Neutron star envelopes: (micro)physics and thermal radiation

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in collaboration with

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and

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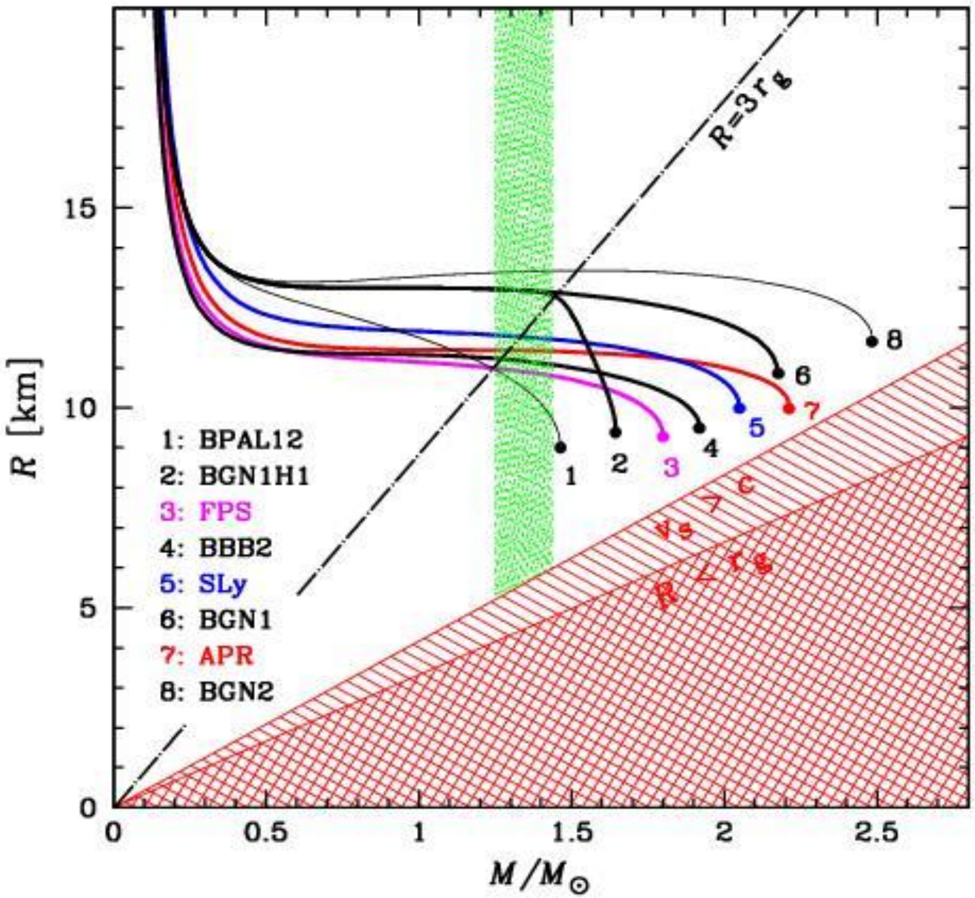
1. Motivation: *Importance of the envelopes*
2. Plasma EoS: *fully ionized / partially ionized, nonmagnetic / magnetic*
3. Radiative opacities: *Magnetized atmospheres*
4. Conduction: *Thermal structure and luminosity*
5. The effects of superstrong magnetic fields: *Uncertainties*
6. [An application example]

Neutron star models

Motivation

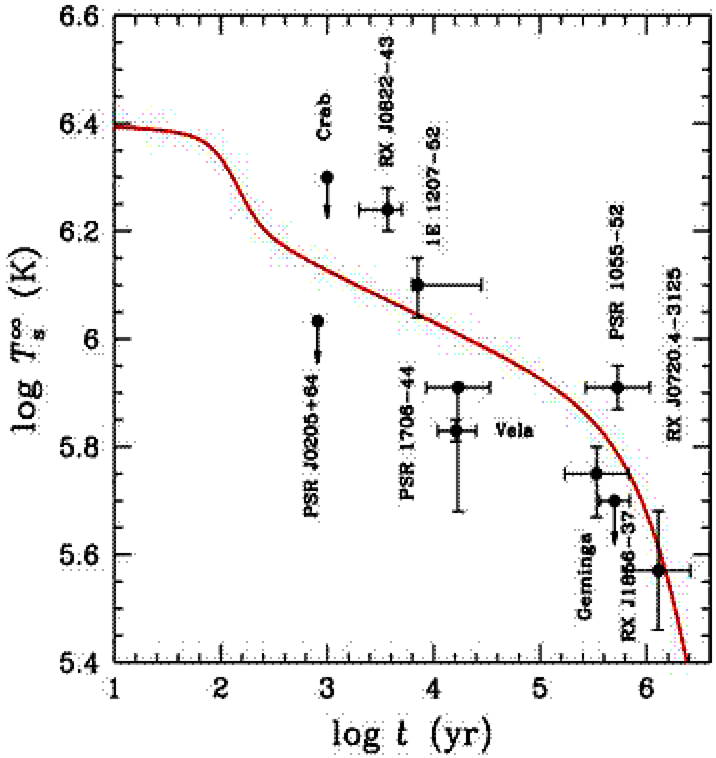


Stellar mass–radius relation for different EOSs

[from **Haensel, Potekhin, & Yakovlev,** ***Neutron Stars. 1. Equation of State and Structure*** (Springer, New York, 2007)]

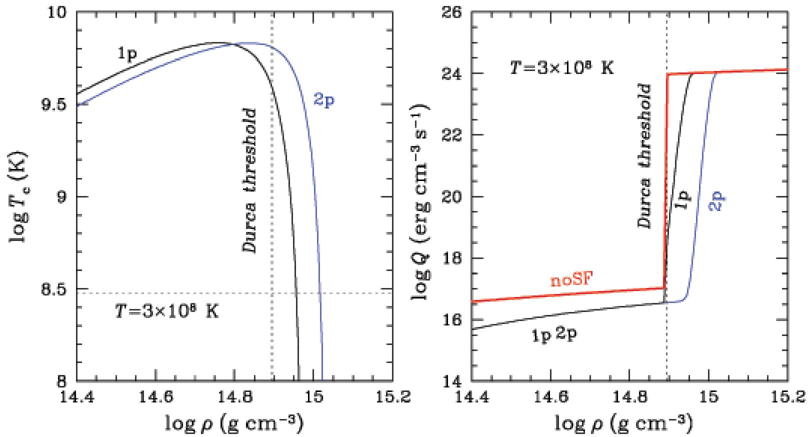
Thermal evolution

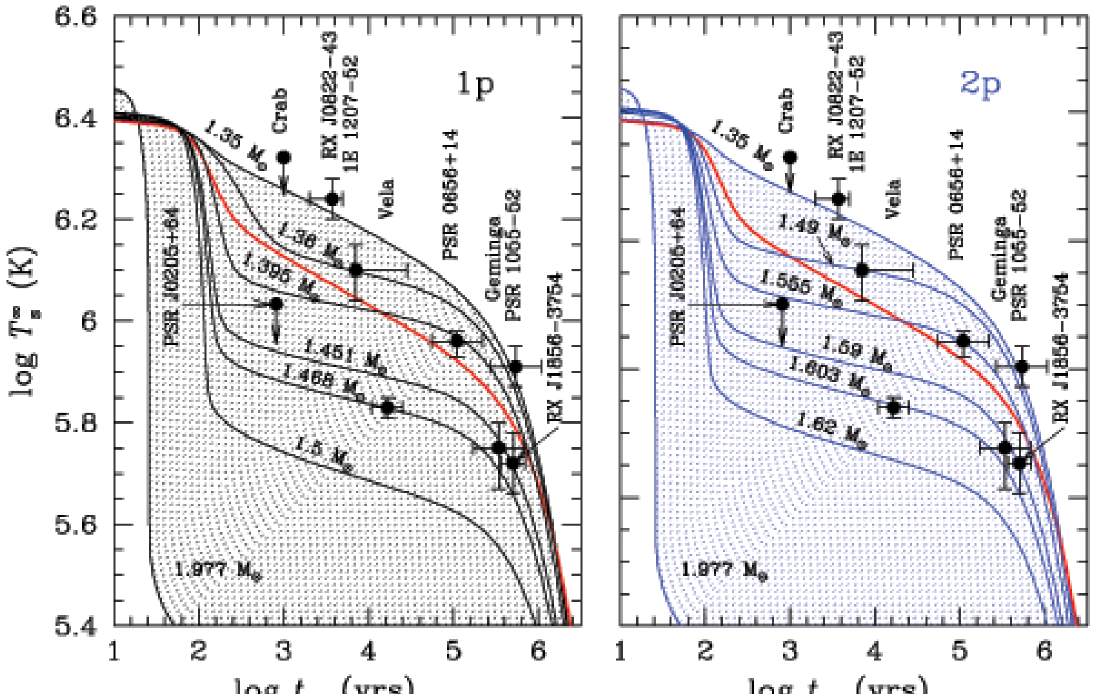
"Basic cooling curve"
of a neutron star
(no superfluidity, no exotica)



Neutron star cooling
[Yakovlev *et al.* (2005) *Nucl. Phys. A* **752**, 590c]

Cooling of neutron stars with proton superfluidity in the cores





- Relation between ***internal*** (core) temperature and ***effective temperature*** (surface luminosity)
    - requires studying **thermal conduction** and **temperature profiles** in heat-blanketing envelopes
- Knowledge of the shape and features of the ***radiation spectrum*** at given effective temperature
    - requires modeling neutron star **surface layers** and propagation of electromagnetic radiation in them

Solution of both problems relies on
modeling thermodynamic and kinetic properties
of ***outer neutron-star envelopes*** –
dense, strongly magnetized plasmas

Magnetic field affects thermodynamics properties
and the heat conduction of the plasma,
as well as radiative opacities

- Strong magnetic field B :

$\hbar\omega_c = \hbar eB/m_c c > 1$ a.u.

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

- Superstrong field :

$\hbar\omega_c > m_c c^2$

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

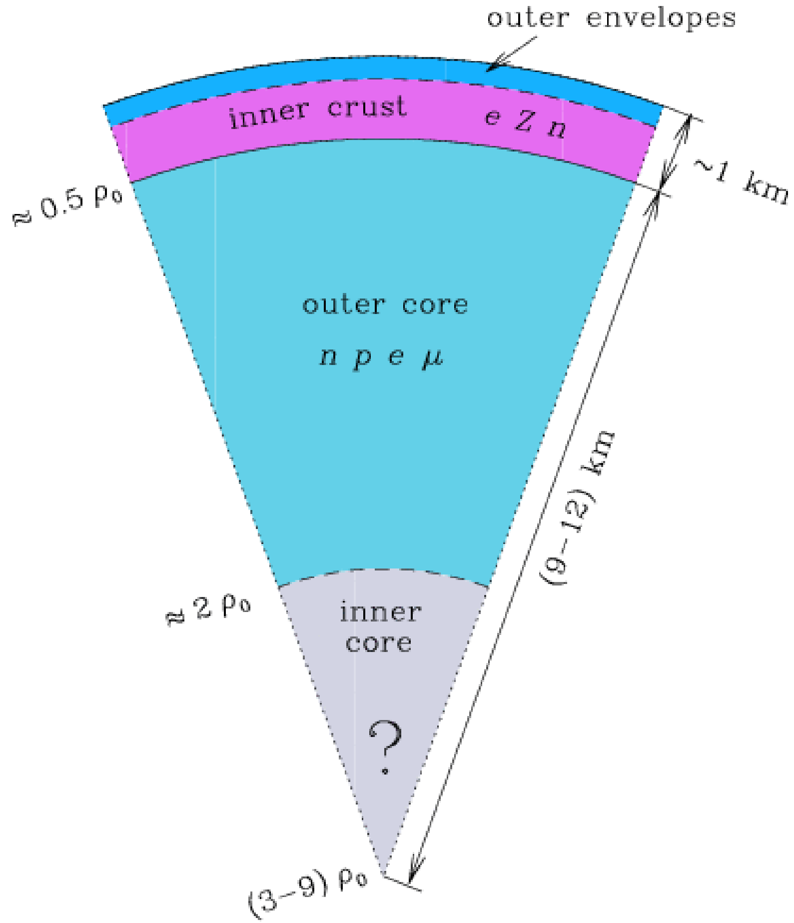
- Strongly quantizing :

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

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

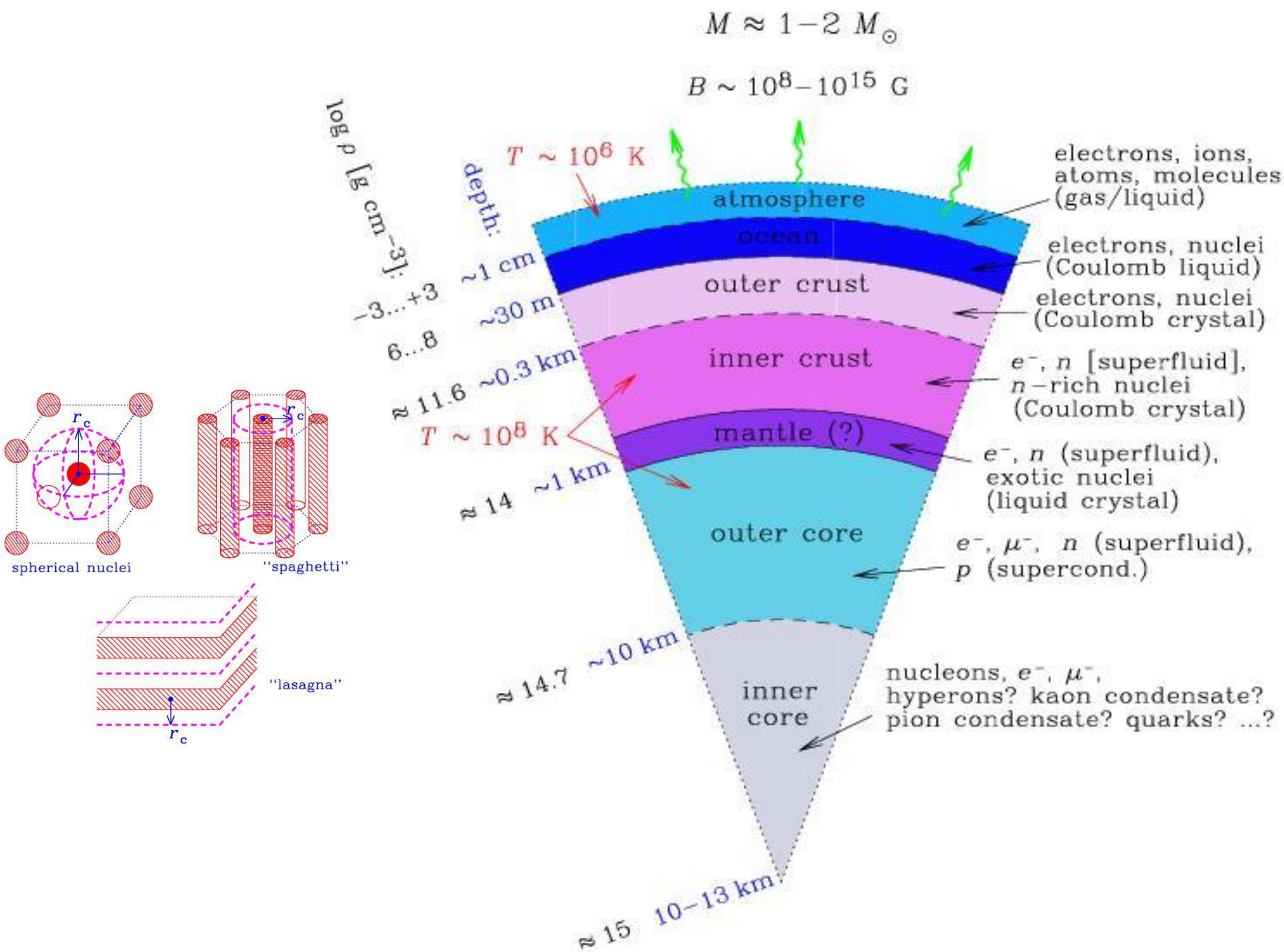
Importance

Neutron star structure

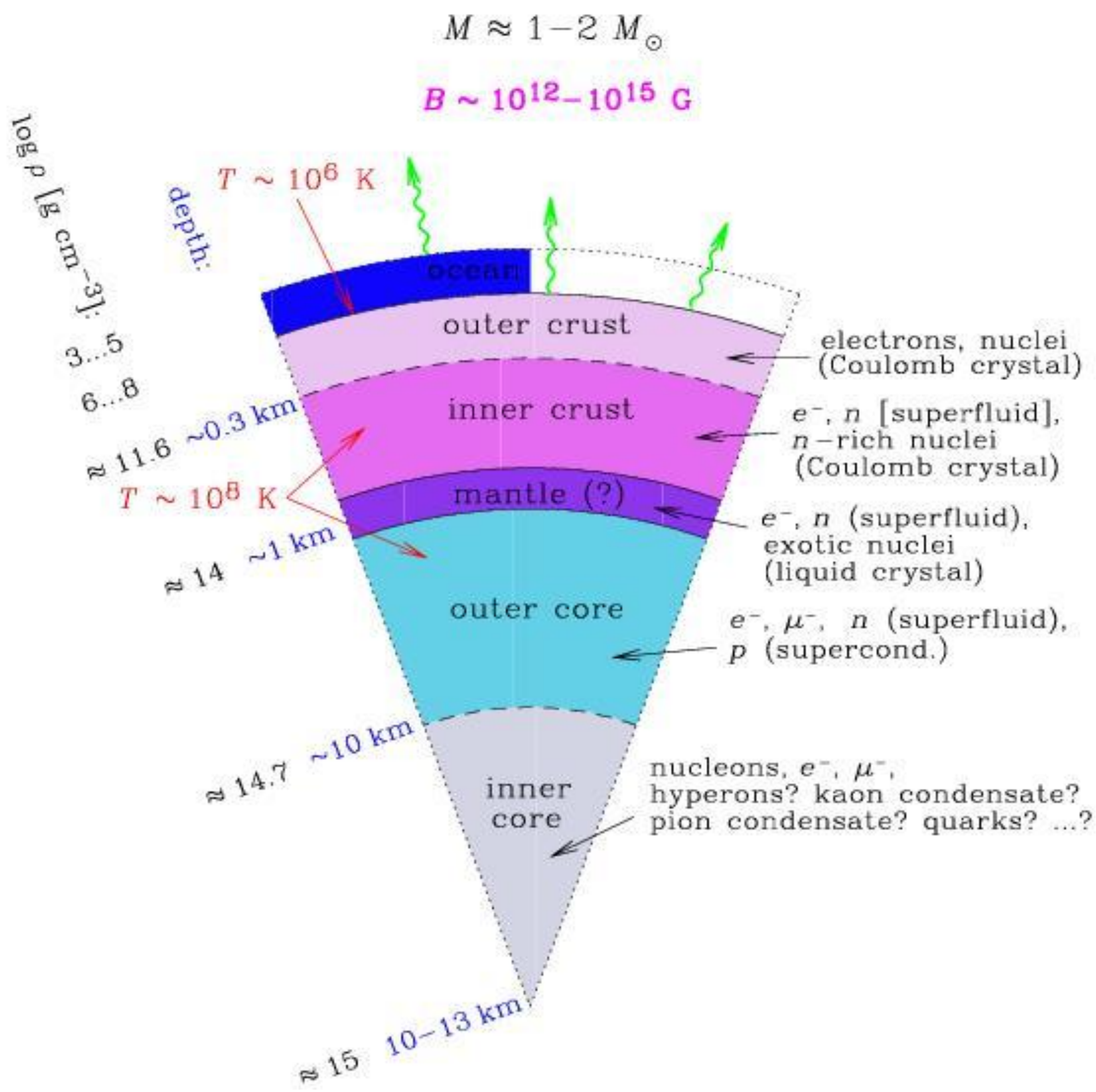


Importance

Neutron star structure in greater detail



Neutron star without atmosphere: possible result of a phase transition



Equation of state of electron-ion plasmas

Ideal Fermi gas

Fitting and asymptotic formulae:

S. I. Blinnikov, N. V. Dunina-Barkovskaya, D. K. Nadyozhin, *Astrophys. J. Suppl. Ser.*, **106**, 171 (1996); erratum: *ibid.*, **118**, 603 (1998);
G. Chabrier, A. Y. Potekhin, *Phys. Rev. E*, **58**, 4941 (1998); updated 2009.

An alternative – numerical calculation of tables and interpolation:

F. X. Timmes, D. Arnett, *Astrophys. J. Suppl. Ser.*, **125**, 277 (1999);
F. X. Timmes, F. D. Swesty, *Astrophys. J. Suppl. Ser.*, **126**, 501 (2000).

Exchange-correlation interaction of electrons

S. Tanaka, S. Mitake, S. Ichimaru, *Phys. Rev. A*, **32**, 1896 (1985);
S. Ichimaru, H. Iyetomi, S. Tanaka, *Phys. Rep.*, **149**, 91 (1987).

Ion liquid

Best Monte Carlo calculations of the internal energy at $1 < \Gamma < 190$:
J. M. Caillol, *J. Chem. Phys*., **111**, 6538 (1999).

Debye – Hückel formula + corrections up to $O(\Gamma^{9/2} \ln \Gamma)$:
E. G. D. Cohen, T. J. Murphy, *Phys. Fluids*, **12**, 1404 (1969).

Fit formula reproducing the Caillol's results at $1 < \Gamma < 190$ with a fractional error about $1/10^6$, and also the Cohen – Murphy formula at $\Gamma<0,3$
A. Y. Potekhin, G. Chabrier, *Phys. Rev. E*, **62**, 8554 (2000)

Quantum corrections

J. P. Hansen, *Phys. Rev. A*, **8**, 3096 (1973)

Next order corrections – J. P. Hansen, P. Vieillefosse, *Phys. Lett. A*, **53**, 187 (1975).

Numerical results beyond perturbation theory are wanted for quantum liquid!

Coulomb (Wigner) crystal

Harmonic approximation: analytic formulae

D. A. Baiko, A. Y. Potekhin, D. G. Yakovlev, 2001, *Phys. Rev. E*, **64**, 057402

Classical anharmonic corrections

R. T. Farouki, S. Hamaguchi, *Phys. Rev. E*, **47**, 4330 (1993): Monte-Carlo + fits (11 versions)

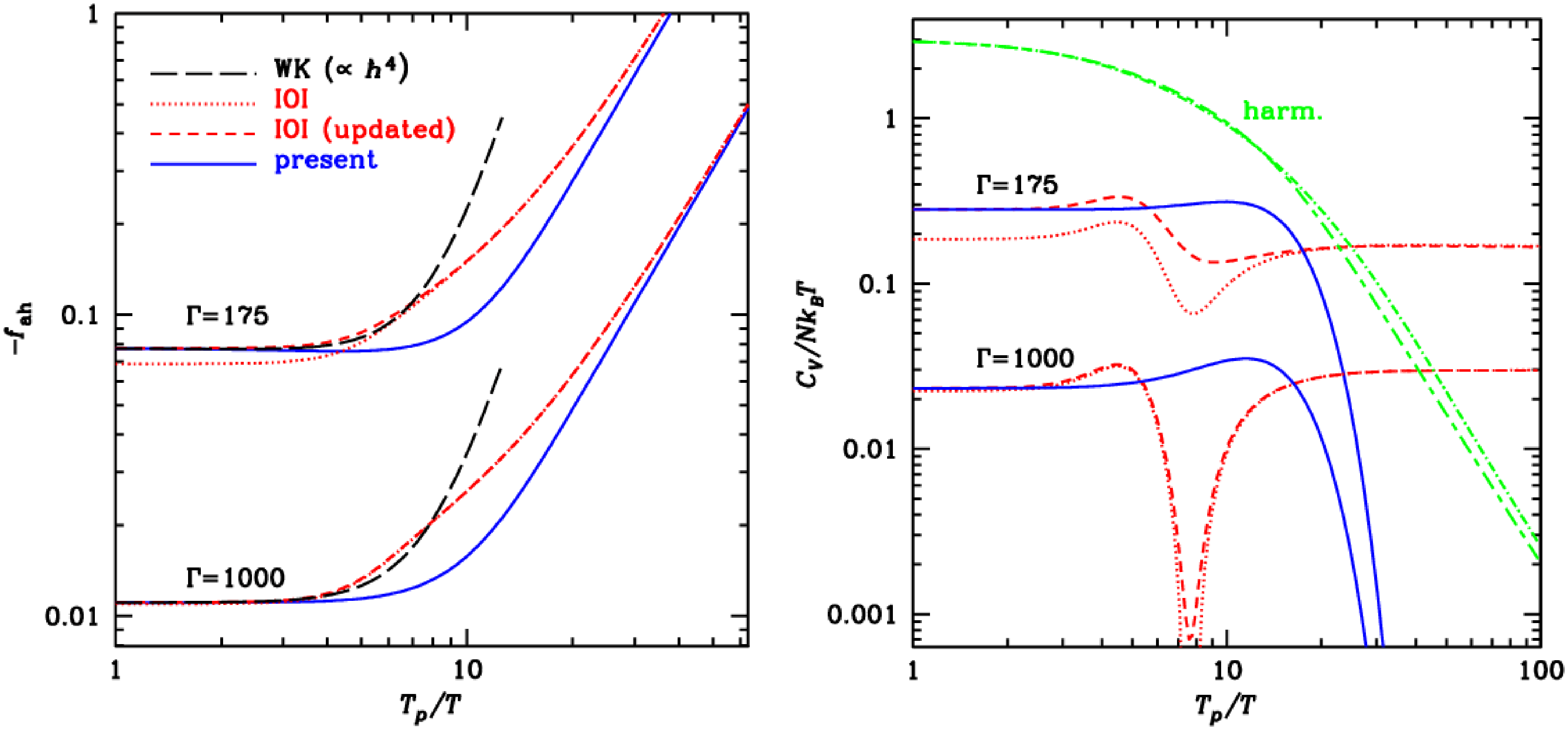
Quantum anharmonic corrections

W.J. Carr, Jr., R.A. Coldwell-Horsfall, A.E. Fein, *Phys. Rev.*, **124**, 747 (1961): zero temperature

J. P. Hansen, P. Vieillefosse, *Phys. Lett. A*, **53**, 187 (1975): high-temperature perturbation

EoS: fully ionized, nonmagnetic

Anharmonic corrections



WK (Wigner – Kirkwood): J. P. Hansen & P. Vieillefosse, *Phys. Lett. A*, **53**, 187 (1975) – perturbation.
IOI: H. Iyetomi, S. Ogata, S. Ichimaru, *Phys. Rev. B*, **47**, 11703 (1993) – simulations and analytic model.
"present": Potekhin & Chabrier – interpolation (unpublished)

Reliable and usable numerical results beyond perturbation theory and beyond the harmonic model are wanted for quantum crystal!

Equation of state of multicomponent electron-ion plasmas (2009)

1. Strongly nonideal Coulomb plasma

For every component j one can write $$f_{\mathrm{ex}} \equiv \frac{F_{\mathrm{ex}}}{N_{\mathrm{i}} k_{\mathrm{B}} T} = f_{\mathrm{ii}} + f_{\mathrm{ie}} + Z_j f_{ee}$$

Linear **M**ixing **R**ule

$$f_{\mathrm{ex}}^{\mathrm{LM}}(\Gamma) \approx \sum_j x_j f_{\mathrm{ex}}(\Gamma_j, x_j = 1), \quad \Gamma_j = \Gamma \frac{Z_j^{5/3}}{\langle Z^{5/3} \rangle}$$

2. Extremely weakly nonideal Coulomb plasma

Debye – Hückel approximation (nonlinear!)

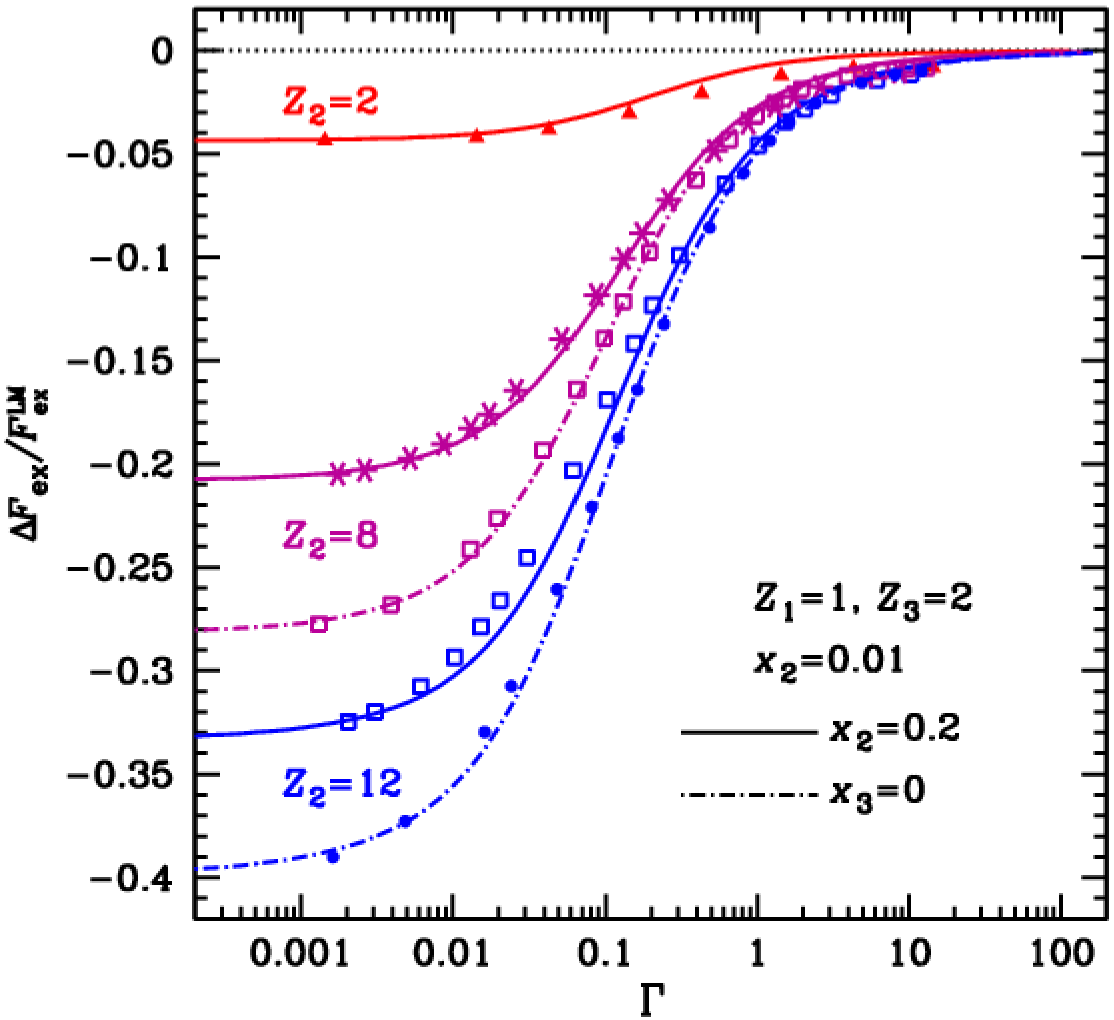
$$f_{ee}^{\mathrm{DH}} = -\frac{\Gamma_e^{3/2}}{\sqrt{3}} \qquad f_{\mathrm{ii}}^{\mathrm{DH}} = f_{ee}^{\mathrm{DH}} \zeta_{\mathrm{ii}}^{\mathrm{DH}}, \quad \zeta_{\mathrm{ii}}^{\mathrm{DH}} = \frac{\langle Z^2 \rangle^{3/2}}{\langle Z \rangle^{1/2}}$$

3. Moderate Coulomb coupling – ???

A.Y. Potekhin & G. Chabrier – *Phys. Rev. E* **79**, 016411 (2009);
Potekhin, Chabrier, A.I. Chugunov, F. Rogers, H.E. DeWitt – *Phys. Rev. E* (submitted)

EoS: fully ionized, nonmagnetic

Examples for three-component plasmas



Electron-ion interaction

Electron polarization in Coulomb liquid

Potekhin & Chabrier, *Phys. Rev. E*, **62**, 8554 (2000): HNC calculations + fit

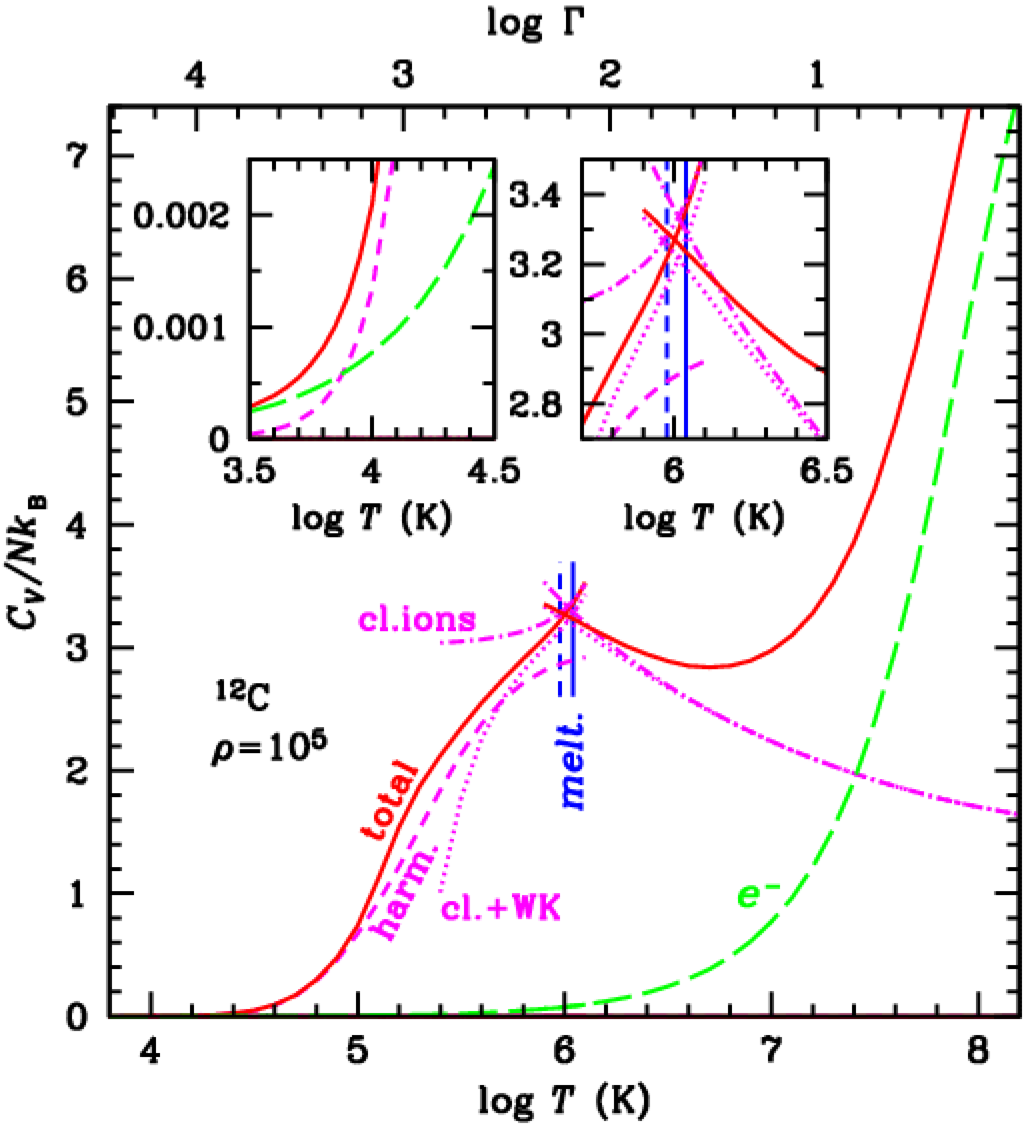
Electron polarization in Coulomb crystal

For Yukawa potential model – S. Hamaguchi, R. T. Farouki, D. H. E. Dubin, *Phys. Rev. E*., **56**, 4671 (1997).
In the harmonic approximation – D. A. Baiko, *Phys. Rev. E*., **66**, 056405 (2002).
Quasiclassical perturbation theory – Potekhin & Chabrier, *Phys. Rev. E*, **62**, 8554 (2000) + update (unpublished).

Numerical results beyond perturbation theory and beyond Yukawa and harmonic models are wanted!

EoS: fully ionized, nonmagnetic

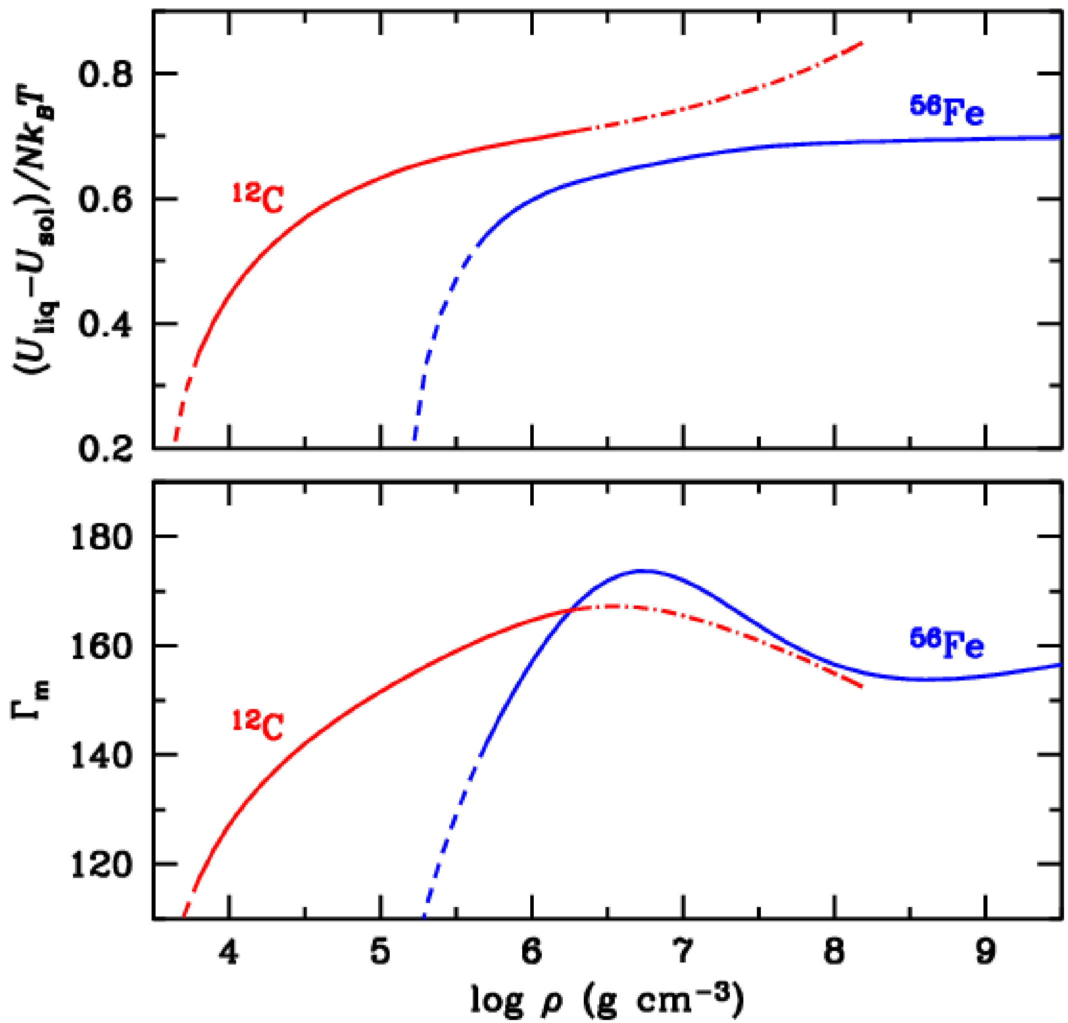
Heat capacity of plasma in a white dwarf or a neutron star envelope



Various contributions to the heat capacity of carbon at density 10^5 g cm^{-3}

EoS: fully ionized, nonmagnetic

Melting of a neutron star envelope

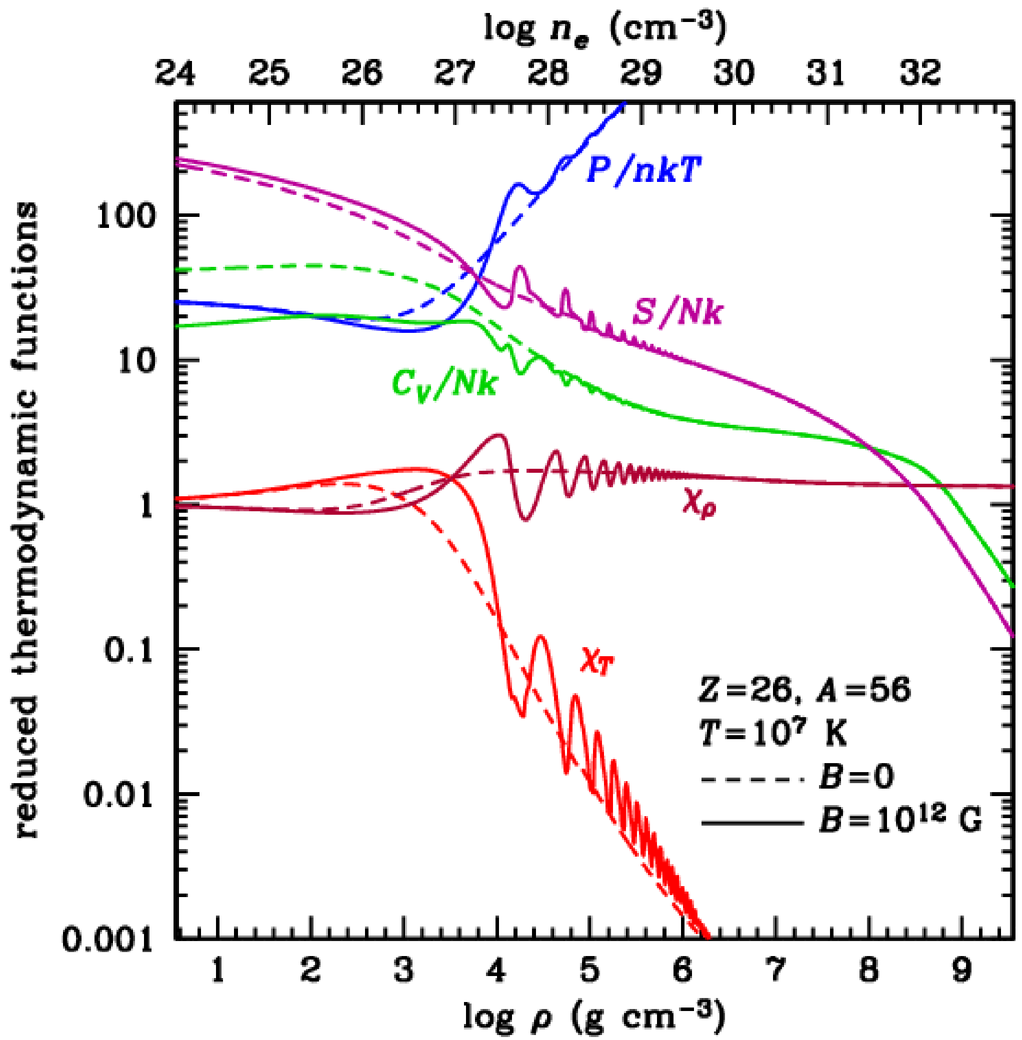


Top: Latent heat of carbon and iron as function of denity.
Bottom: Coulomb coupling parameter Γ value at the melting point.

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

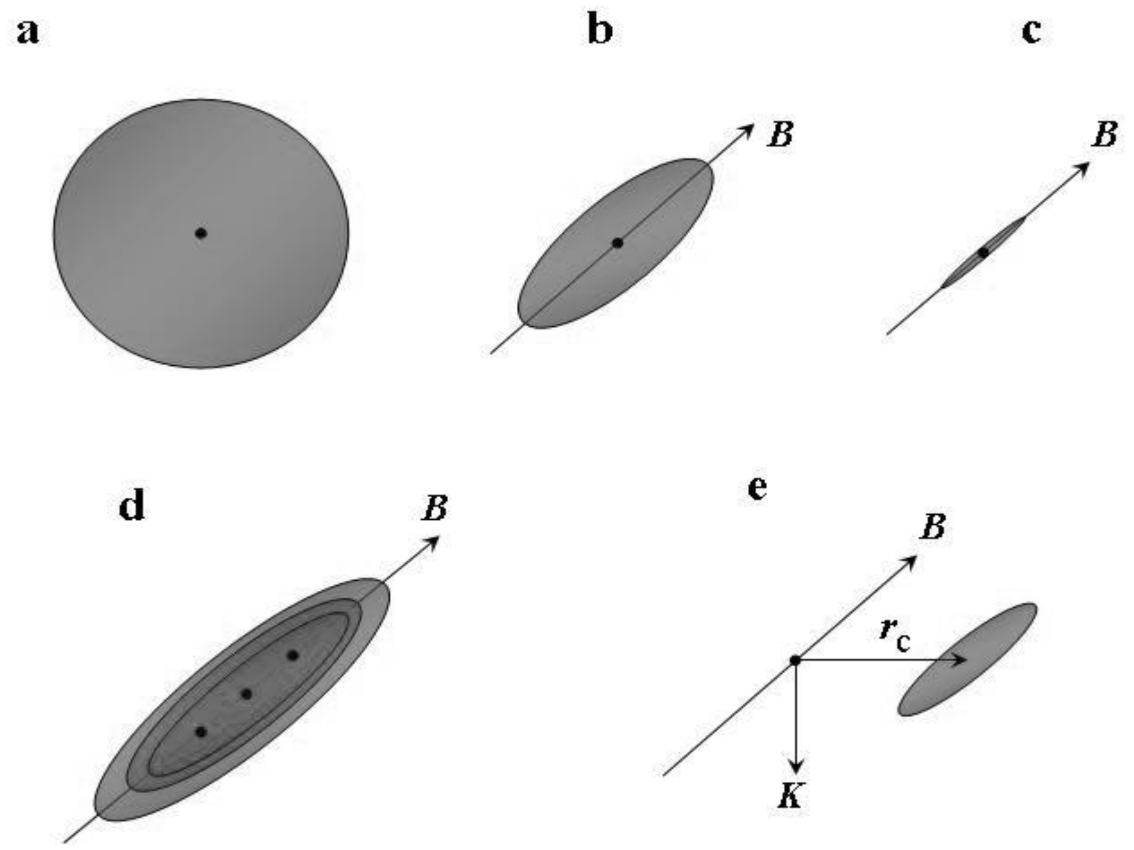
EoS: fully ionized, magnetic

Equation of state in *magnetic* neutron star envelopes



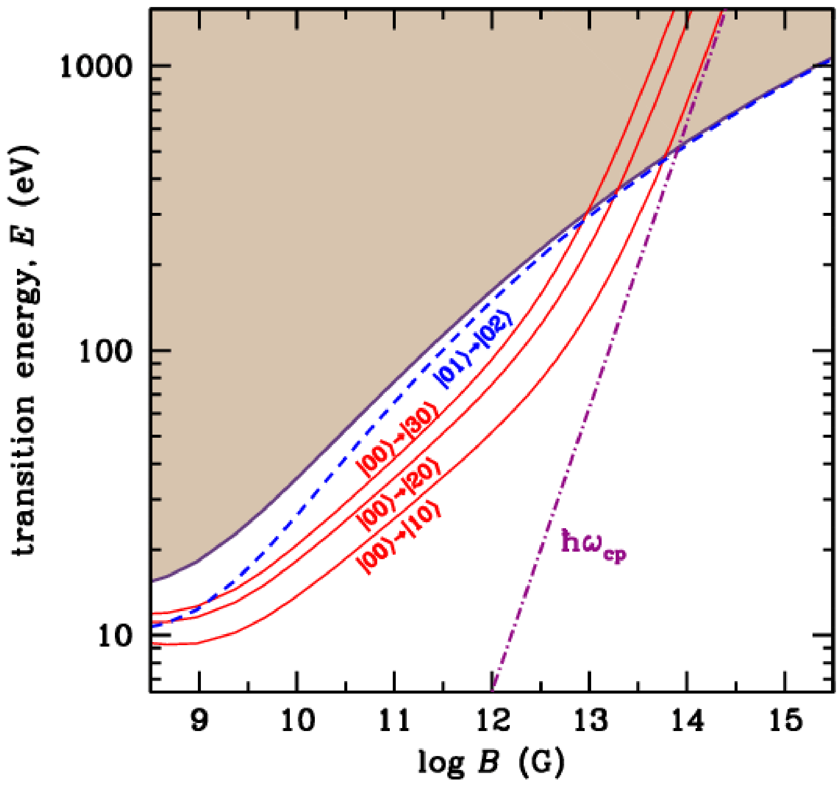
Normalized thermodynamic functions of fully ionized iron without magnetic field (dashed lines) and in a strong magnetic field (solid lines)

Bound species in a strong magnetic field

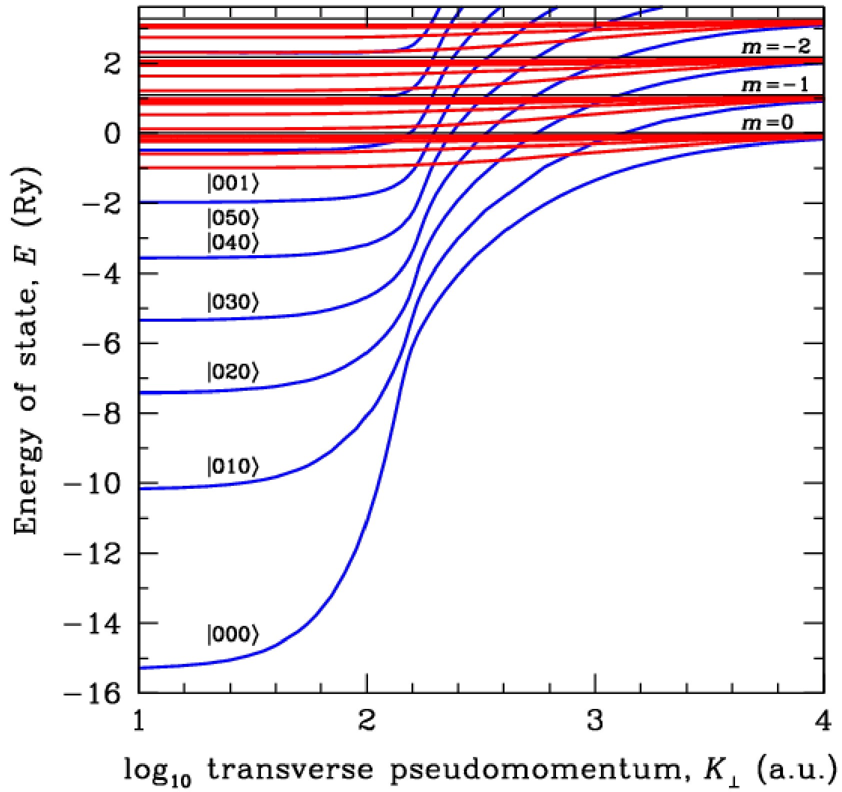


The effects of a strong magnetic field on the atoms and molecules.
a–**c**: H atom in the ground state (**a**: B<<10^9 G, **b**: B~10^{10} G, **c**: B~10^{12} G).
d: The field stabilizes the molecular chains (H_3 is shown).
e: H atom moving across the field becomes decentered.

H atom in strong magnetic fields



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

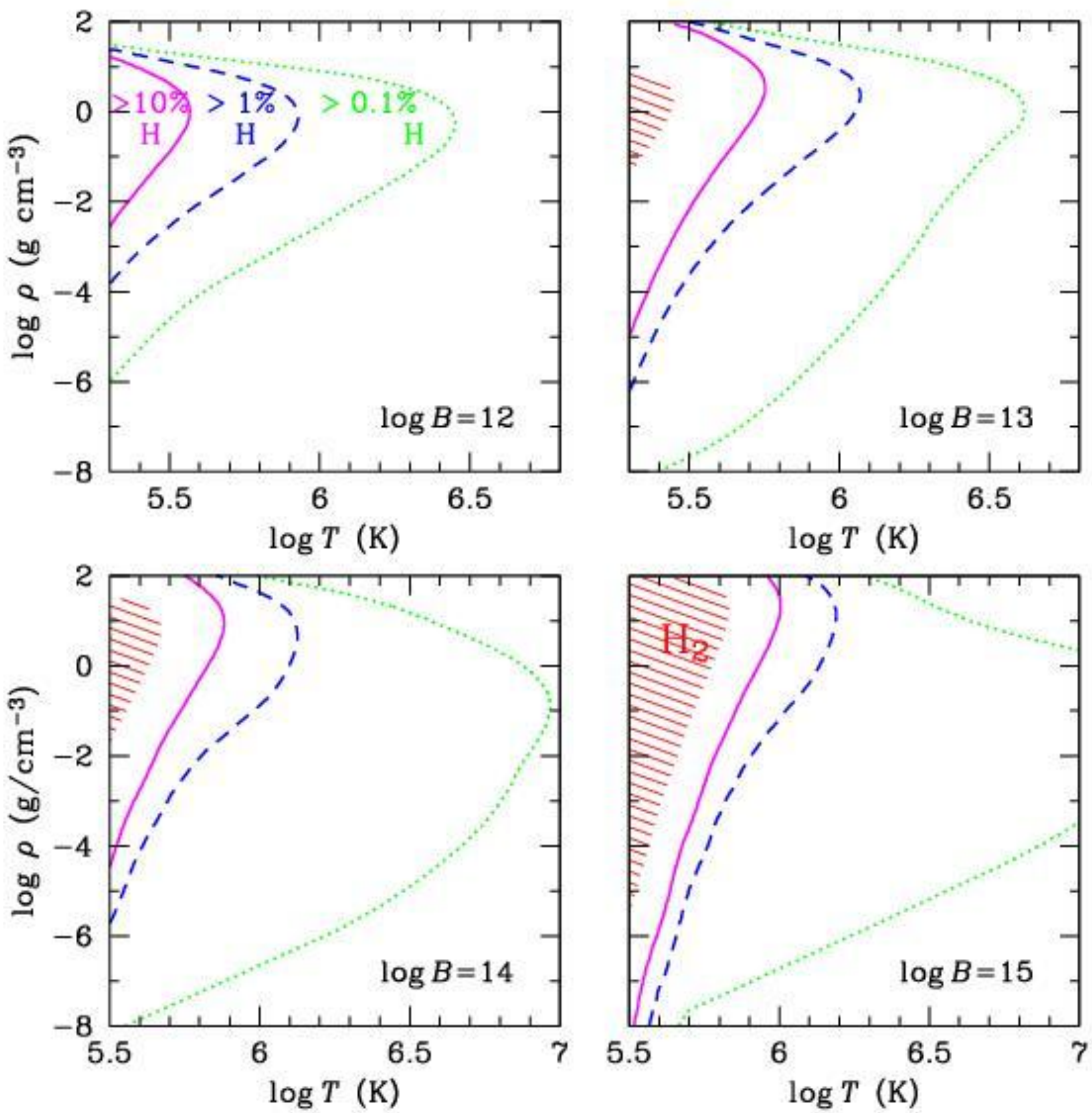


Binding energies of the hydrogen atom in the magnetic field B=2.35x10^{12} G as functions of its state of motion across the field
[Potekhin (1994) *J.Phys.B: At. Mol. Opt. Phys.* **27**, 1073]

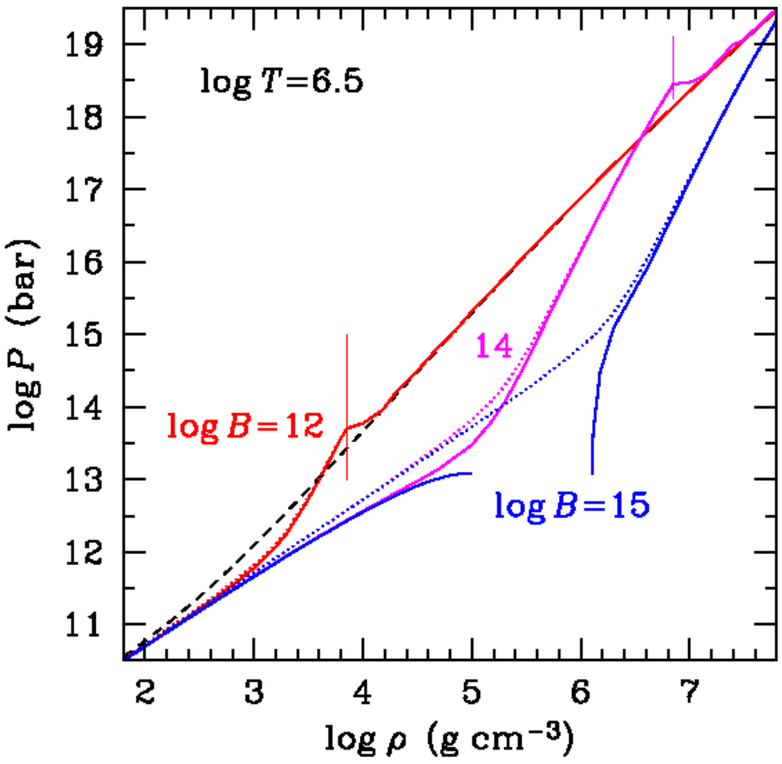
http://www.ioffe.ru/astro/NSG/Hmagnet/

EoS: partially ionized, magnetic

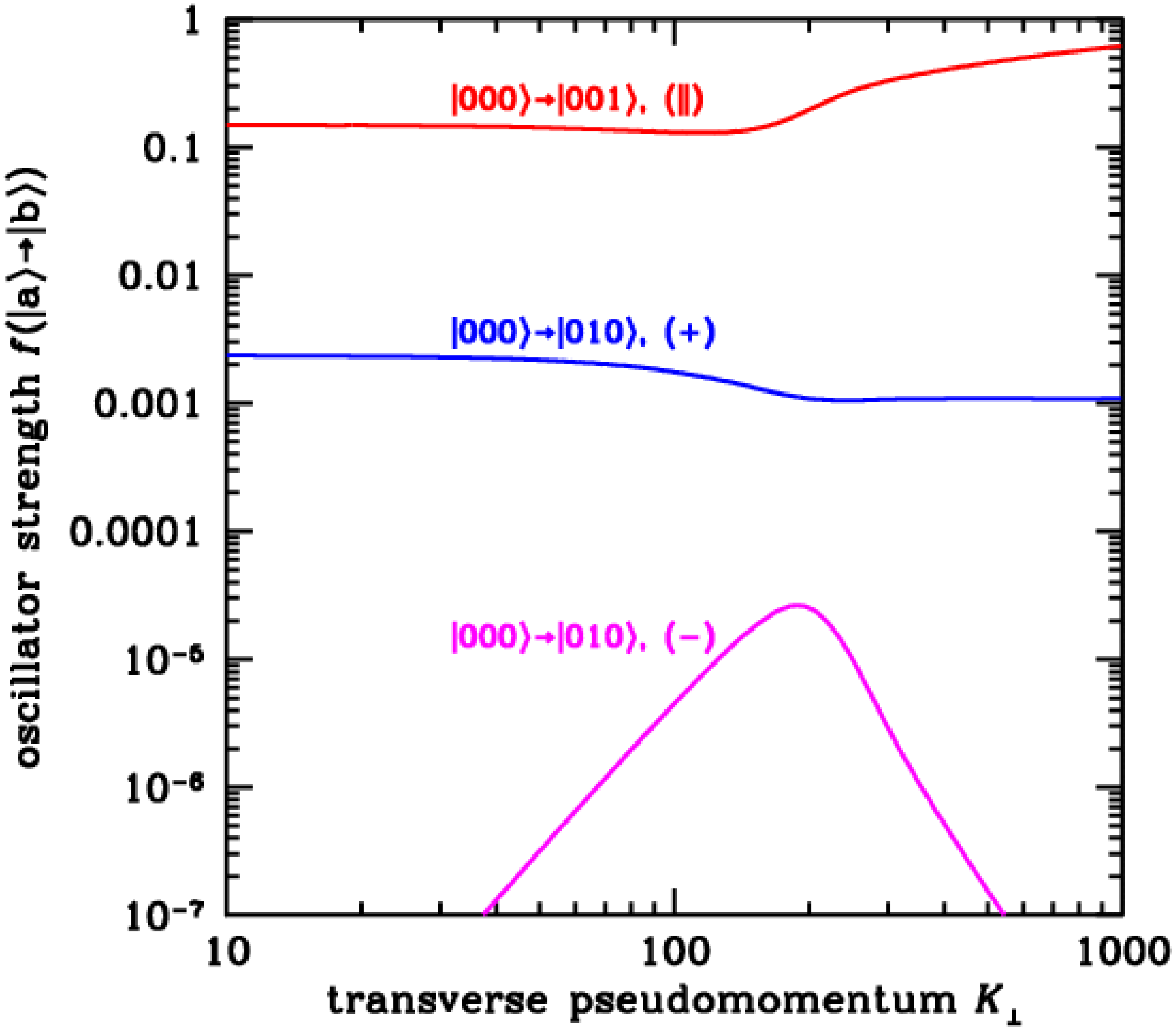
Partial ionization/recombination in hydrogen plasmas with strong magnetic fields



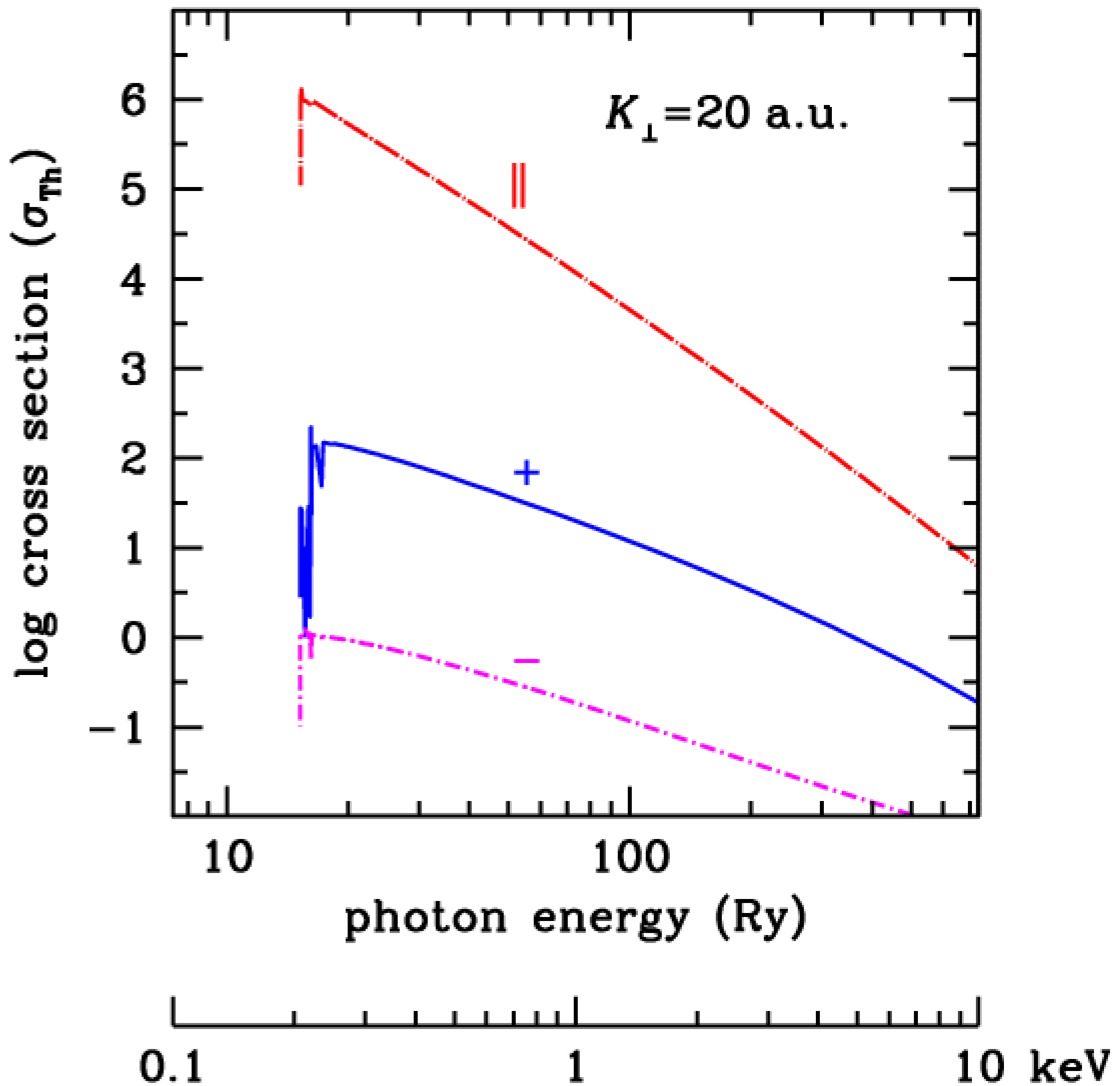
Equation of state of hydrogen in strong magnetic fields: The effects of nonideality and partial ionization



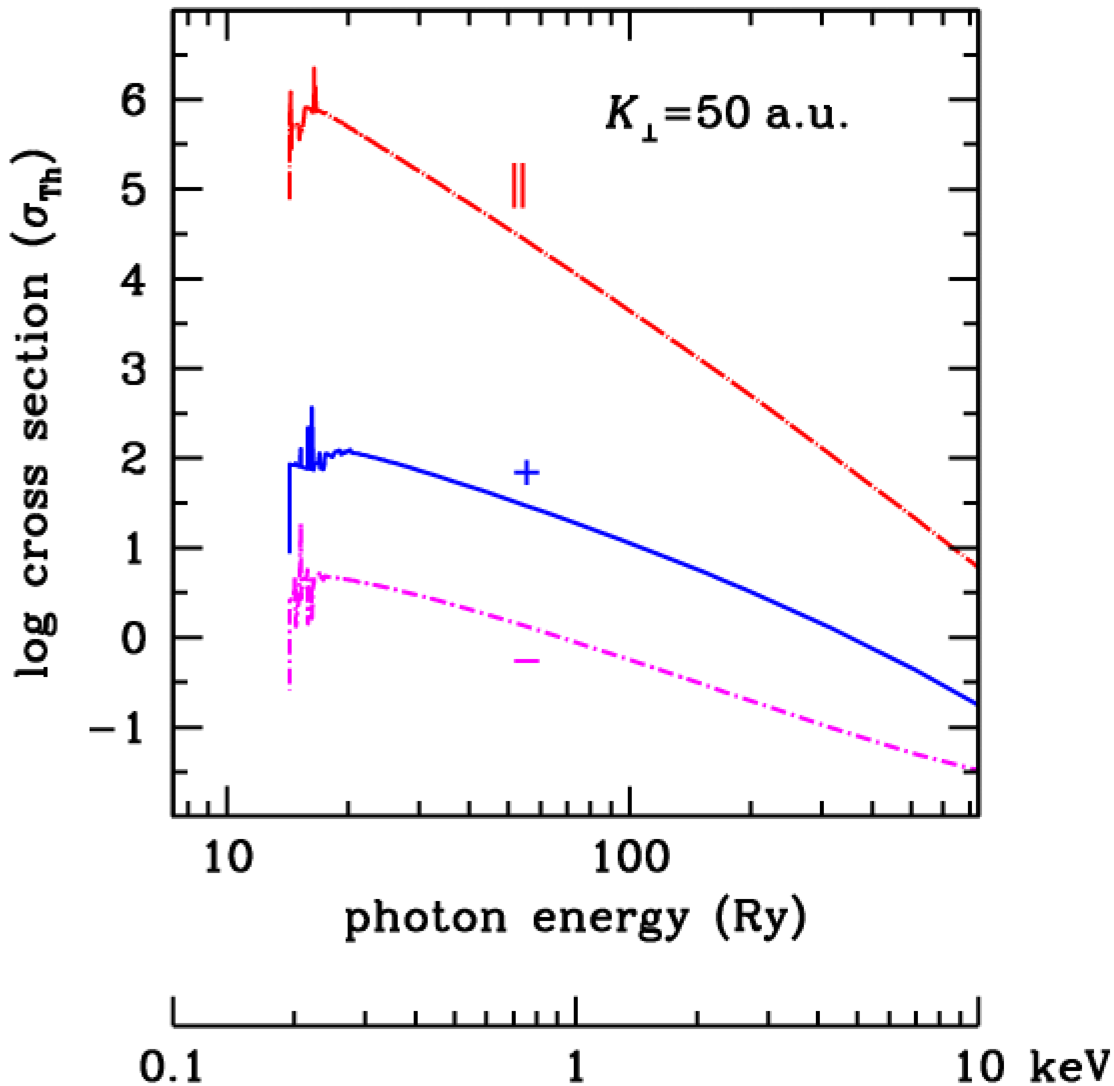
EOS of ideal (dotted lines) and nonideal (solid lines) H plasmas at various field strengths.
Potekhin, Chabrier, & Shibanov, *Phys. Rev. E* **60**, 2193 (1999);
Potekhin & Chabrier, *ApJ* **600**, 317 (2004)



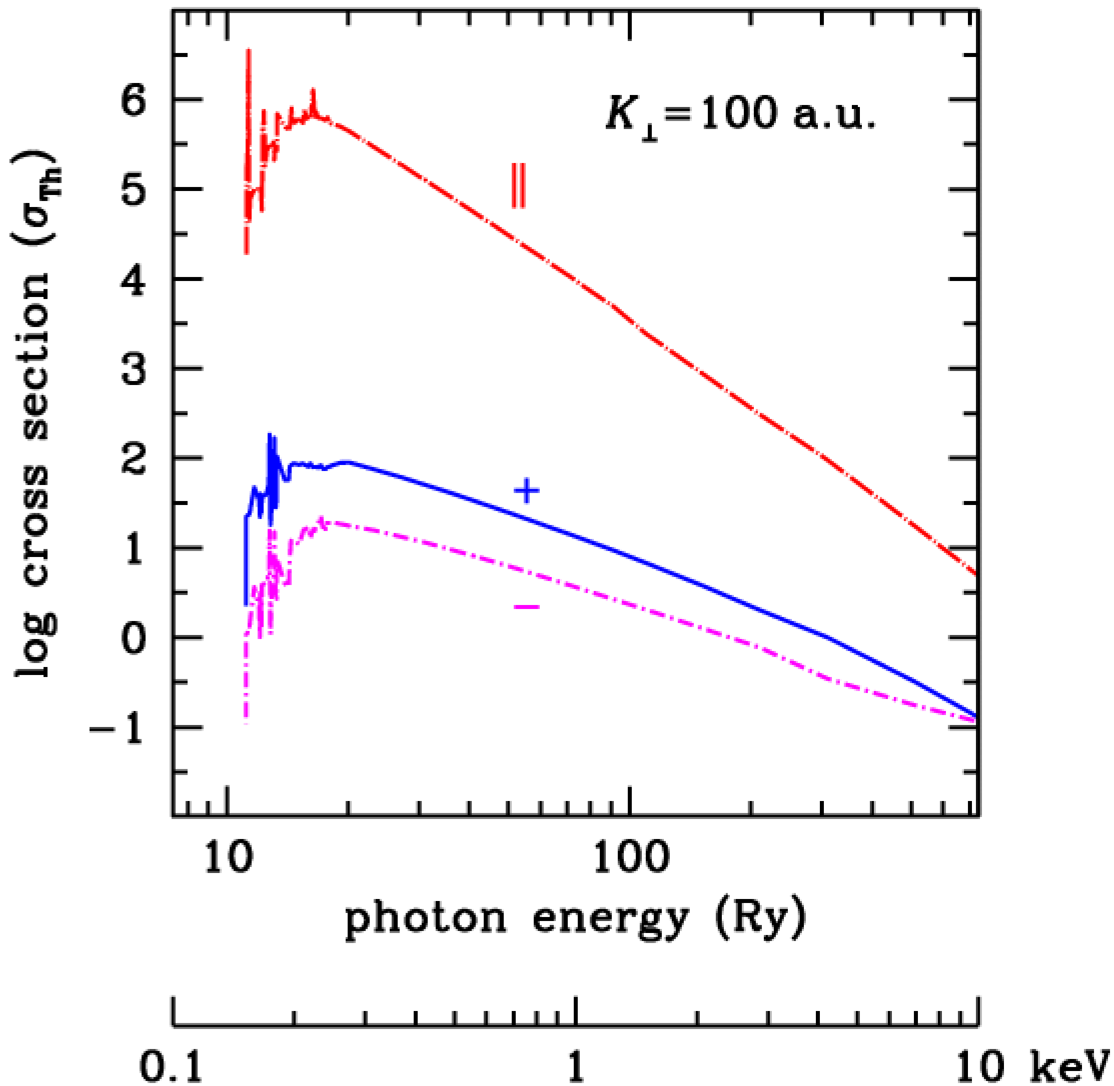
Oscillator strengths for transitions between 2 levels of the hydrogen atom at B=2.35x10^{12} G, as functions of pseudomomentum
[Potekhin (1994) *J.Phys.B: At. Mol. Opt. Phys.* **27**, 1073]



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



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



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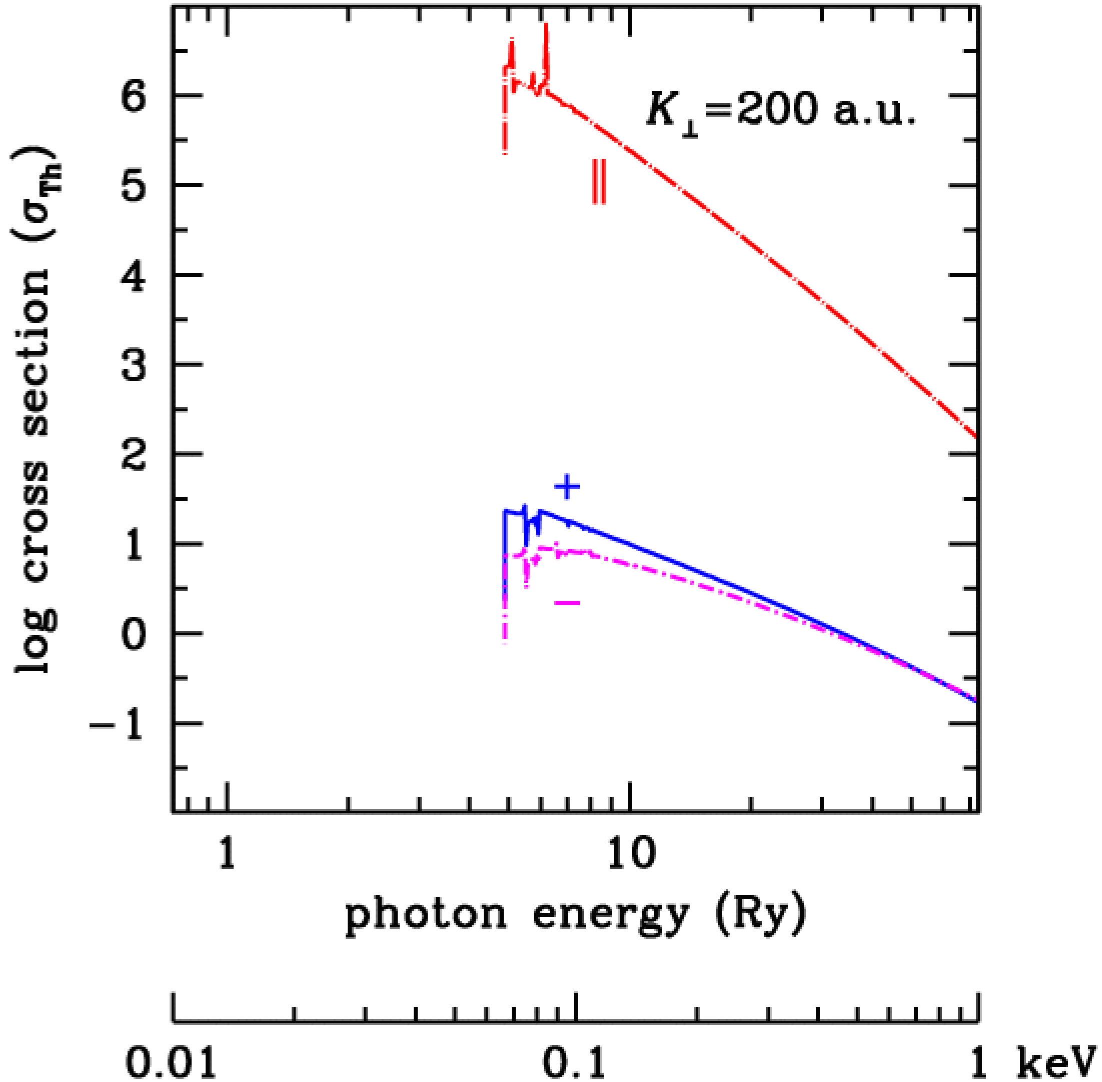
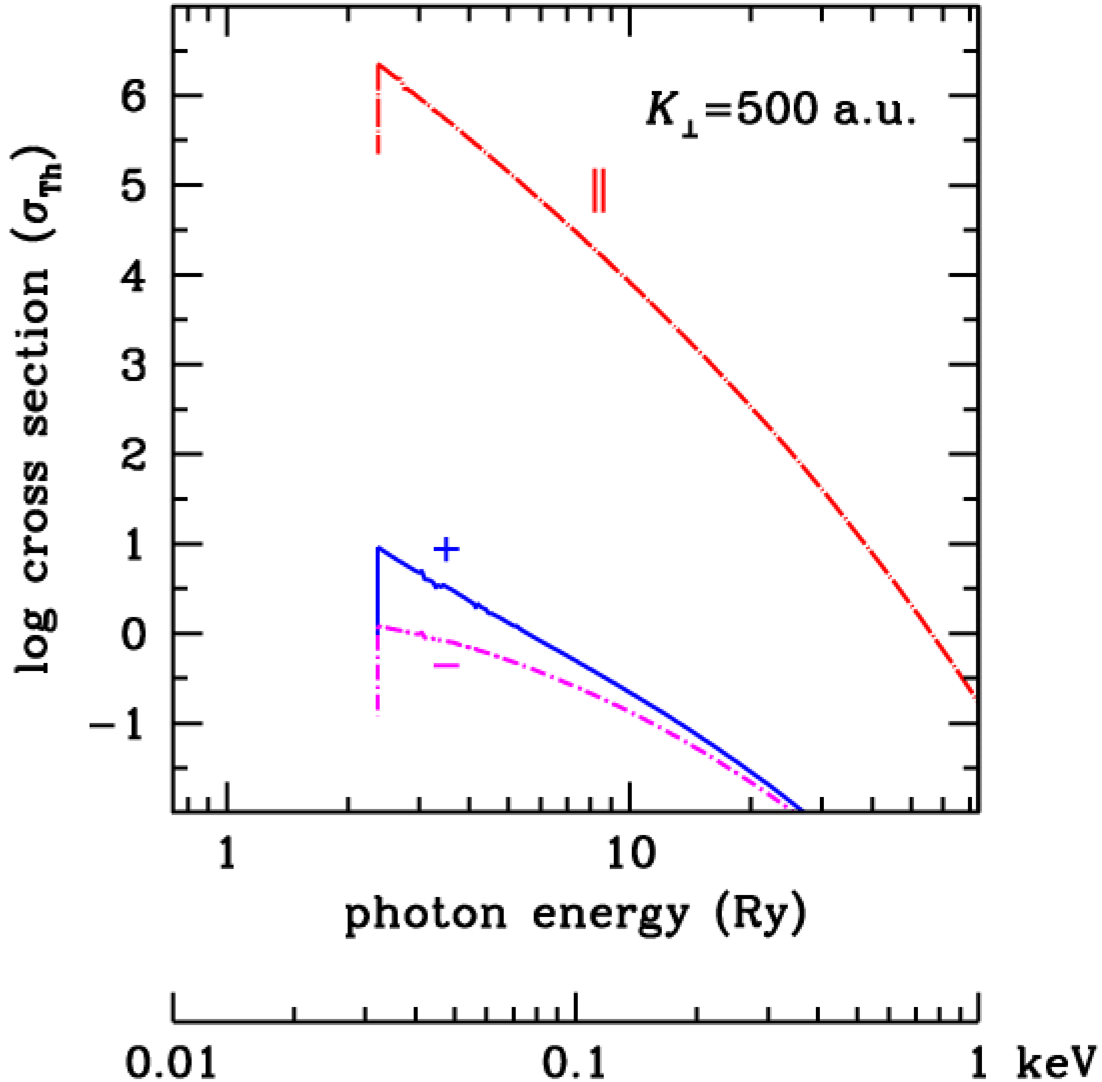
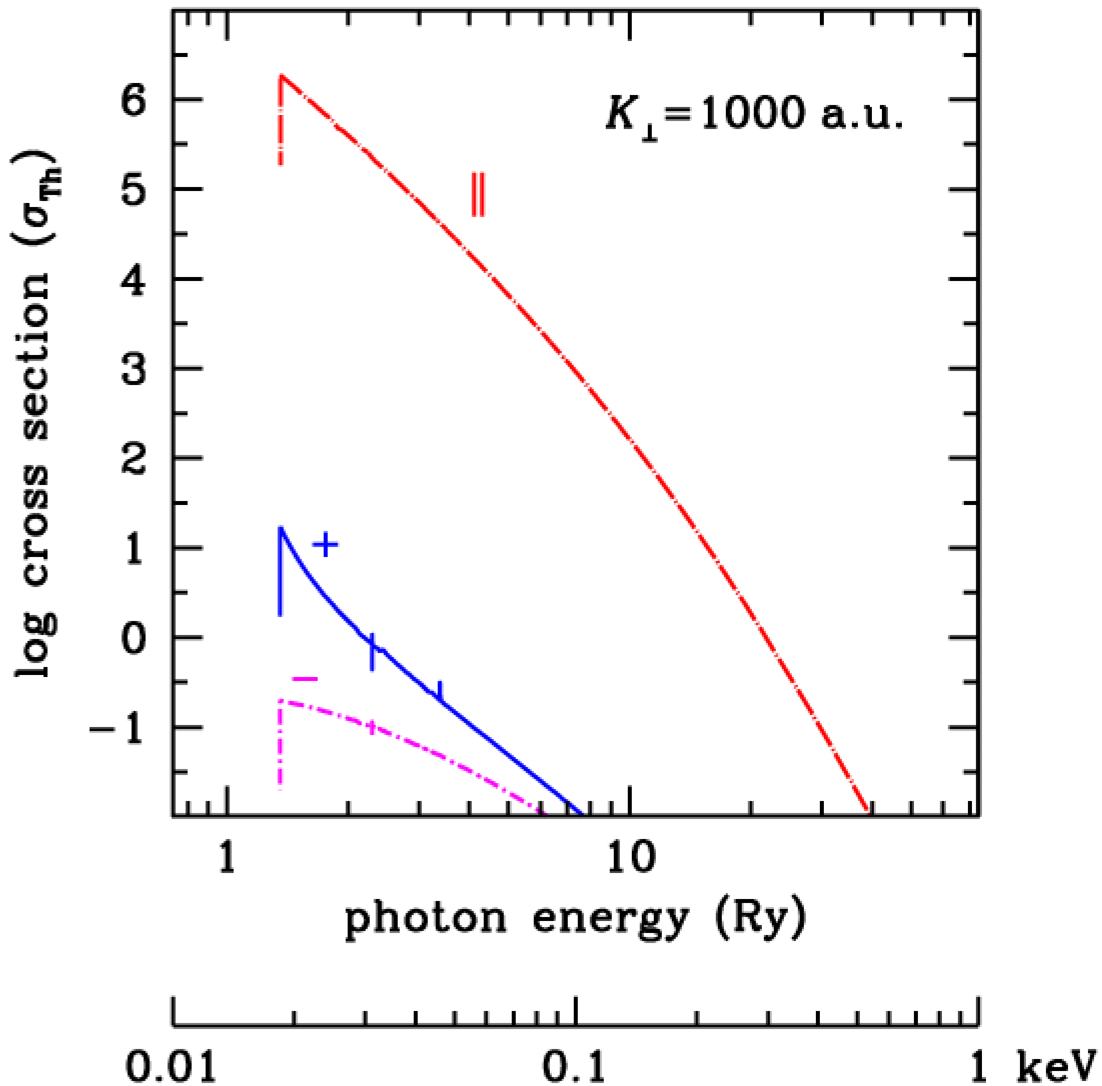
[Potekhin & Pavlov (1997) *Astrophys. J.* **483**, 414]



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

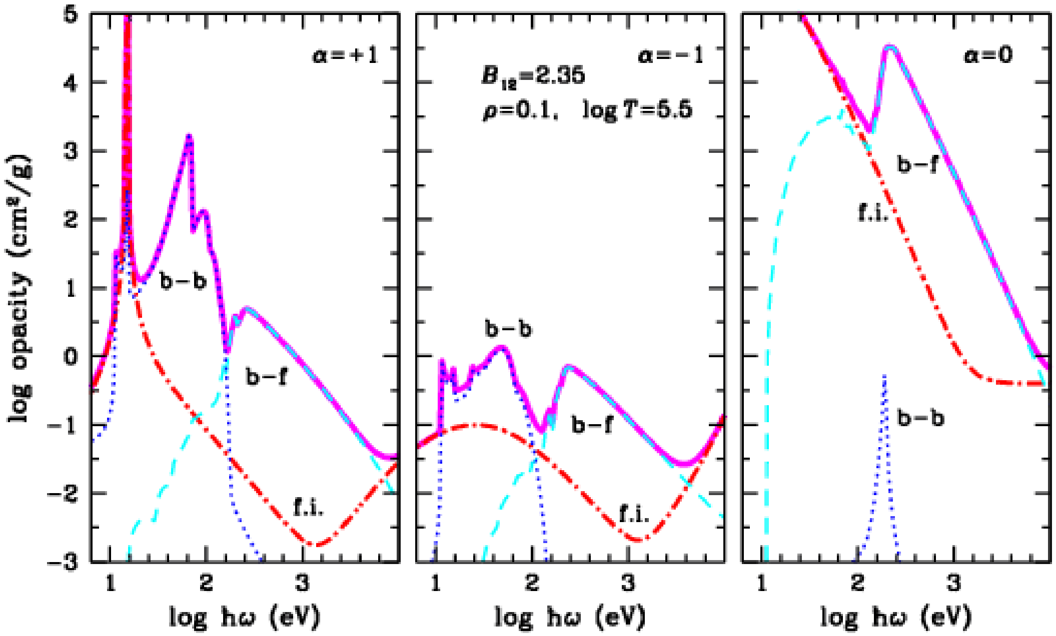


Photoionization cross sections for the ground-state H atom at B=2.35x10^{12} G
[Potekhin & Pavlov (1997) *Astrophys. J.* **483**, 414]

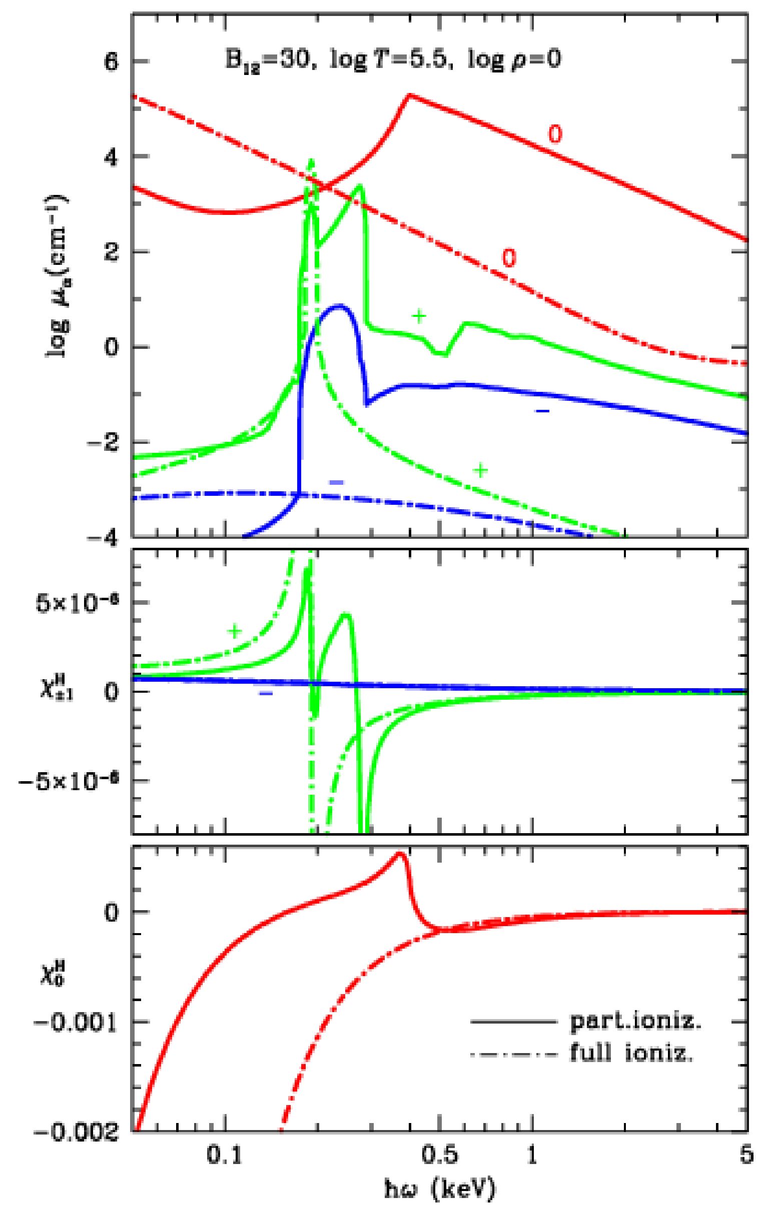


Photoionization cross sections for the ground-state H atom at B=2.35x10^{12} G
[Potekhin & Pavlov (1997) *Astrophys. J.* **483**, 414]

Plasma absorption and polarizabilities in strong magnetic fields: The effects of nonideality and partial ionization

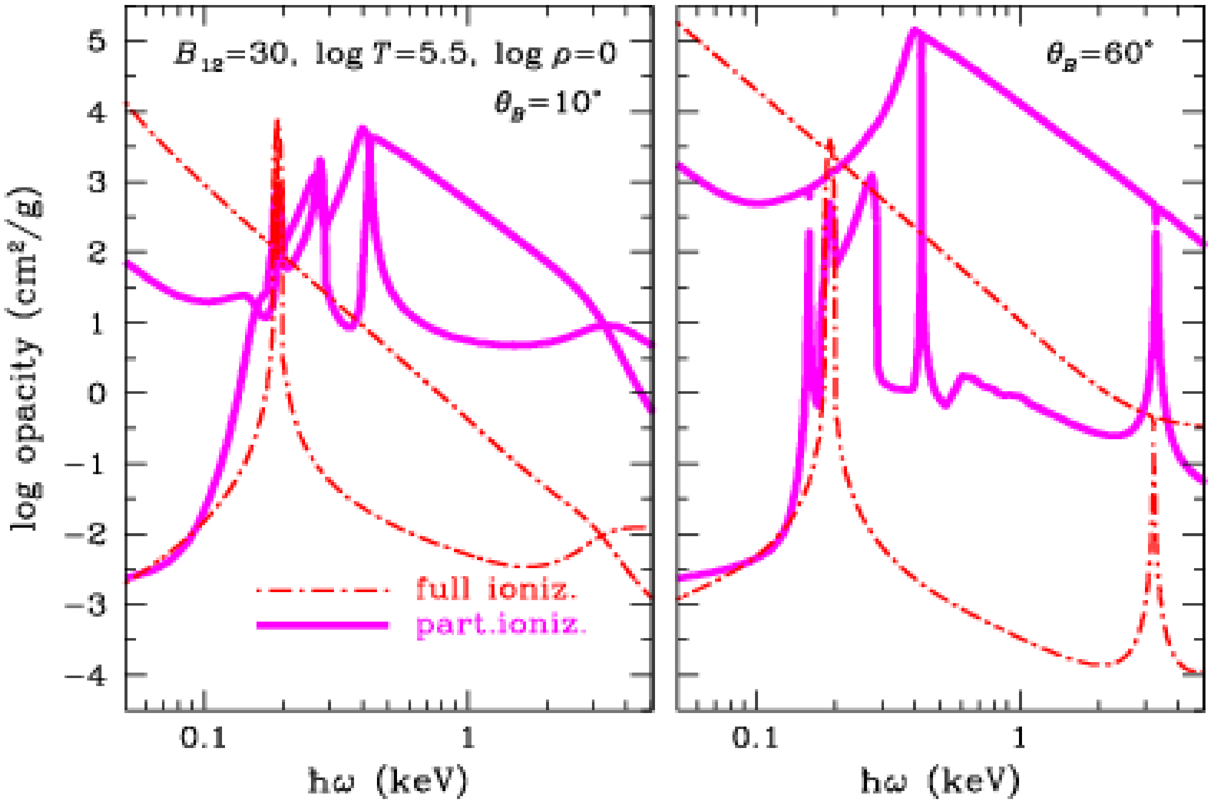


Spectral opacities for 3 basic polarizations.
Solid lines – taking into account bound states,
dot-dashes –full ionization
[Potekhin & Chabrier (2003) *ApJ* **585**, 955]



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



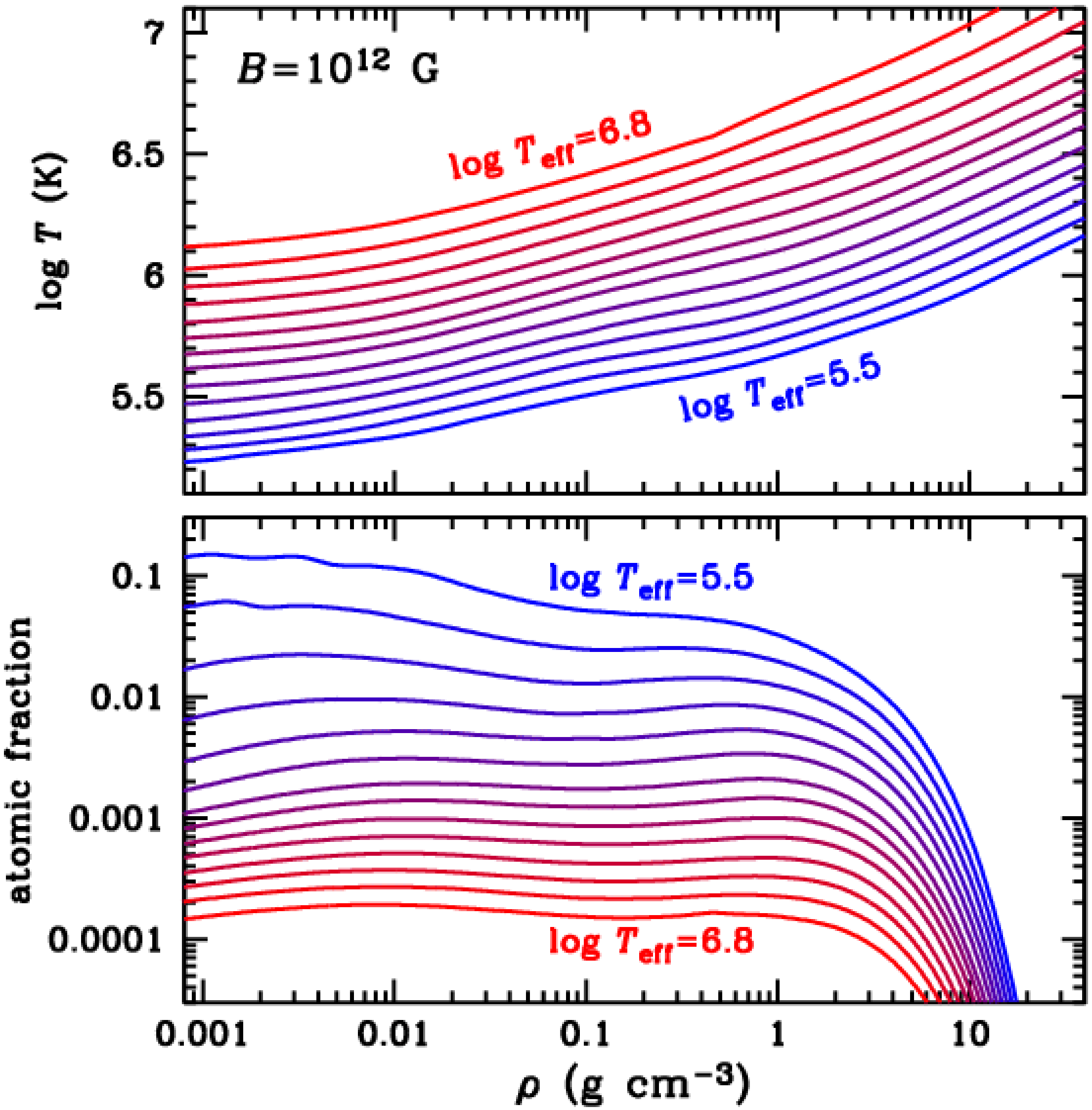
Opacities for two normal modes of electromagnetic radiation in models of an ideal fully ionized (dash-dot) and nonideal partially ionized (solid lines) plasma

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

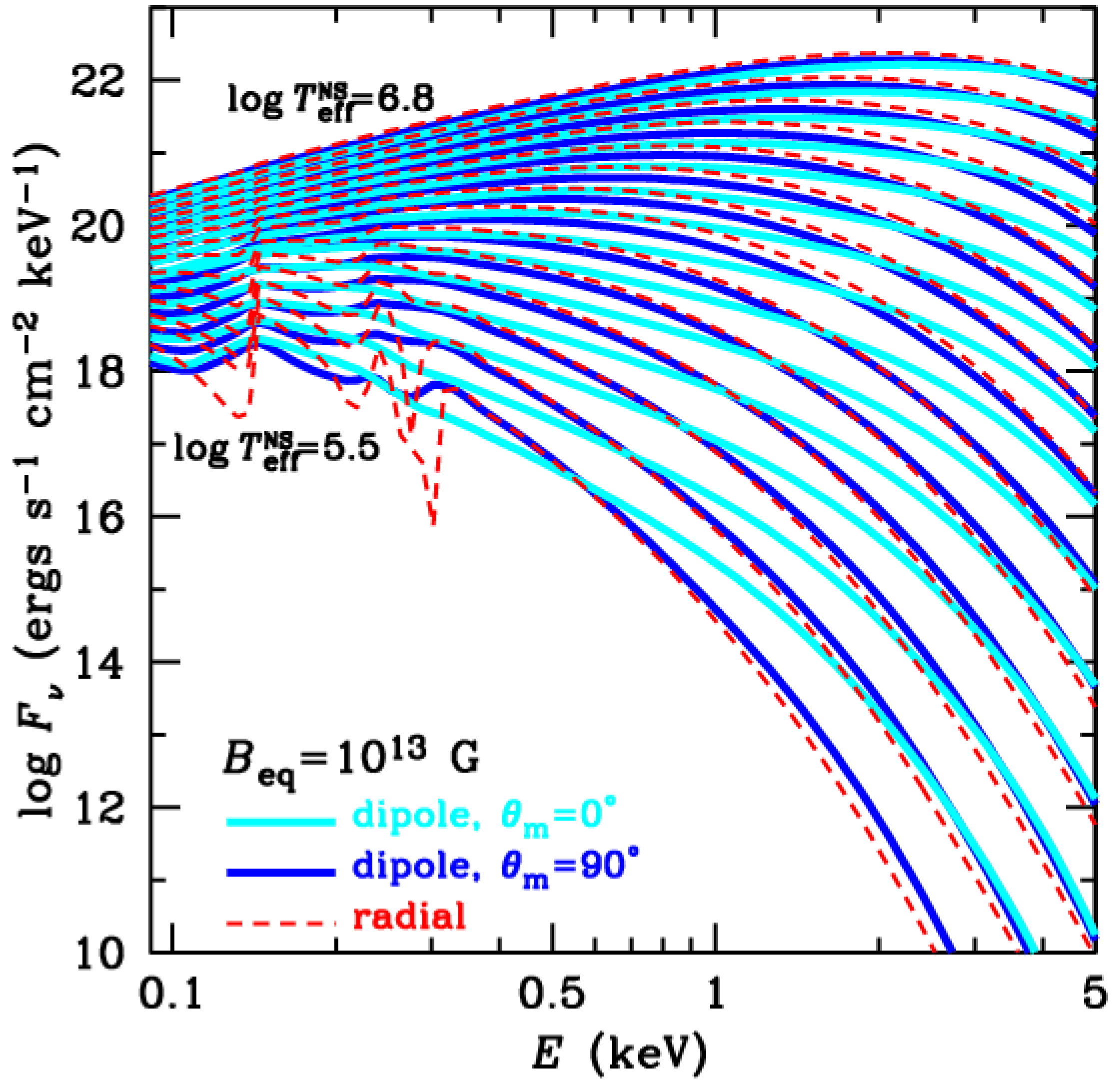
[Potekhin, Lai, Chabrier, & Ho (2004) *ApJ* **612**, 1034]

Modeling results: temperature profiles and the atomic fractions



Result of modelling: spectra, dipole model

(Wynn Ho)



NSMAX: ***N**eutron **S**tar **M**agnetic **A**tmosphere: **X**-ray spectra*

W.C.G. Ho, A.Y. Potekhin, & G. Chabrier, *ApJS* **178**, 102 (2008)

NS Magnetic Atmosphere Model

The NSMAX model interpolates from a grid of neutron star (NS) atmosphere spectra to produce a final spectrum that depends on the parameters listed below. The atmosphere spectra are obtained using the latest equation of state and opacity results for a partially ionized, strongly magnetized hydrogen plasma. The models are constructed by solving the coupled radiative transfer equations for the two photon polarization modes in a magnetized medium, and the atmosphere is in radiative and hydrostatic equilibrium. The atmosphere models mainly depend on the surface effective temperature $T_{\rm eff}$ and magnetic field strength B and inclination Θ_B; there is also a dependence on the surface gravity $g=(1+z_g)GM/R^2$, where $1+z_g=(1-2GM/R)^{1/2}$ is the gravitational redshift and M and R are the NS mass and radius, respectively.

Two sets of models are given: one set with a single surface $\boldsymbol{B}$ and $T_{\rm eff}$ and a set which is constructed with $\boldsymbol{B}$ and $T_{\rm eff}$ varying across the surface according to the magnetic dipole model (for the latter, θ_m is the angle between the direction to the observer and the magnetic axis). The effective temperatures span the range $\log T_{\rm eff}$=5.5-6.8. The models with single ($\boldsymbol{B}$,$T_{\rm eff}$) cover the energy range 0.05-10 keV, while the models with ($\boldsymbol{B}$,$T_{\rm eff}$)-distributions cover the range 0.09-5 keV.

The model parameters are :

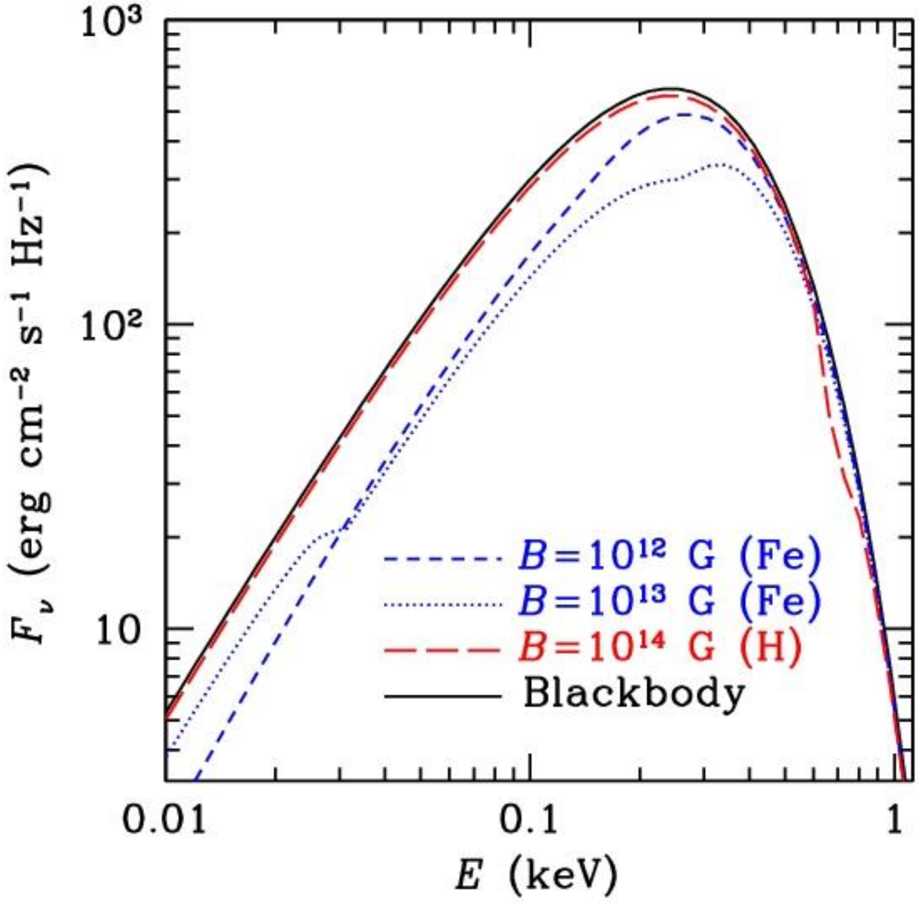
`par1`	=	$\log T_{\rm eff}$, surface (unredshifted) effective temperature
`par2`	=	$1+z_g$, gravitational redshift
`par3`	=	switch indicating model to use (see nsmax.dat or **list**)
`A`	=	$(R_{\rm em}/d)^2\,(1+z_g)^{-1}$, normalization, where $R_{\rm em}$ is the size (in km) of the emission region and d is the distance (in kpc) to the object. Note: `A` is added automatically by XSPEC.

The **source code**, **lmodel.dat entries**, **input model list**, and **model data files** (in one tar file) are available. A list of the models currently available can be found **here**. The model data files should either be placed in the $XANADU/spectral/modelIonData (v12), $XANADU/spectral/xspec/manager (v11) directory, or the XSPEC command `xset NSMAX_DIR directory-path` should be used to define the directory containing the model data files.

Model spectra

An alternative (or supplement):
Radiation from condensed surface
(Matt van Adelsberg)

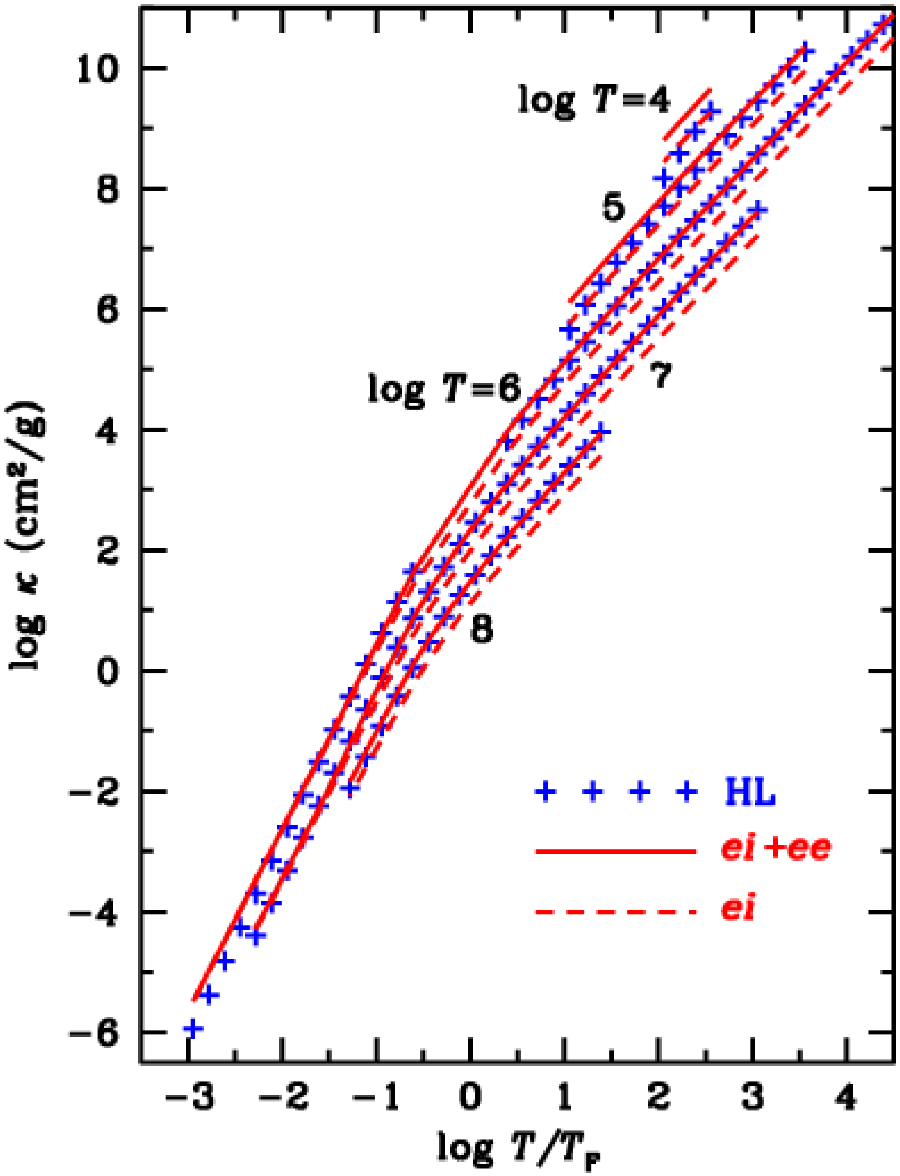
van Adelsberg, Lai, & Potekhin (2005) *ApJ* **628**, 902

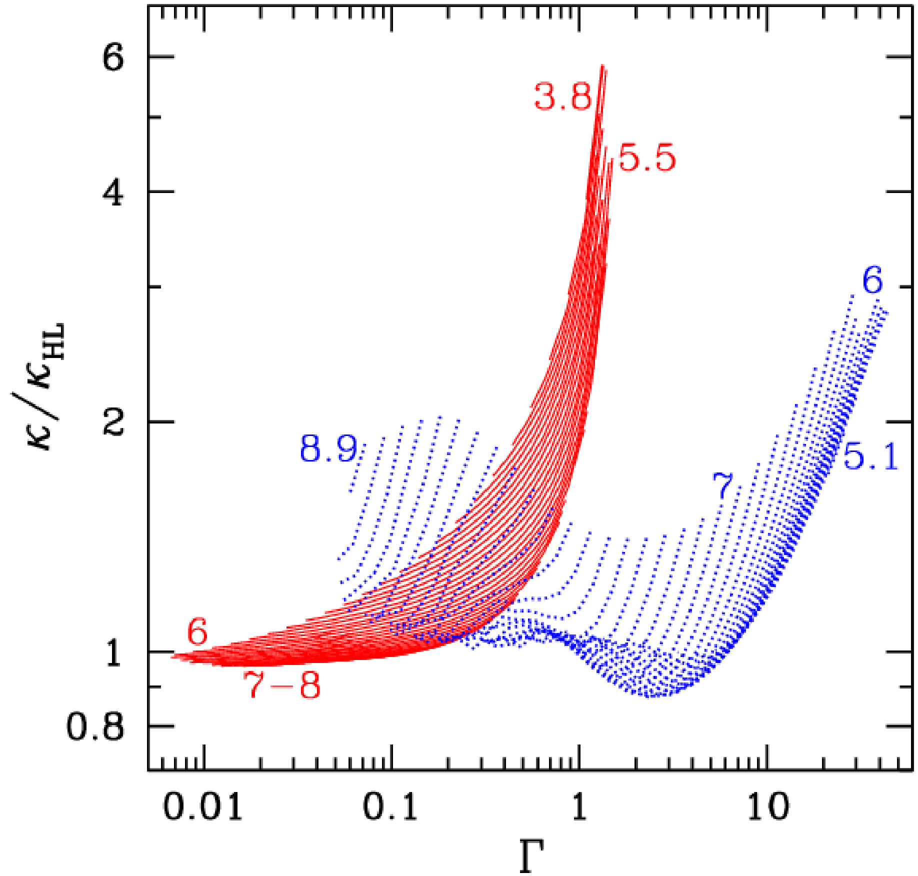


Monochromatic flux from the condensed surface in various cases
[Matthew van Adelsberg, for Potekhin *et al.* (2006) *J.Phys.A: Math. Gen.* **39**, 4453]

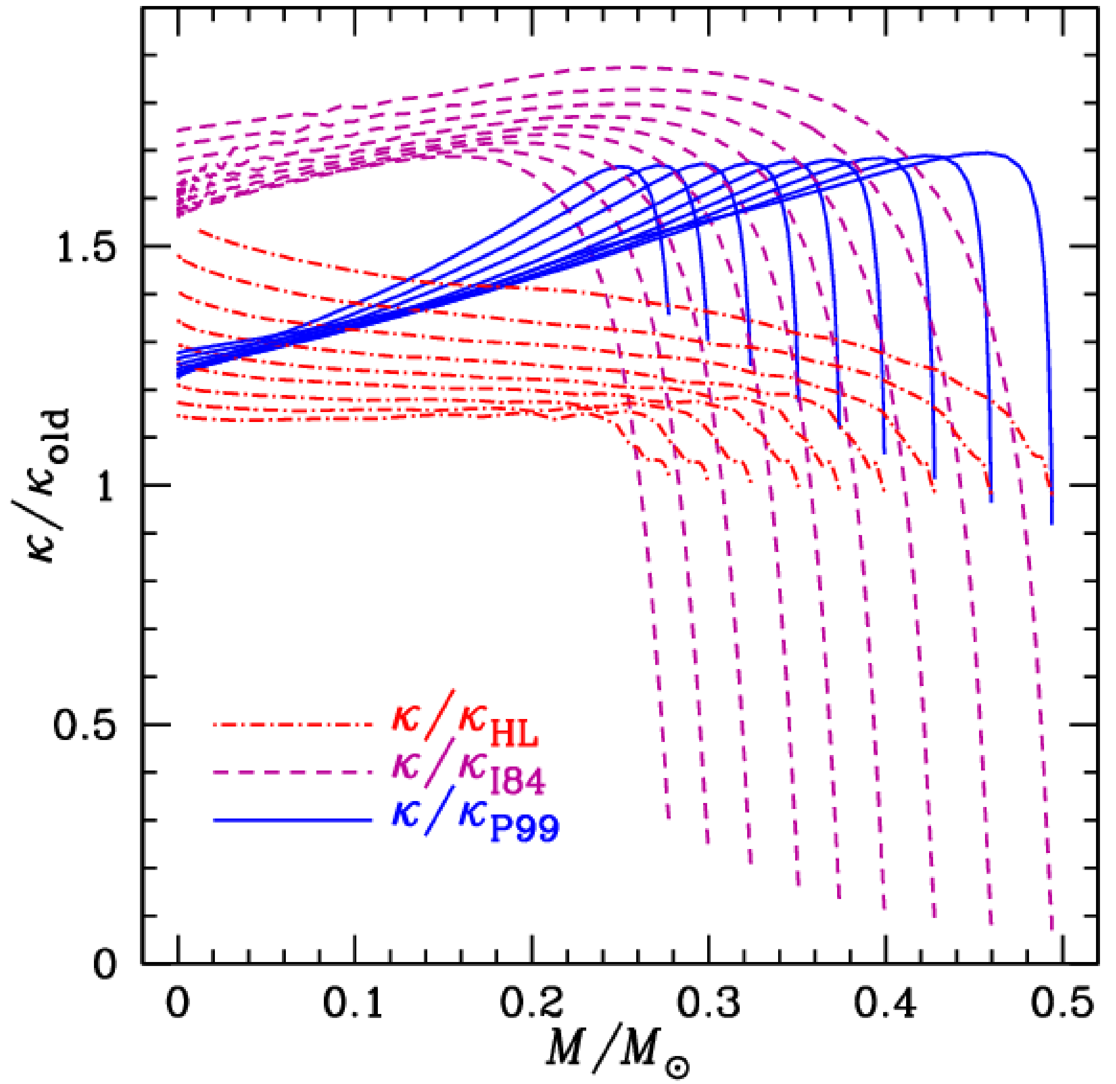
Stellar heat conductivities
Basic data sources

W.B.Hubbard & M.Lampe (1966 – 1969)	***ei+ee*** degenerate and non-degenerate electrons; non-relativistic, classical ions. Tables for H, He, C and a few mixtures.
N.Itoh *et al*. (1976 – 1994)	***ei***, strongly degenerate electrons (arbitrary relativity), strongly coupled ions. Inaccurate treatment near the liquid/solid phase boundary.
D.G.Yakovlev et al. (1980 – 2001)	***ei***: (i) **liquid**: classical ions (strongly and weakly coupled) with a good structure factor; non-Born correction; (ii) **solid**: quantum treatment, account of multi-phonon processes. Allowance for **strong magnetic fields**. ***ee***: strongly degenerate electrons; inaccurate treatment at relativistic densities.
P.S.Shternin & D.G.Yakovlev (2006) S.Cassisi et al. (2007) A. Chugunov & P. Haensel (2007)	***ee***: improved at relativistic densities. ***ee***: extension to arbitrary degeneracy. ***Ie, ii***: ion thermal conduction.





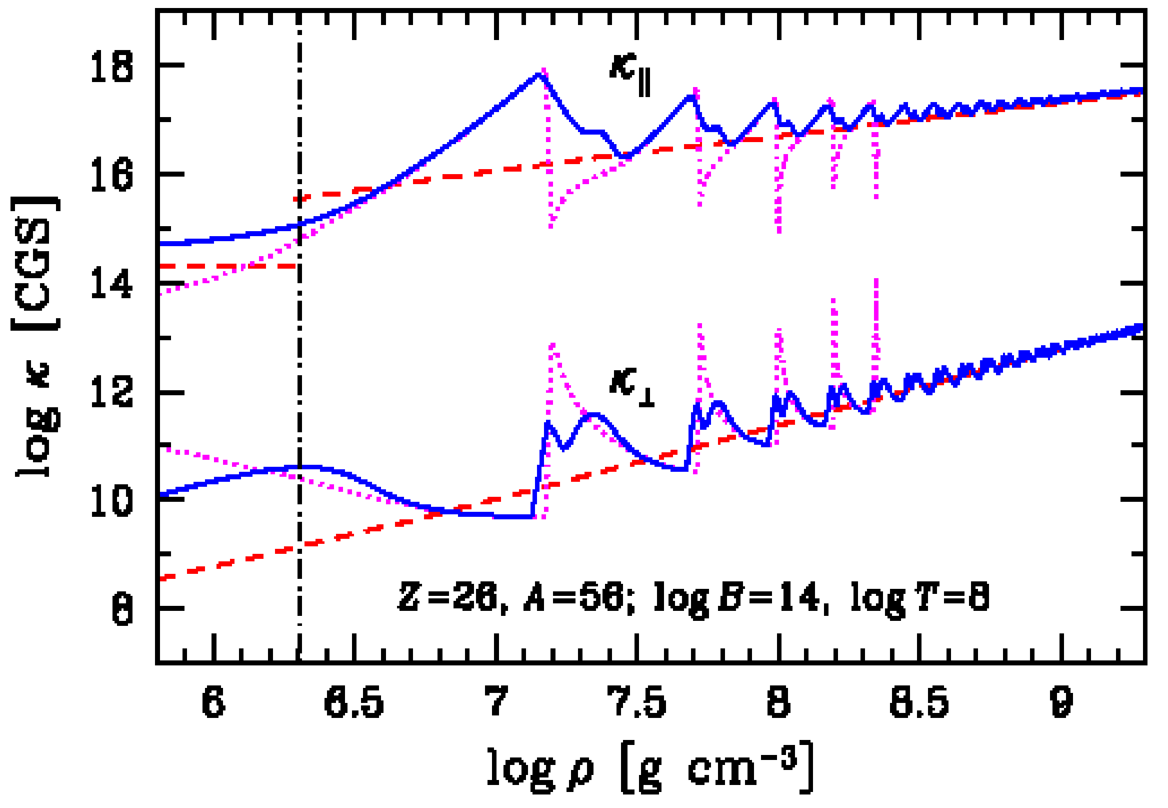
Conductive opacities of helium as functions of degeneracy (left) and Coulomb coupling parameter (right): comparison to Hubbard & Lampe tables [S.Cassisi, A.Potekhin, A.Pietrinferni, M.Catelan, M.Salaris, *ApJ* **661**, 1094 (2007)]



Improvement of conduction opacities in RGB stellar cores relative to some previous models.

Cassisi, Potekhin, Pietrinferni, Catelan, Salaris, *ApJ* **661**, 1094 (2007)

Thermal conductivities in a strongly magnetized envelope

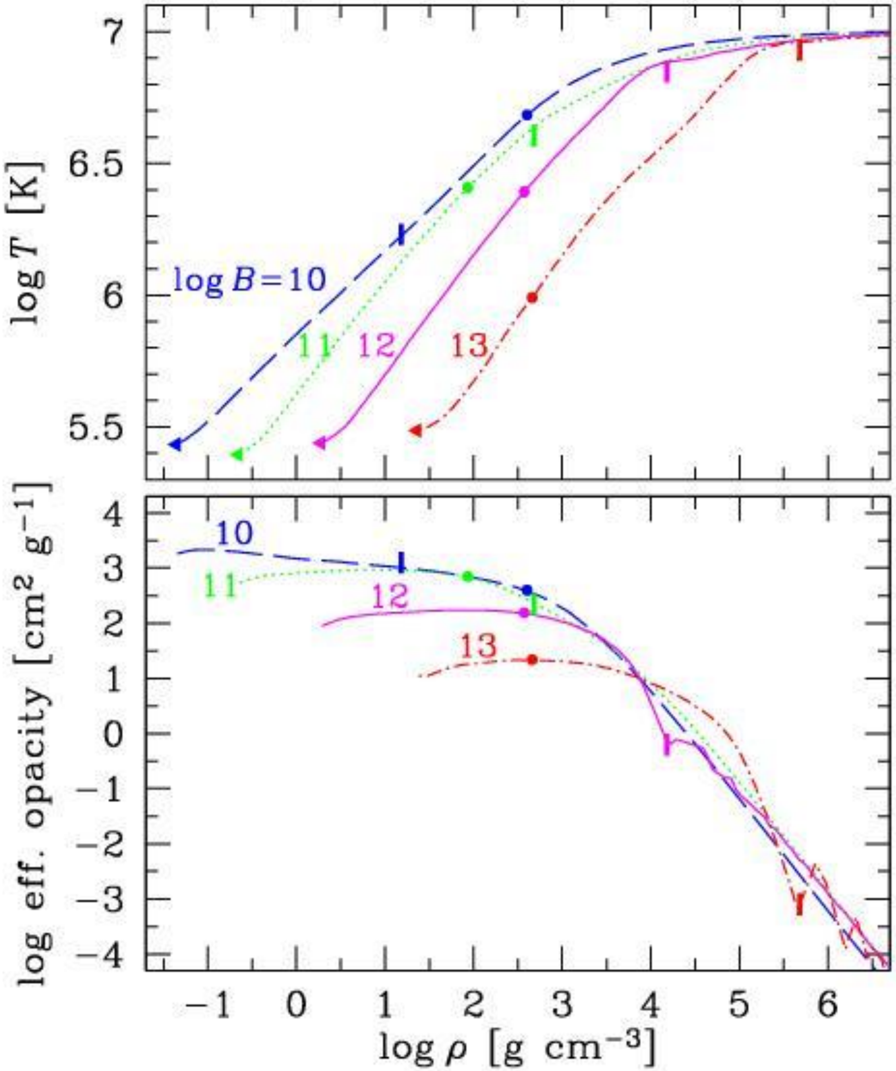


Solid – exact, dots – without T-integration, dashes – magnetically non-quantized

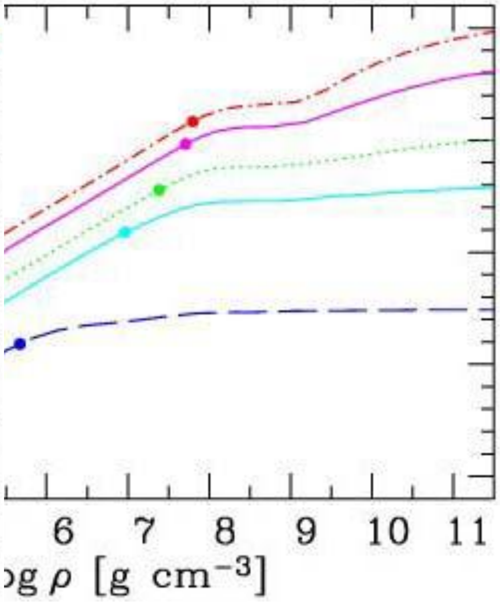
[Ventura & Potekhin (2001), in *The Neutron Star – Black Hole Connection*, ed. Kouveliotou *et al.* (Dordrecht: Kluwer) 393]

Heat flux: $\boldsymbol{F} = -\kappa_{\|}\nabla_{\|}T - \kappa_{\perp}\nabla_{\perp}T - \kappa_{\wedge}\boldsymbol{b}\times\nabla T, \quad \boldsymbol{b} = \frac{\boldsymbol{B}}{B}$

Thermal structure with a magnetic field

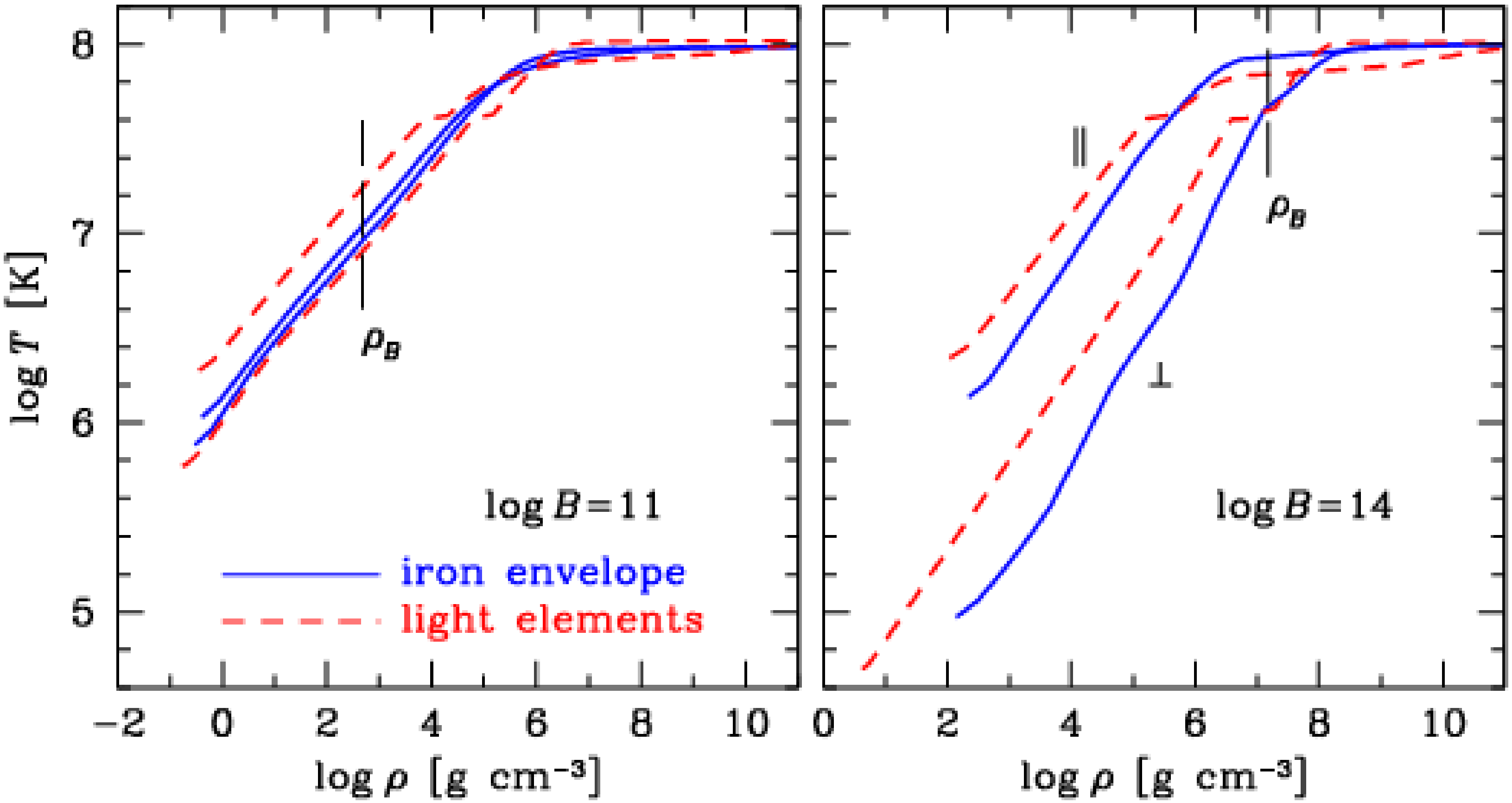


$T_{\mathrm{b}}=10^7$ K, different B

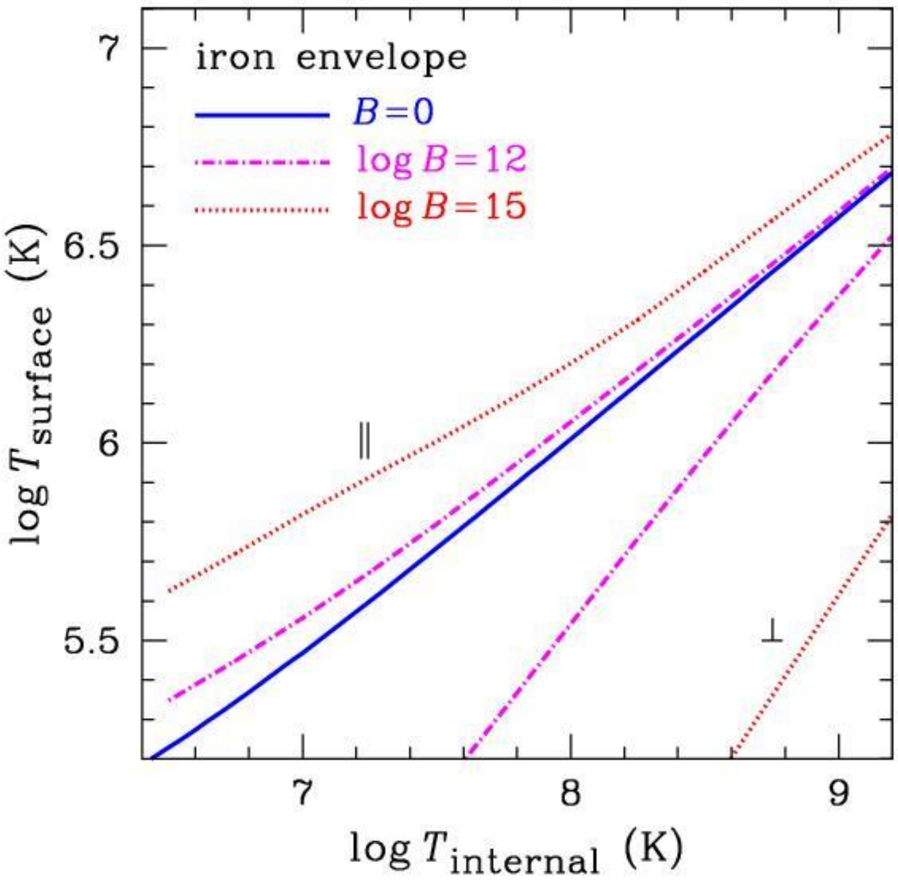


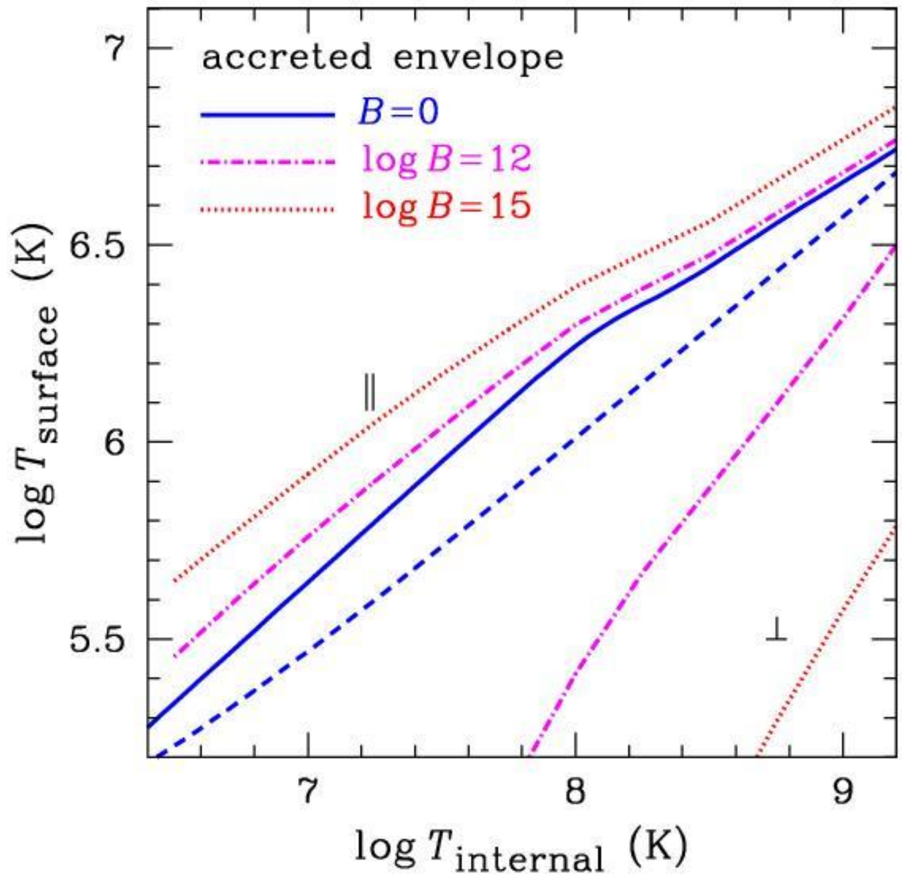
G, different T

Thermal structure with a magnetic field and different chemical compositions of the envelope



Temperature drops in magnetized envelopes of neutron stars

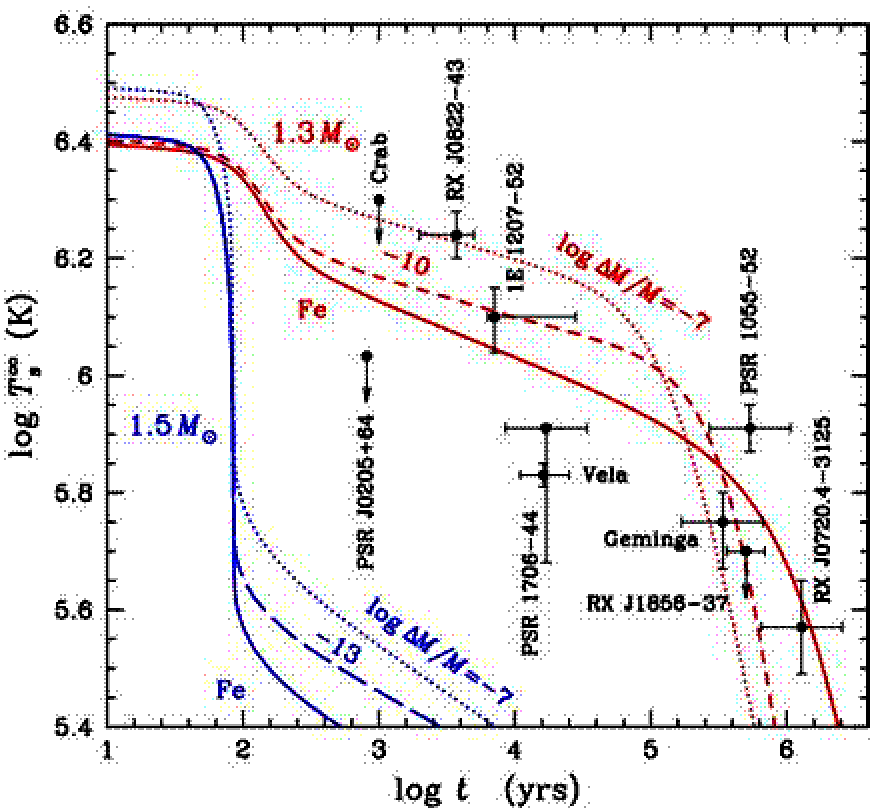


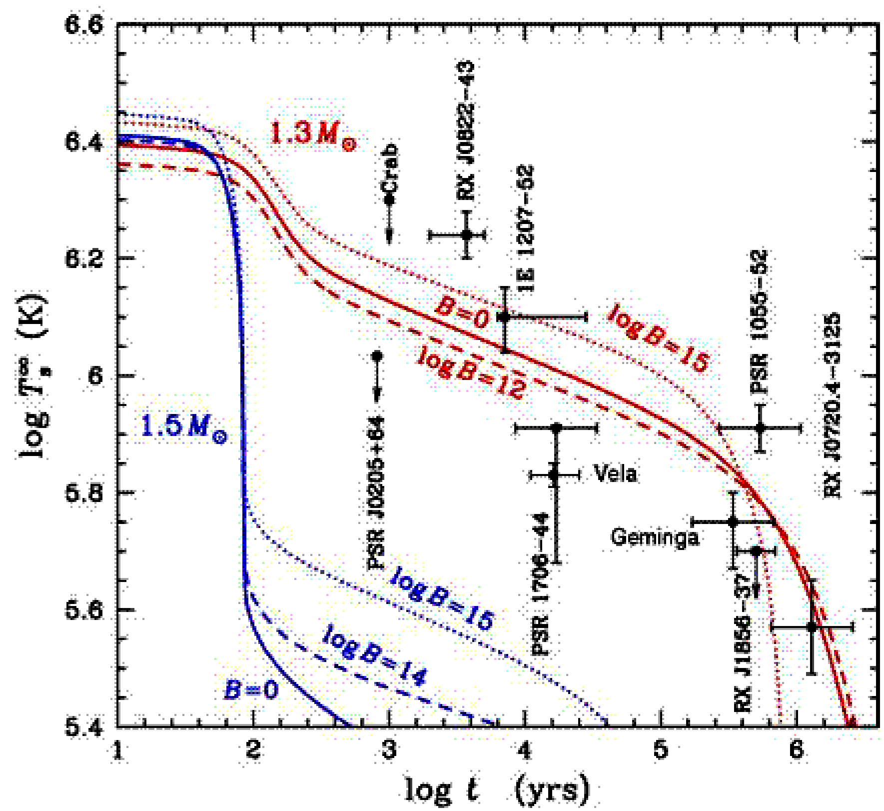


[based on Potekhin *et al.* (2003) *ApJ* **594**, 404]

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

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



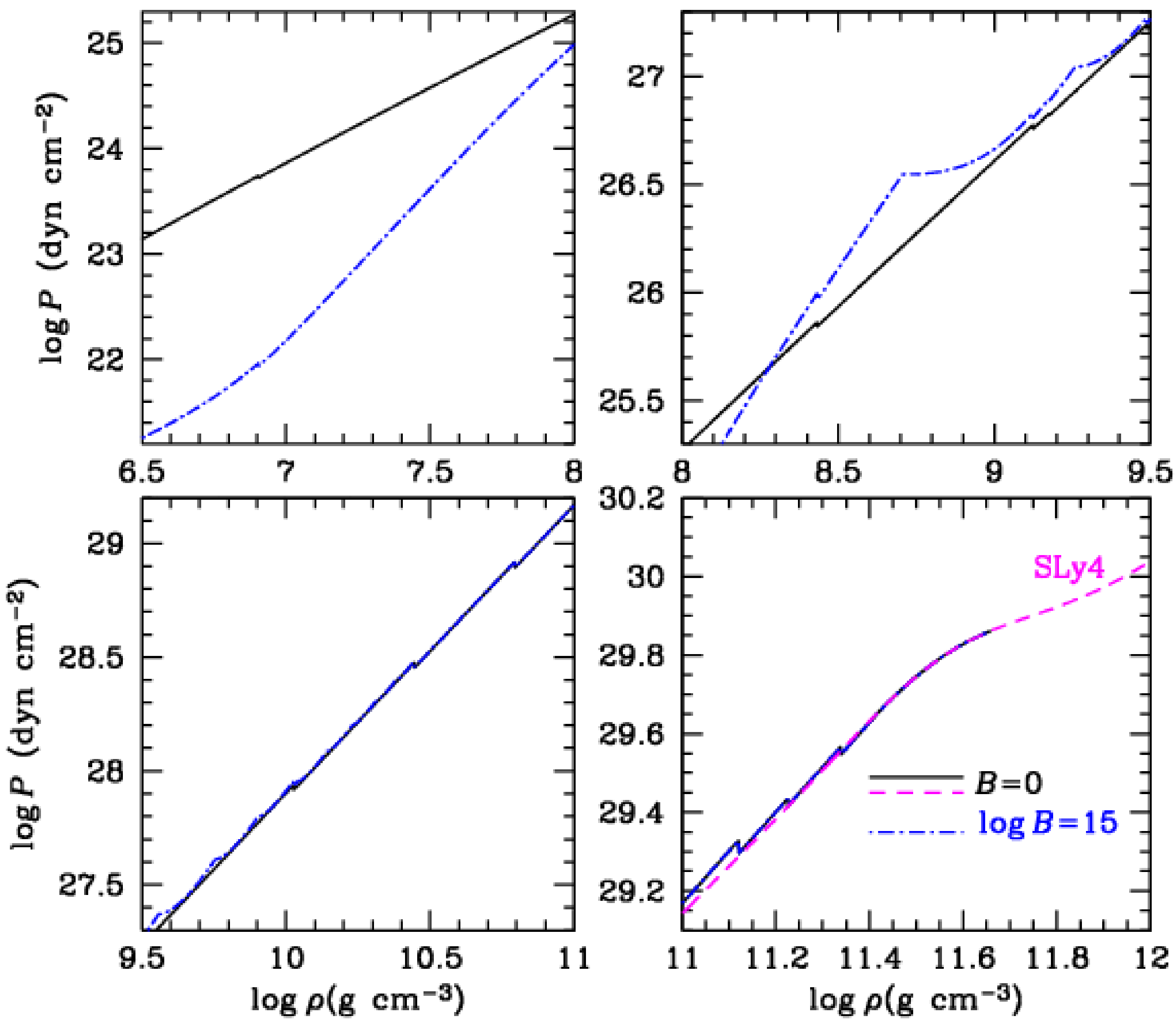


[Chabrier, Saumon, & Potekhin, *J.Phys.A: Math. Gen.* **39**, 4411 (2006);
used data from Yakovlev *et al*, *Nucl. Phys. A* **752**, 590c (2005)]

Challenges from the **superstrong** fields ($B > 10^{14}$ G)

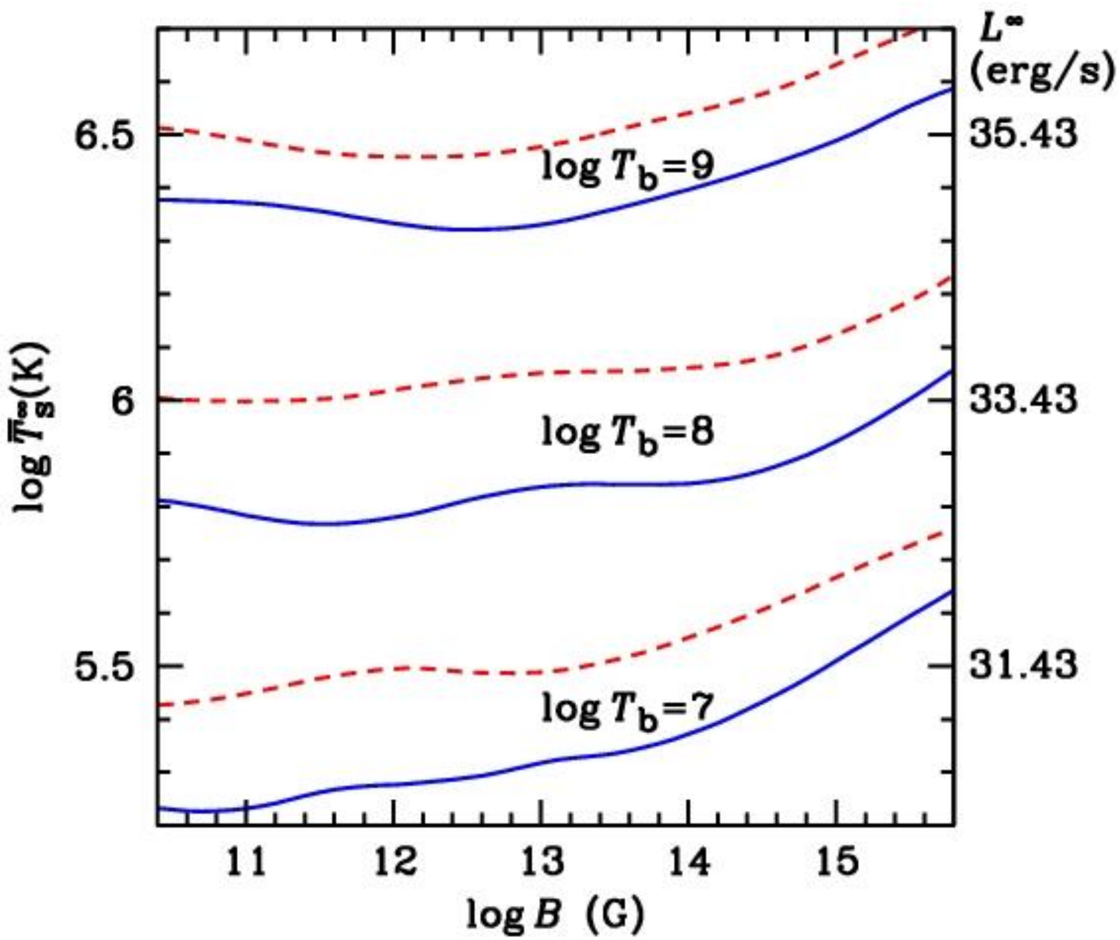
1. ***Mechanical structure: field affects EoS also in the inner crust***
2. ***Thermal structure: field affects luminosity***
3. *[Possibly]* ***non-isotropic heat transport in the inner crust***
4. ***Surface layers: molecules, chains, and magnetic condensation***
5. ***Radiative transfer: vacuum polarization and mode conversion***
6. ***Energy transport below the plasma frequency***
7. ***Non-LTE distribution of ions over Landau levels***

Superstrong field affects EOS



Dependence of pressure on density for ground-state matter with zero and superstrong magnetic fields

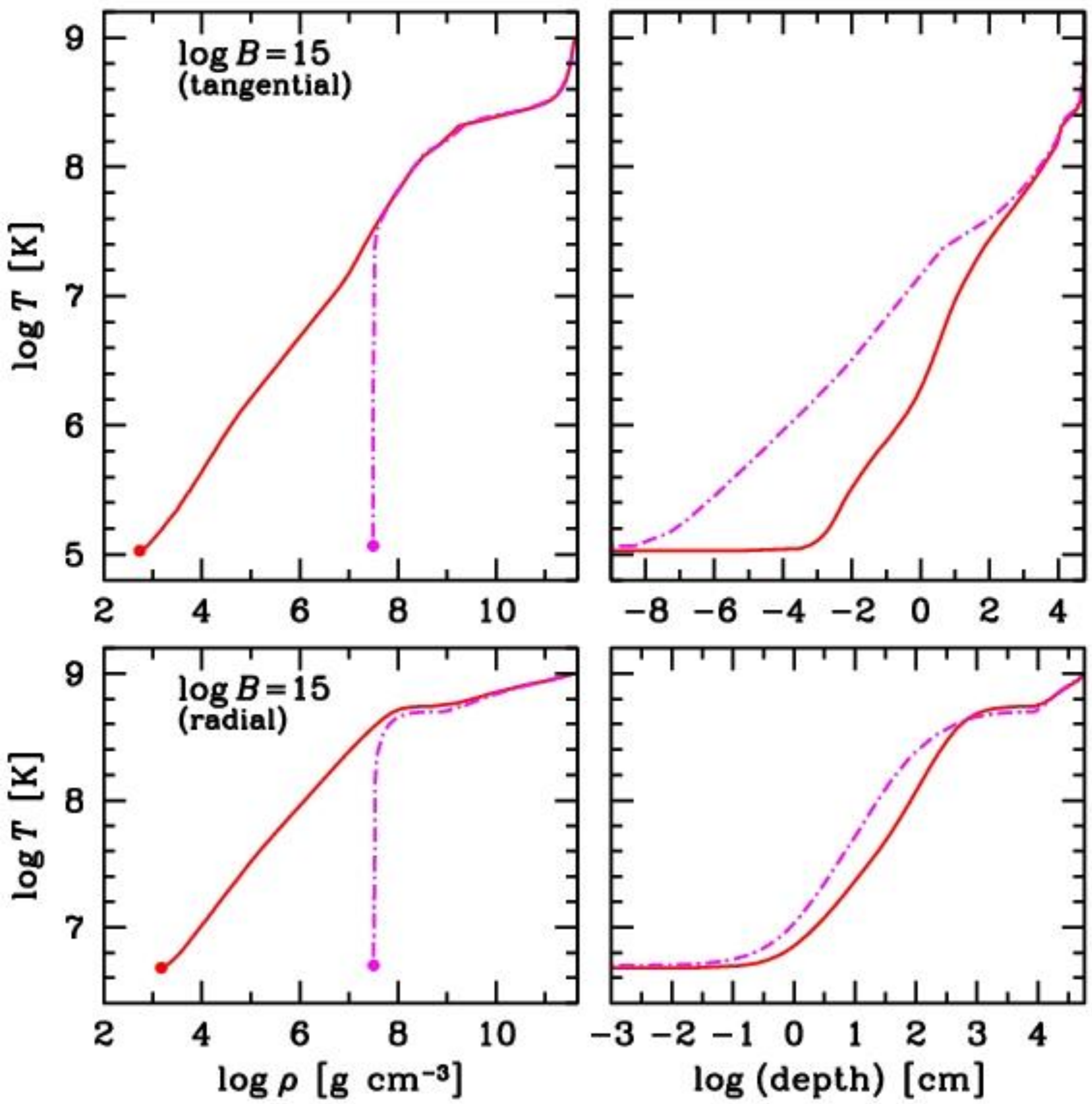
Superstrong field affects total luminosity



Dependence of the mean effective temperature on the magnetic field strength for the light-element (dashed lines) and iron (solid lines) envelopes.

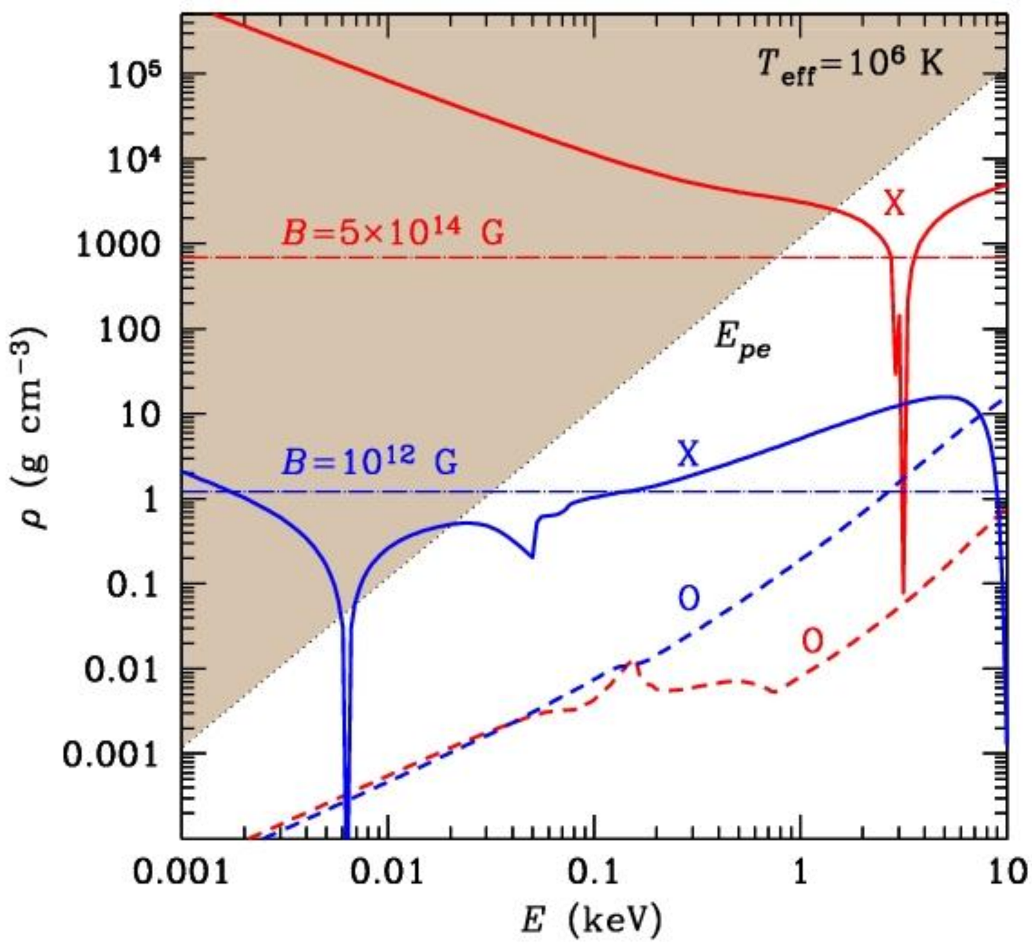
Thick or thin atmosphere?

Superstrong fields



Solid lines – extended atmosphere,
dot-dashed lines – condensed surface

Importance of energy transport below plasma frequency

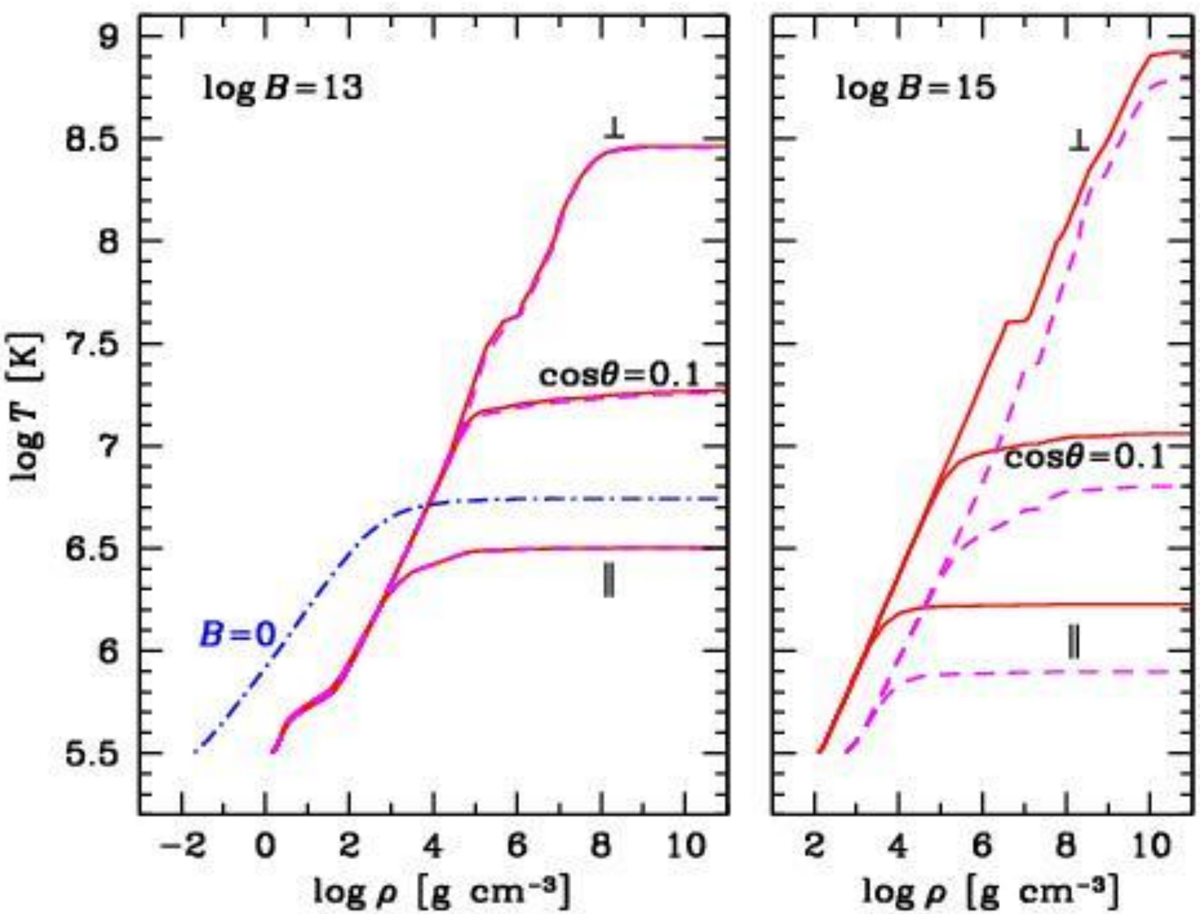


$$E_{pe} = \left(\frac{4\pi \hbar^2 e^2 n_e}{m_e} \right)^{1/2} \approx 28.7\,\rho^{1/2}\ \mathrm{eV}$$

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).

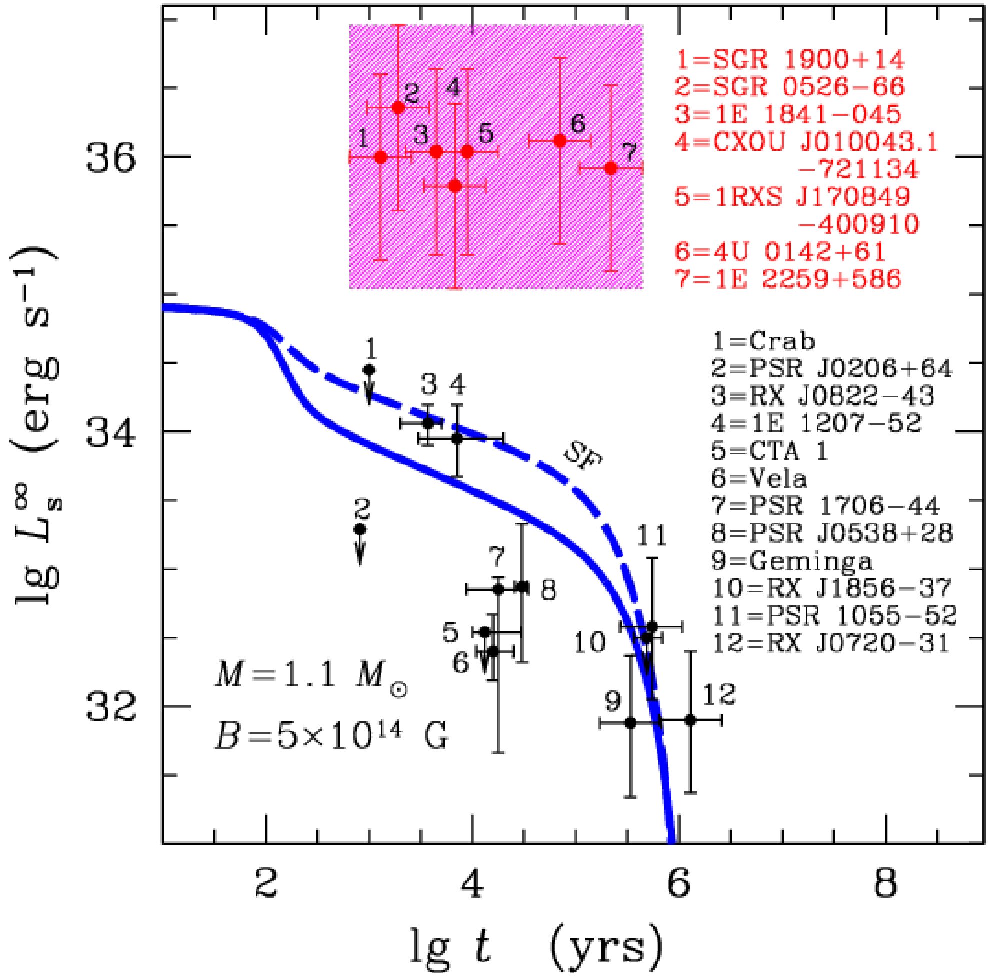
Dot-dashed lines correspond to the radiative surface, the shadowed region corresponds to $E < E_{pl}$.

Importance of energy transport below plasma frequency

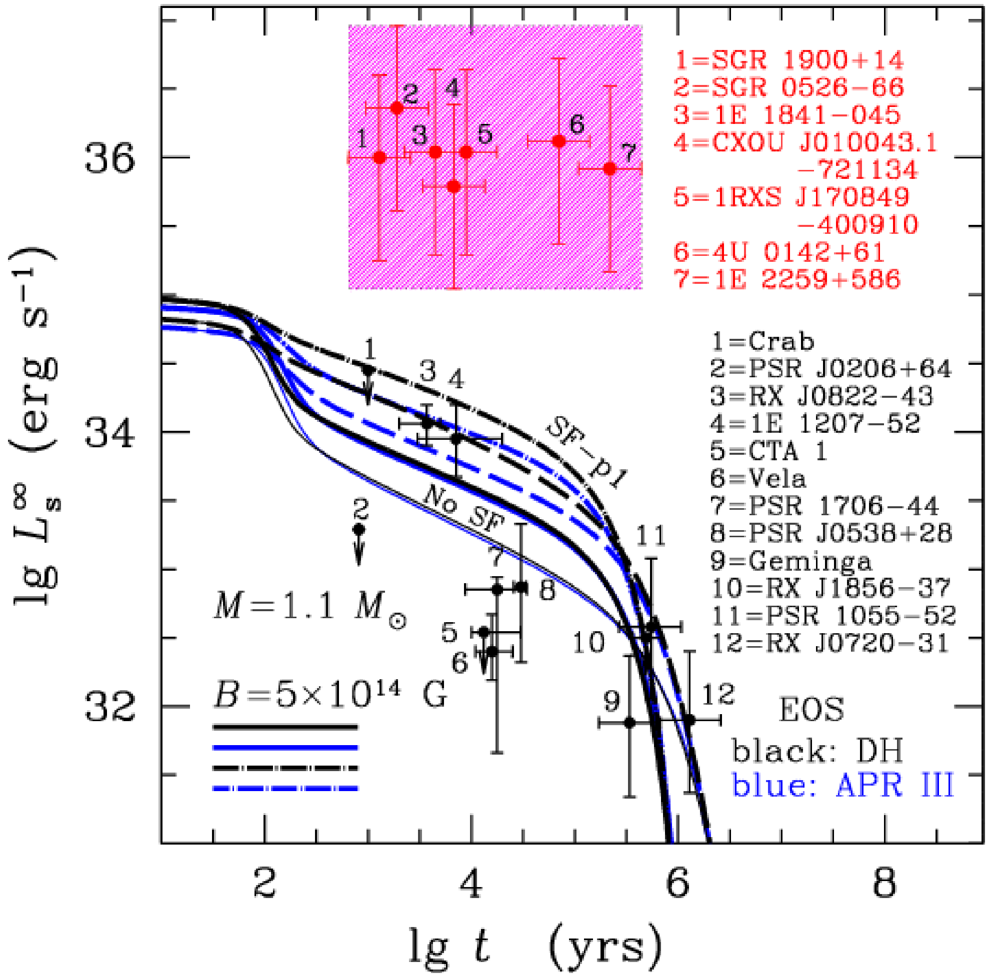


Temperature profiles in the accreted envelope of a neutron star with "ordinary" (left panel) and **superstrong** (right) magnetic field, for the local effective temperature $10^{5.5}$ K, with (solid lines) and without (dashed lines) plasma-frequency cut-off [Potekhin *et al.* (2003) *ApJ* **594**, 404]

Heating and cooling of magnetars



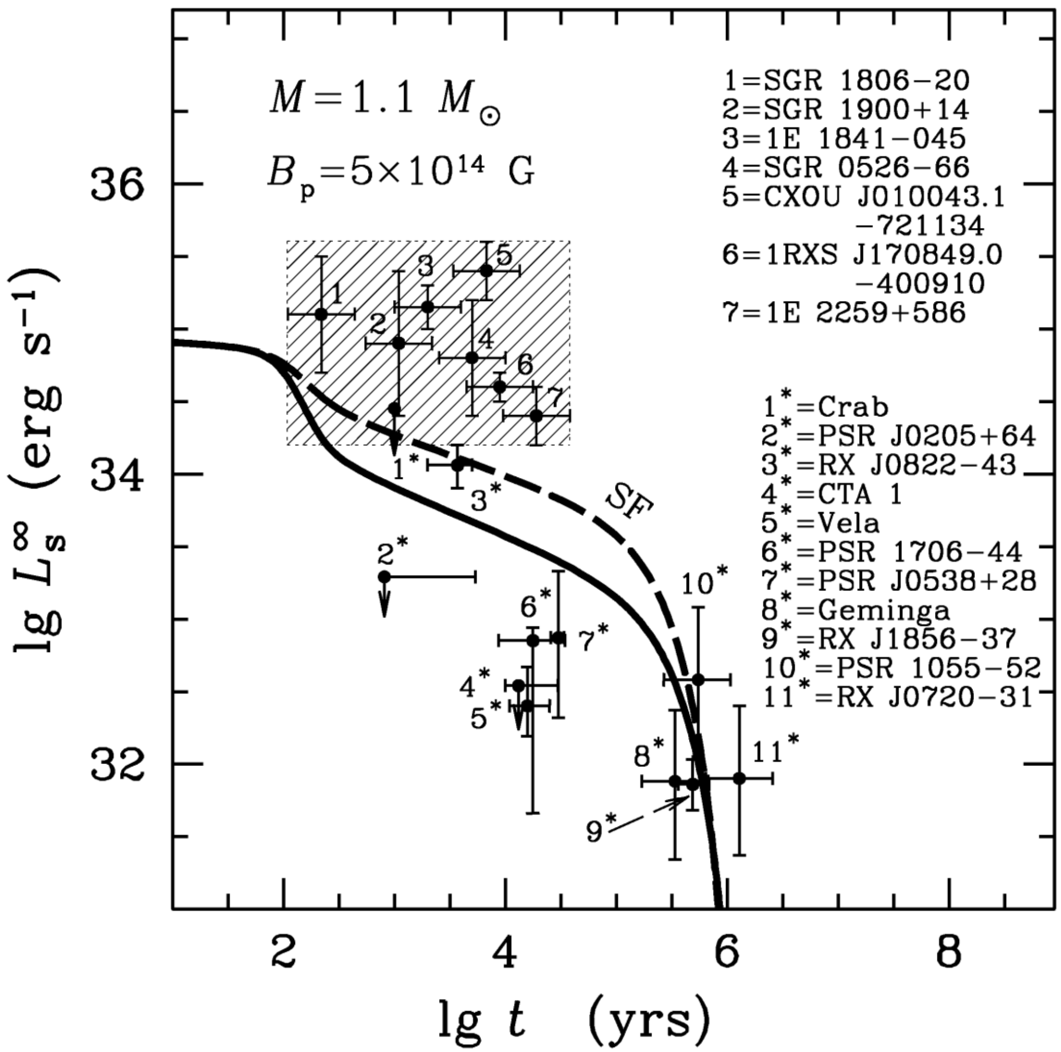
Heating and cooling of magnetars



Application

Heating and cooling of magnetars with accreted envelopes

Kaminker, Potekhin, Yakovlev, Chabrier, *MNRAS* **395**, 2257 (2009)



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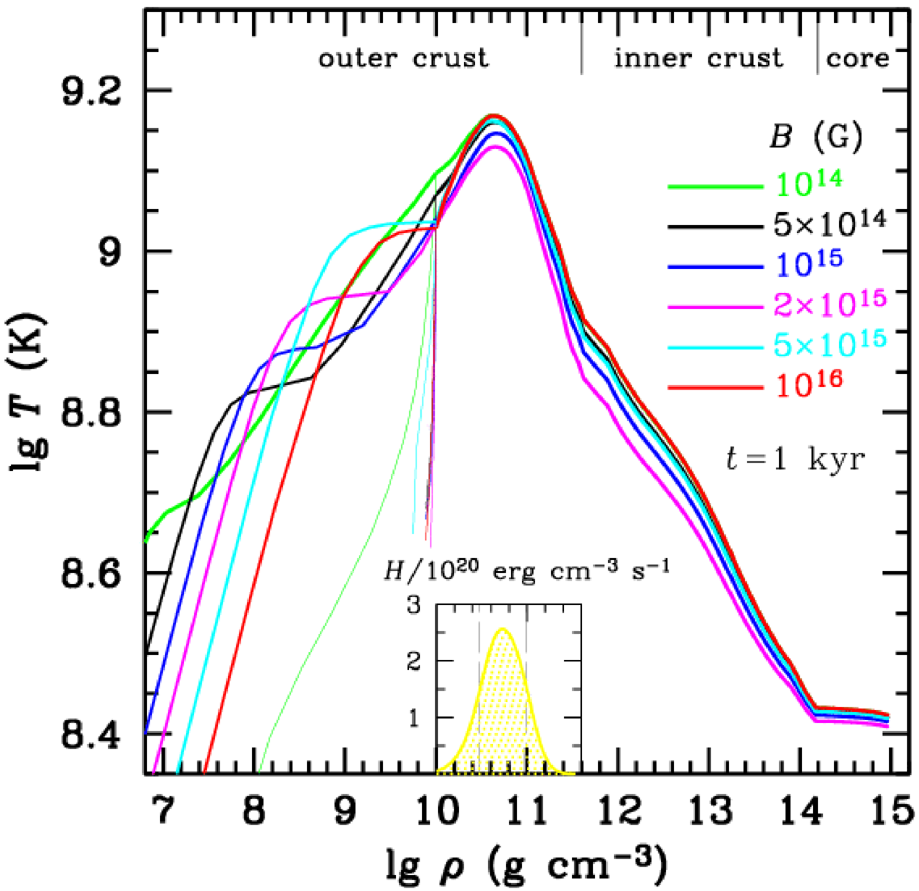

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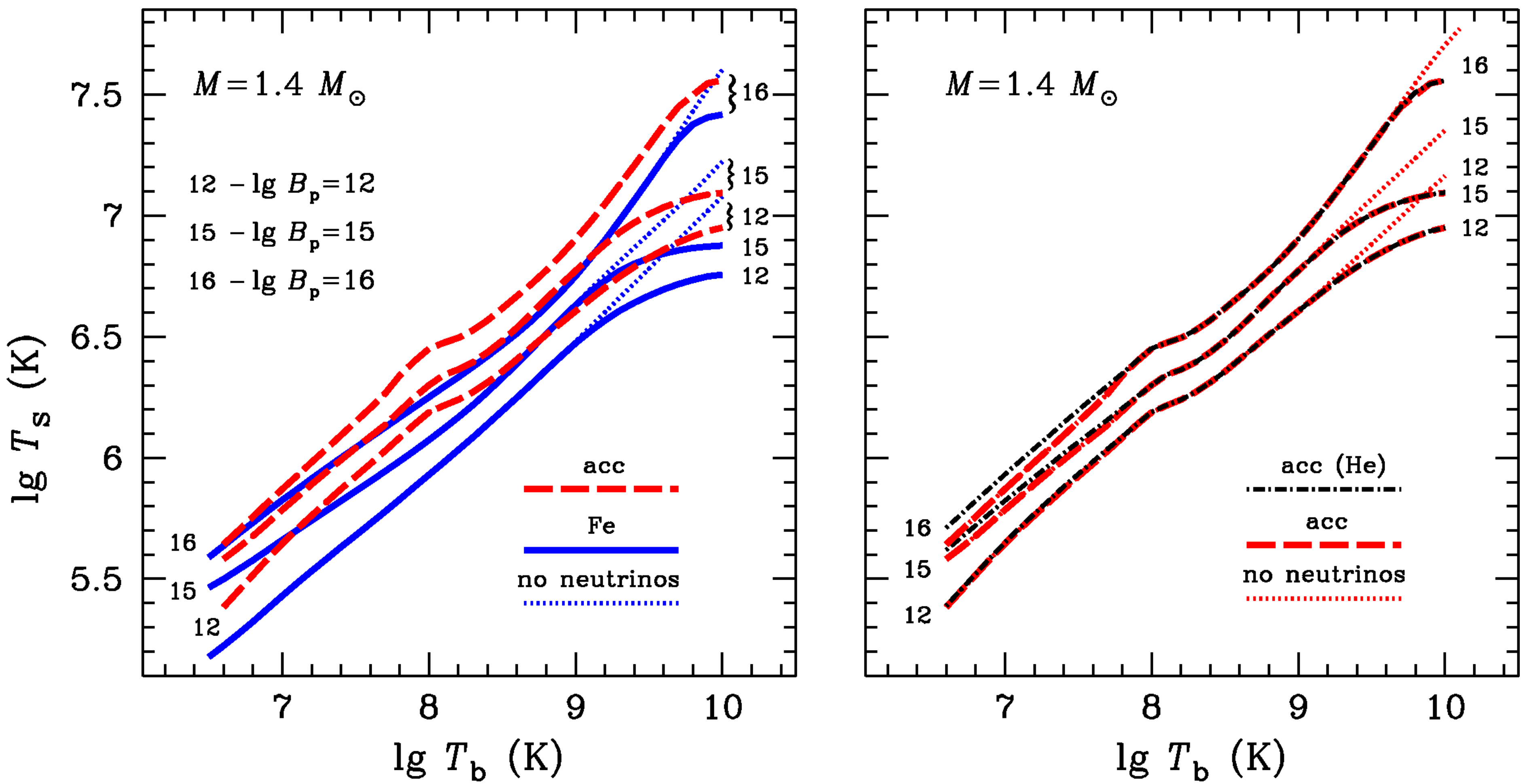
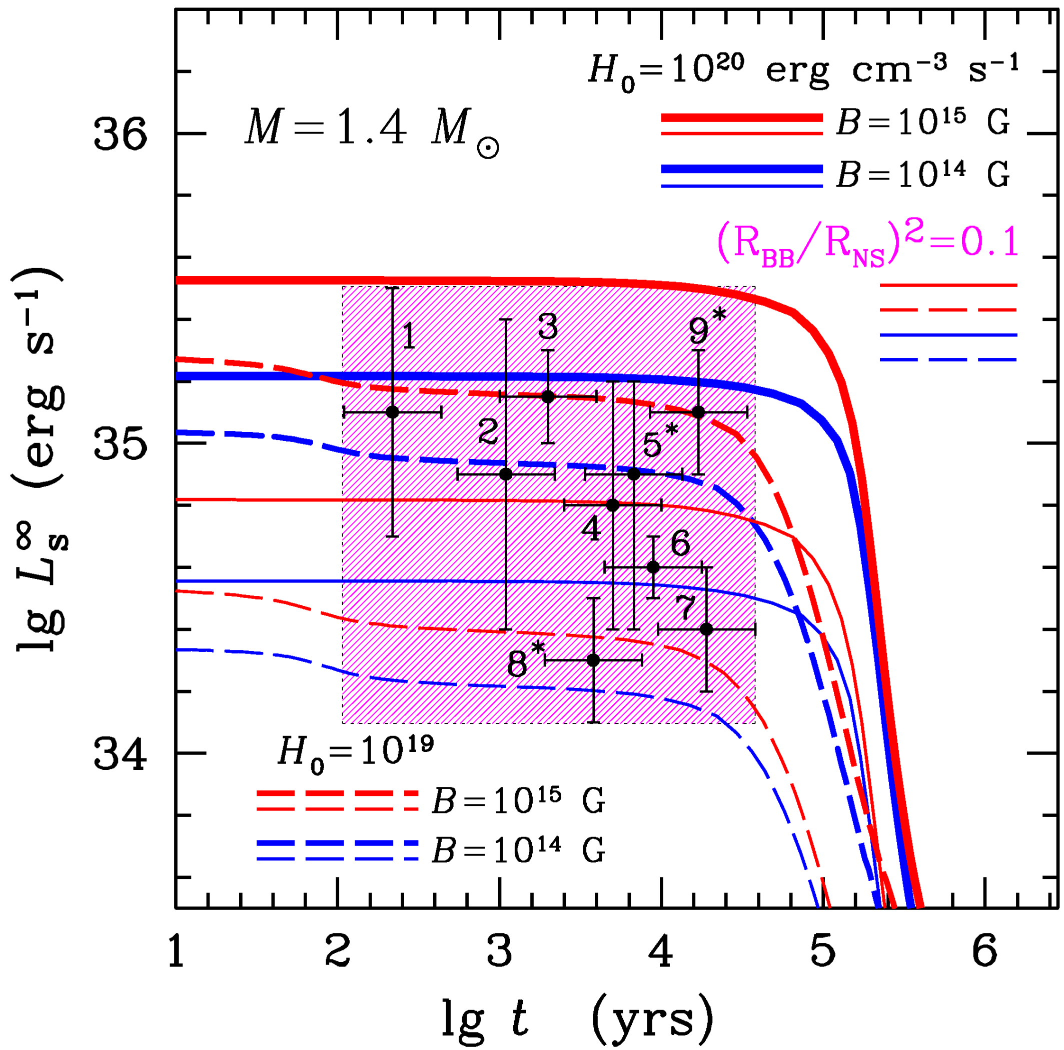


Heating and cooling of magnetars with accreted envelopes

Kaminker, Potekhin, Yakovlev, Chabrier, *MNRAS* **395**, 2257 (2009)



Conclusions

- ***Equation of state*** in neutron-star envelopes is basically known, but there remain uncertain ingredients
- ***Opacities*** with strong magnetic fields are known for hydrogen at relatively high temperatures. [*Note*: For middle-*Z* elements, there are atmosphere models by Kaya Mori and Wynn Ho, with a restricted account of the atomic motion.]
- Practical models of the ***conductivities*** , applicable to neutron stars, are developed in recent years.
- A ***superstrong*** magnetic field
  - on the average, makes the envelope more heat-transparent,
  - accelerates cooling at late epochs,
  - leads to theoretical uncertainties, which require further study.

THANK YOU FOR YOUR ATTENTION!