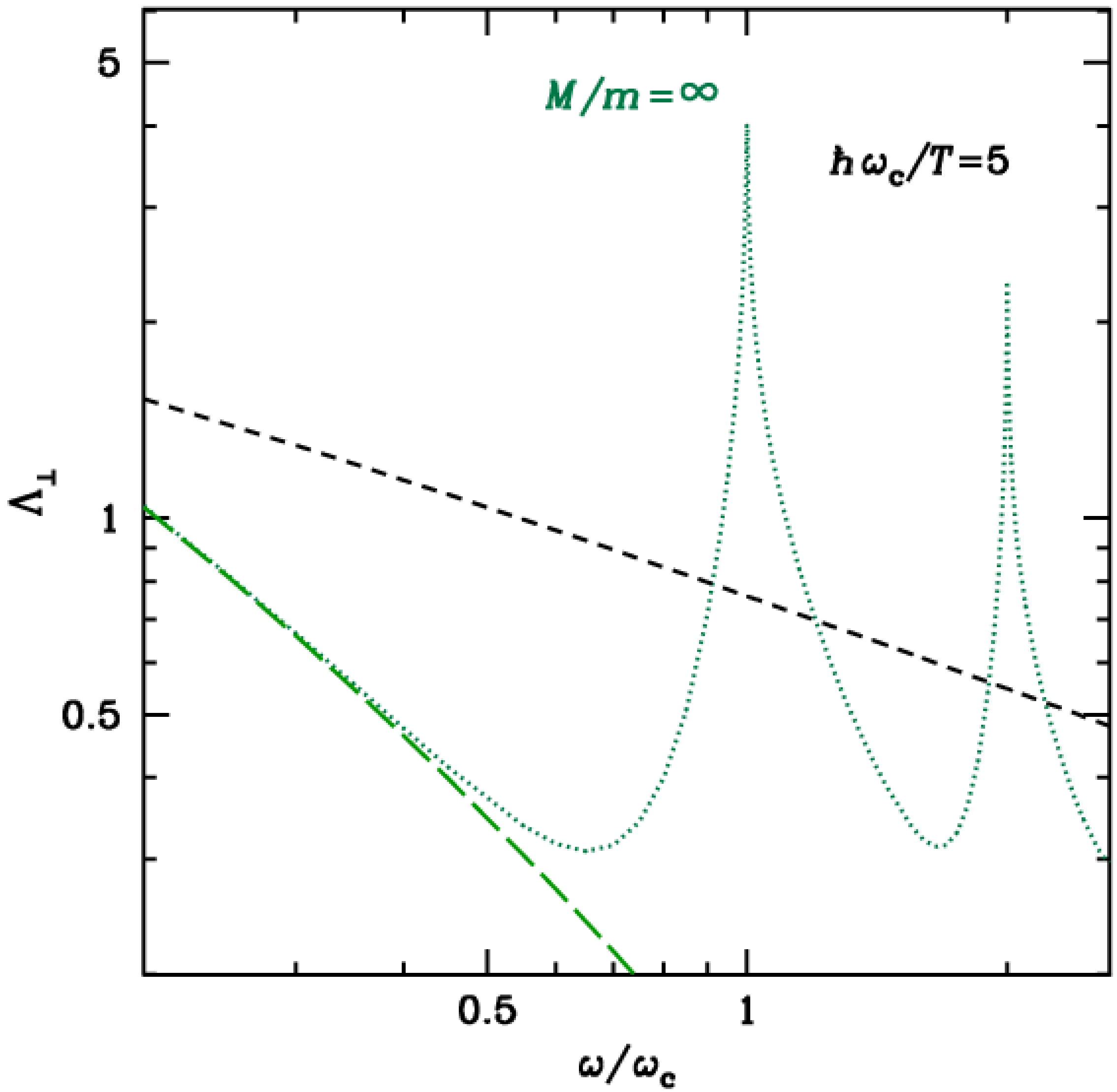
G.G.Pavlov & Yu.A.Shibanov (1978); S.Zane, R.Turolla, A.Treves (2001): electron or proton (ion) free-free cyclotron harmonics?
Electron cyclotron → $B \approx 8\times10^{10}$ G.

V.F.Suleimanov, G.G.Pavlov, K.Werner (2010) *ApJ* **714**, 630 (free-free cyclotron harmonics)

J.P.Halpern & E.V.Gotthelf (2011) *ApJ* **733**, L28: $B \approx 2.4\times10^{11}$ G or 9.9×10^{10} G (!)

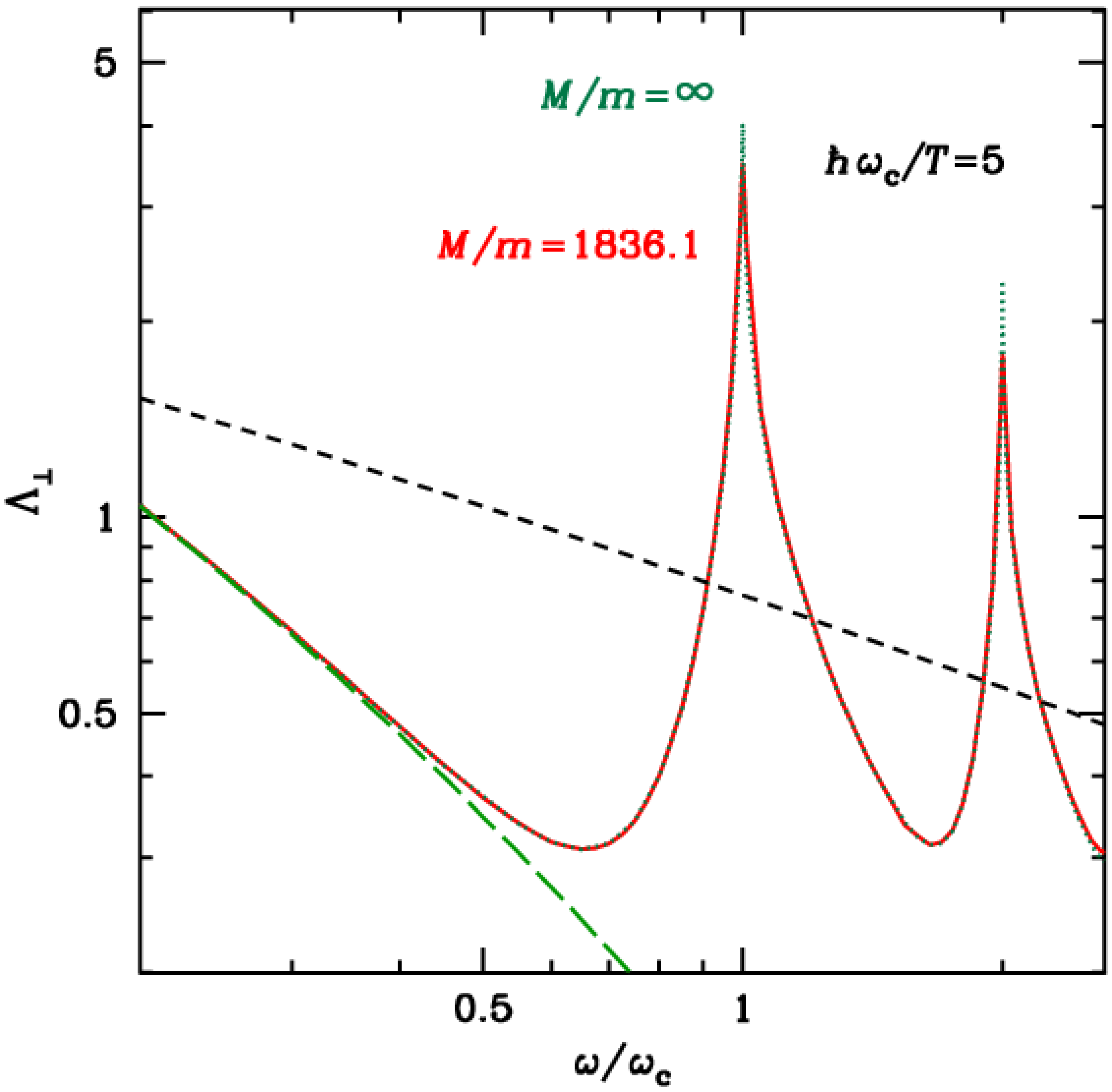
Cyclotron harmonics in spectra of isolated neutron stars



$$\sigma_\alpha(\omega) = \frac{4\pi e^2}{mc}\,\frac{\nu_\alpha^{\rm ff}(\omega)}{(\omega+\alpha\omega_{\rm c})^2 - (\nu_{\rm e}+\nu_\alpha^{\rm ff})^2}$$

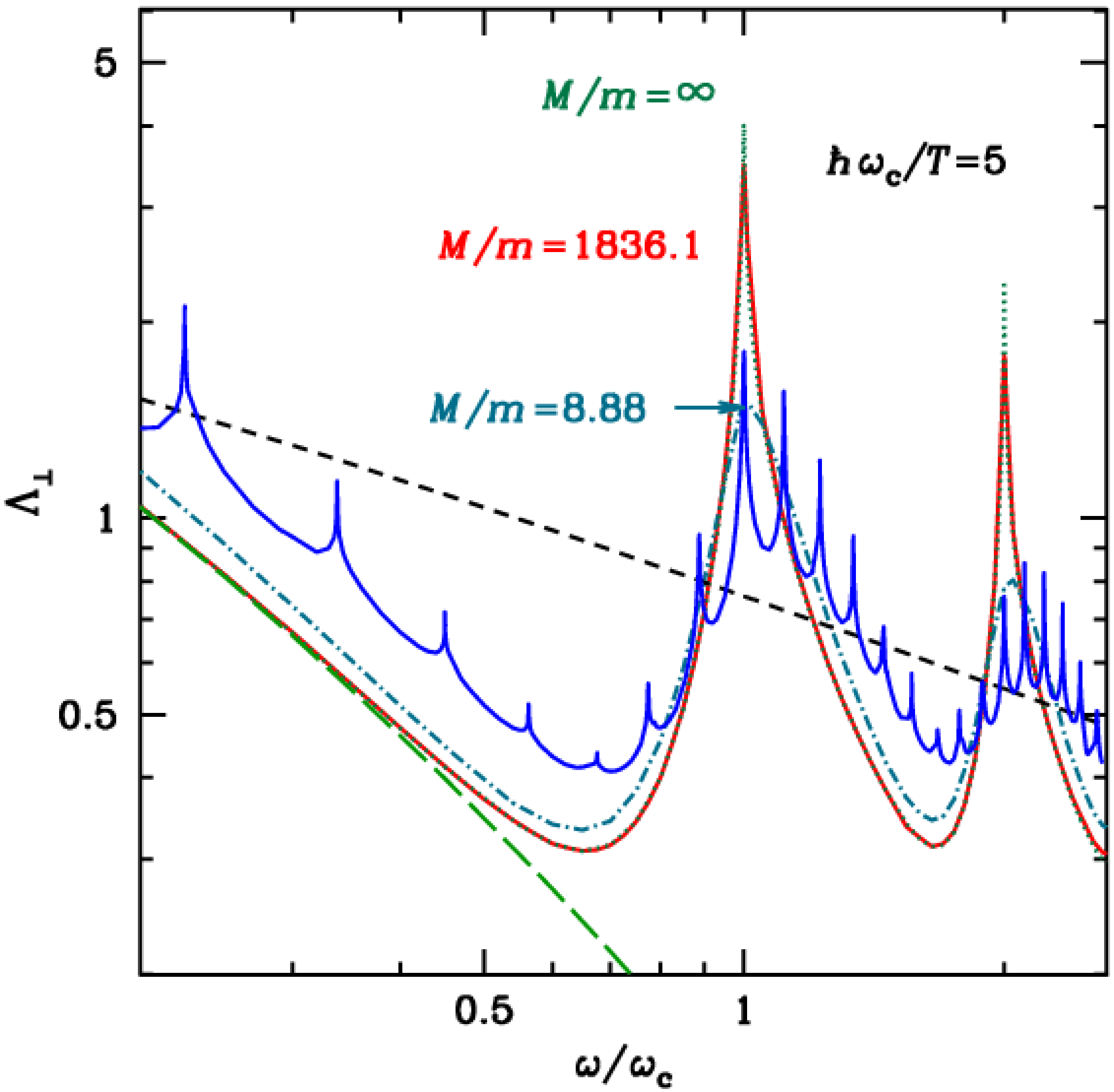
$$\nu_\alpha^{\rm ff} - \frac{4}{3}\sqrt{\frac{2\pi}{mT}}\,\frac{n_{\rm e}\,e^4}{h\omega}\,\Lambda_\alpha^{\rm ff}(\beta_{\rm e},\omega/\omega_{\rm c})$$

Cyclotron harmonics in spectra of isolated neutron stars



V.F.Suleimanov, G.G.Pavlov, K.Werner (2010) *ApJ* **714**, 630:
approximate treatment of proton recoil
(following G.G.Pavlov & A.N.Panov, 1976, *Sov. Phys. JETP* **44**, 300)

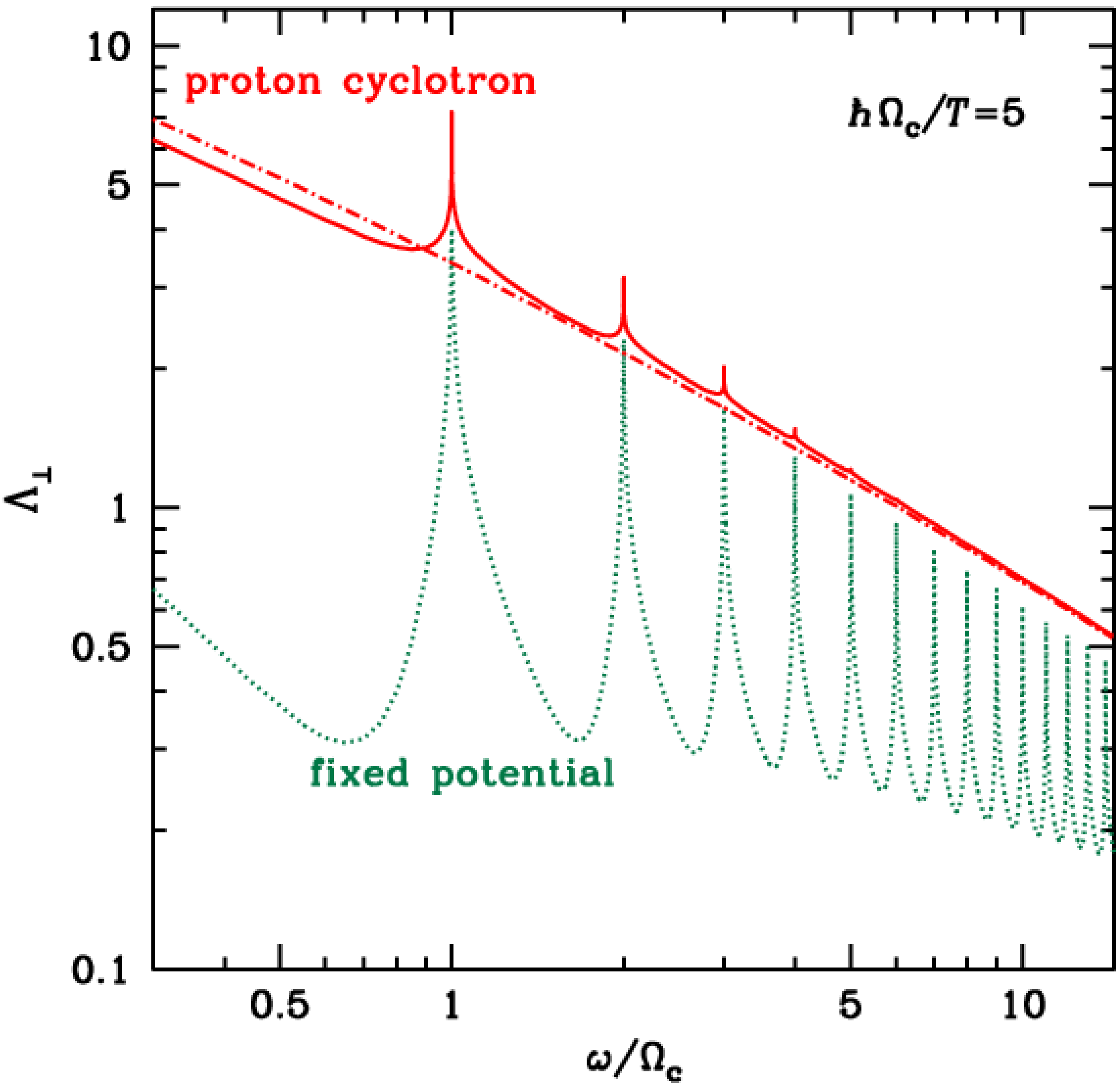
Cyclotron harmonics in spectra of isolated neutron stars



Accurate treatment of the proton-lepton-photon system in quantizing magnetic fields

[Potekhin & Chabrier (2003) *ApJ* **585**, 955; Potekhin (2010) *A&A* **518**, A24]

Cyclotron harmonics in spectra of isolated neutron stars

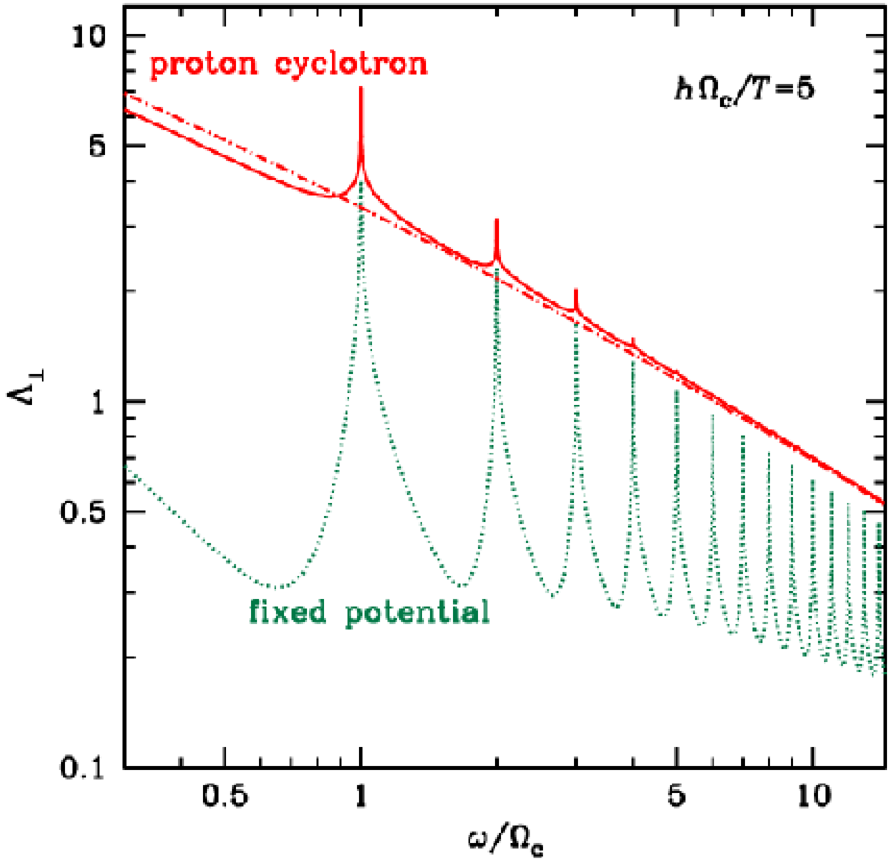


Accurate treatment of the proton-lepton-photon system in quantizing magnetic fields

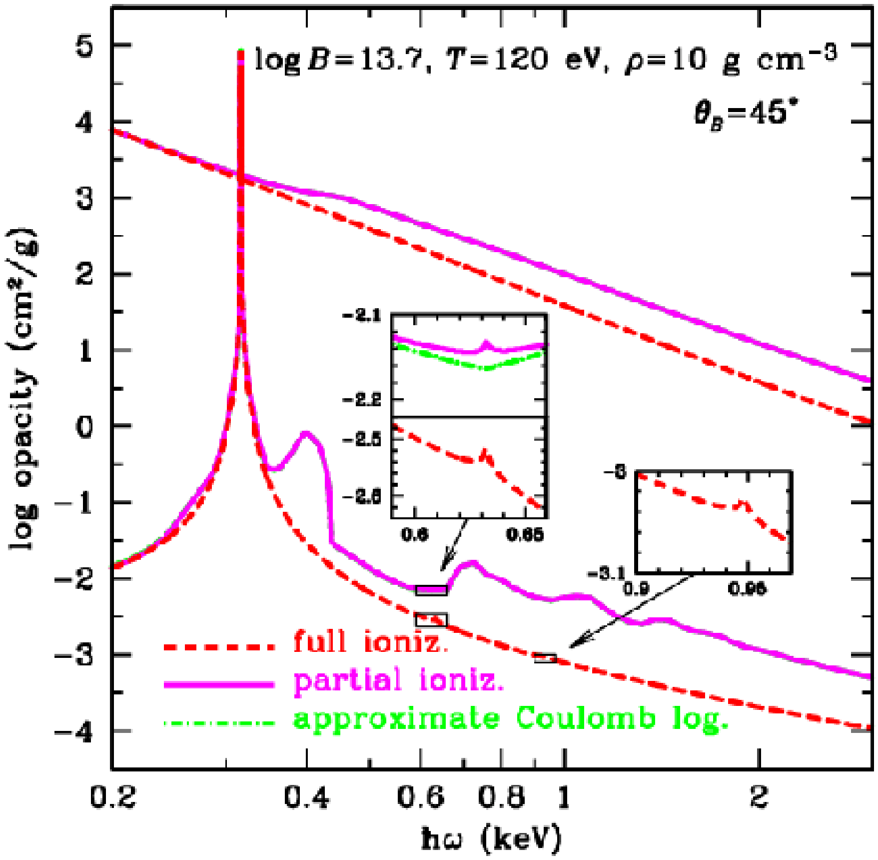
[Potekhin & Chabrier (2003) *ApJ* **585**, 955; Potekhin (2010) *A&A* **518**, A24]

Absence of ion cyclotron harmonics in spectra of isolated neutron stars

A.Y.Potekhin "*Cyclotron harmonics in opacities of isolated neutron star atmospheres*" *Aston. Astrophys.* **518**, A24 (2010)



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.



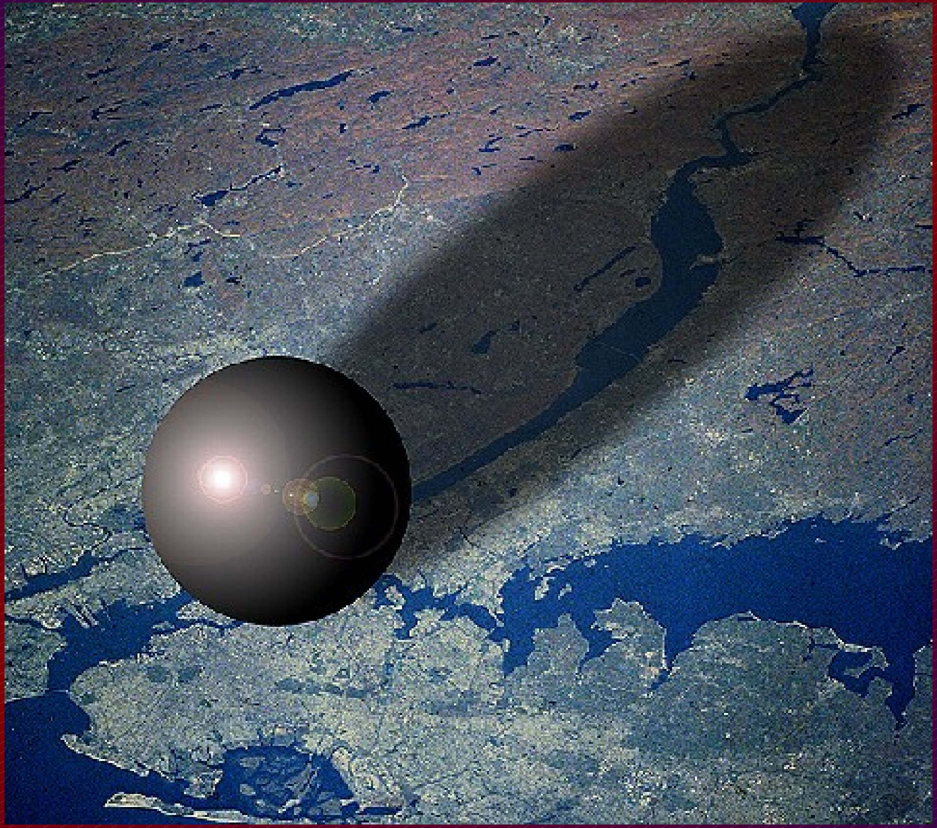
Opacities for O- (upper curves of each type) and X-modes of radiation in the H atmosphere of a NS with $B=5\times10^{13}$ G. Dashes – fully ionized plasma model, solid lines – partially ionized, dot-dashed – partially ionized without free-free cyclotron harmonics.

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

Conclusions

- Practical models of the *EOS* and ***opacities*** of strongly magnetized plasmas, applicable to neutron stars, are developed and applied to modeling thermal structure of neutron-star envelopes and spectra of neutron star thermal radiation.
- 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 require further study.
- ***Superstrong*** magnetic fields (1) induce new effects which can reveal themselves in the spectra and (2) lead to theoretical uncertainties, which require further studies.

THANK YOU FOR YOUR ATTENTION !



[Image credit: NASA/Marshall Space Flight Center]