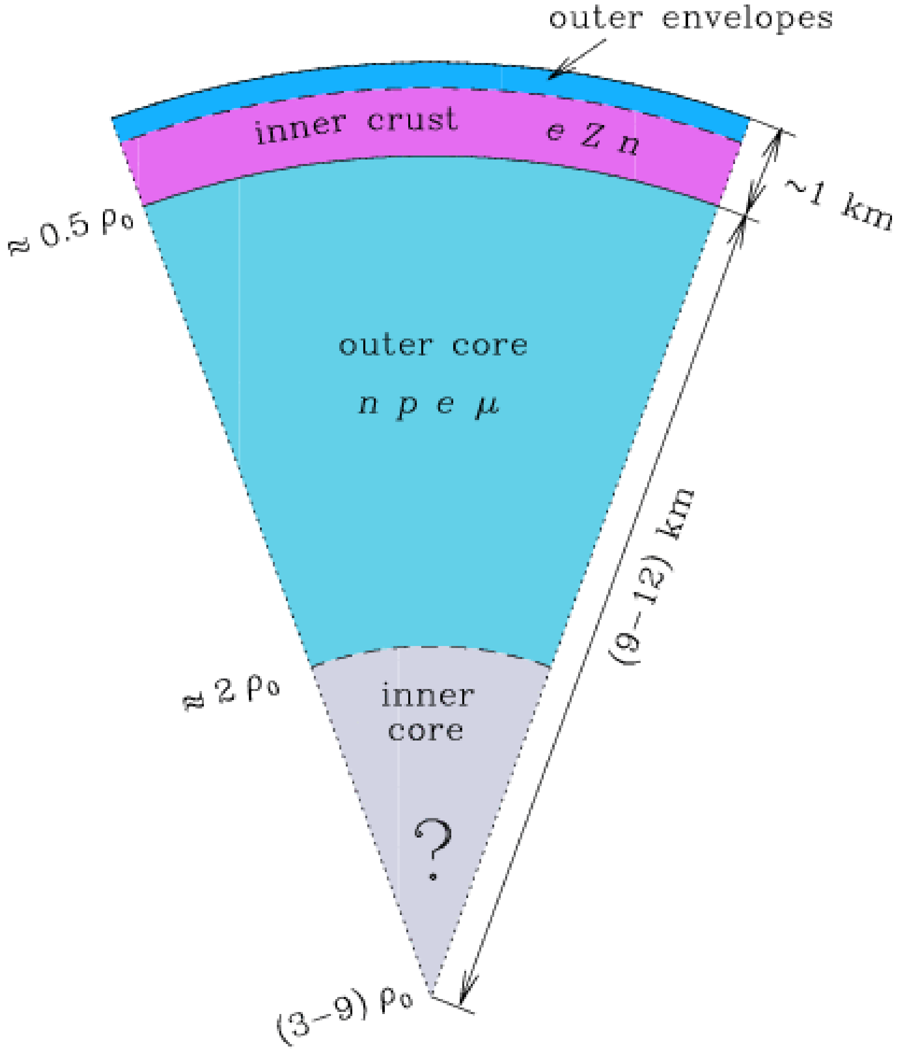
Envelopes and thermal radiation of neutron stars with strong magnetic fields

Alexander Y. Potekhin[1]
in collaboration with
D.G.Yakovlev,[1] A.D.Kaminker,[1] Yu.A.Shibanov,[1] ...
and
Dong Lai,[2] Gilles Chabrier,[3] Pawel Haensel,[4] *and their groups*

[1] *Ioffe Physico-Technical Institute, St.Petersburg, Russia*
[2] *Cornell University, Ithaca, New York, USA*
[3] *Ecole Normale Supérieure de Lyon, France*
[4] *N.Copernicus Astronomical Center, Warsaw, Poland*

- Importance of neutron-star envelopes
- Conductivities and thermal structure of the crust
- Atmosphere and spectrum of thermal radiation
- The effects of superstrong magnetic fields

Neutron-star structure

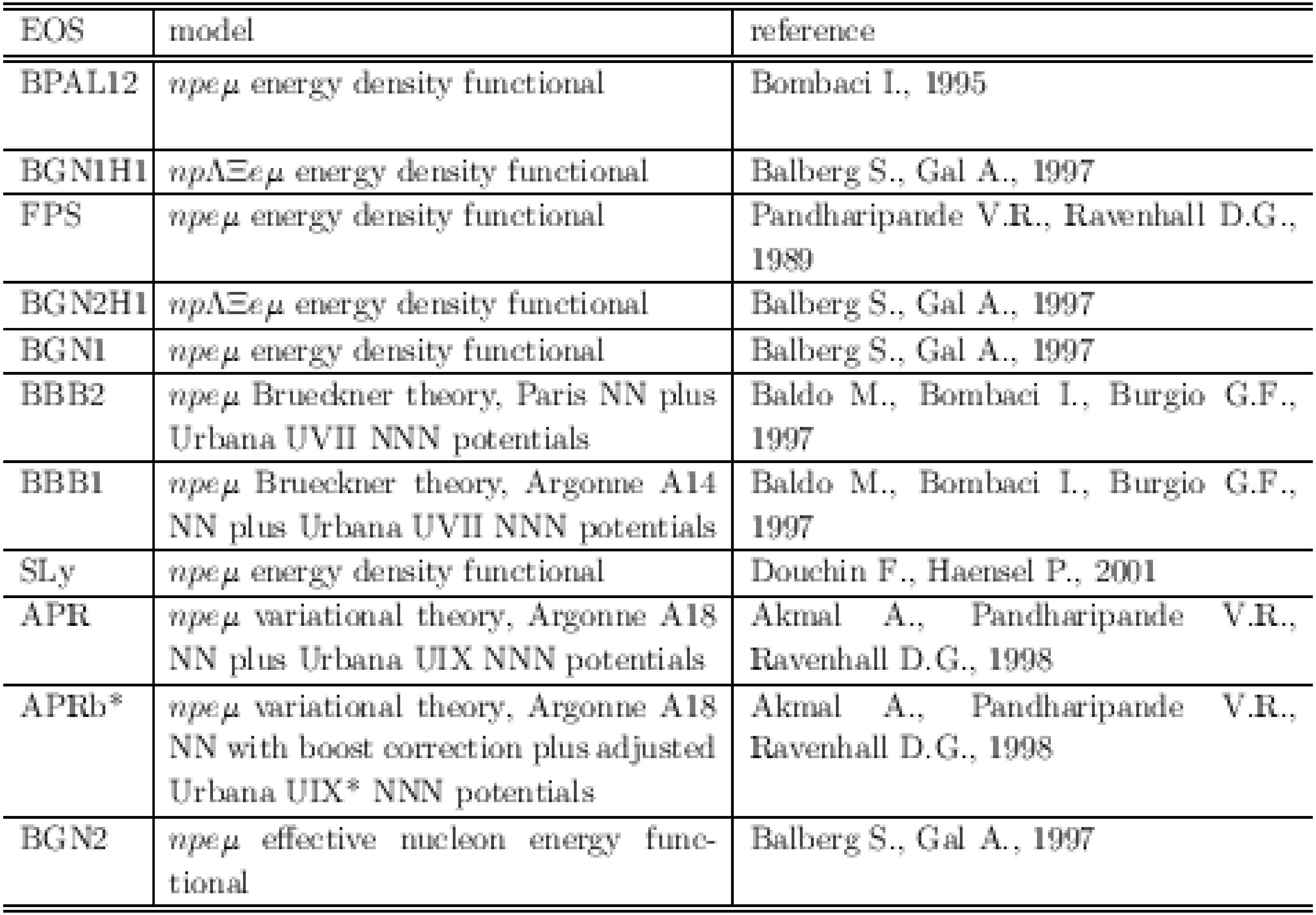


Hypotheses about the inner core

1. ***Hyperonization*** – appearance of hyperons, first of all *Lambda* and *Sigma*$^-$.
2. ***Pion condensation*** – Bose-condensation of pion-like collective excitations.
3. ***Kaon condensation*** (*K*-meson-like excitations with strangeness)
4. ***Phase transition*** to so-called ***quark matter*** composed of light deconfined *u*, *d*, *s* quarks and small admixture of electrons.

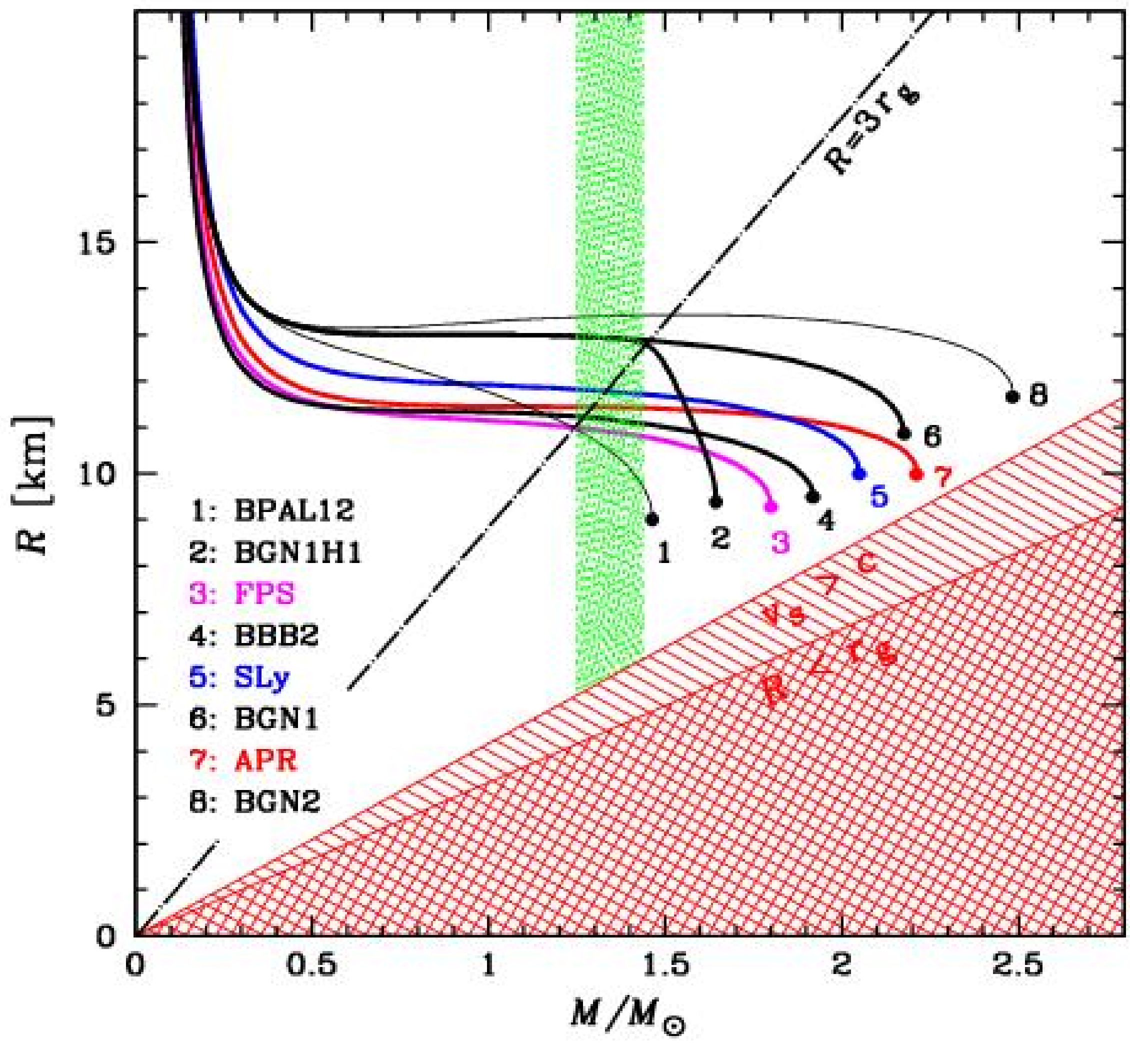
- ✓ Hypotheses 2 – 4 are known as *exotic models of dense matter*.
- ✓ *Composition* of the inner core affects *EOS* and *neutrino cooling rate.*
- ✓ *Superfluidity* in the core affects *cooling rate* and *mechanical properties*.

Some modern models of the EOS of superdense matter



EOS	model	reference
BPAL12	$npe\mu$ energy density functional	Bombaci I., 1995
BGN1H1	$np\Lambda\Xi e\mu$ energy density functional	Balberg S., Gal A., 1997
FPS	$npe\mu$ energy density functional	Pandharipande V.R., Ravenhall D.G., 1989
BGN2H1	$np\Lambda\Xi e\mu$ energy density functional	Balberg S., Gal A., 1997
BGN1	$npe\mu$ energy density functional	Balberg S., Gal A., 1997
BBB2	$npe\mu$ Brueckner theory, Paris NN plus Urbana UVII NNN potentials	Baldo M., Bombaci I., Burgio G.F., 1997
BBB1	$npe\mu$ Brueckner theory, Argonne A14 NN plus Urbana UVII NNN potentials	Baldo M., Bombaci I., Burgio G.F., 1997
SLy	$npe\mu$ energy density functional	Douchin F., Haensel P., 2001
APR	$npe\mu$ variational theory, Argonne A18 NN plus Urbana UIX NNN potentials	Akmal A., Pandharipande V.R., Ravenhall D.G., 1998
APRb*	$npe\mu$ variational theory, Argonne A18 NN with boost correction plus adjusted Urbana UIX* NNN potentials	Akmal A., Pandharipande V.R., Ravenhall D.G., 1998
BGN2	$npe\mu$ effective nucleon energy functional	Balberg S., Gal A., 1997

Neutron star models

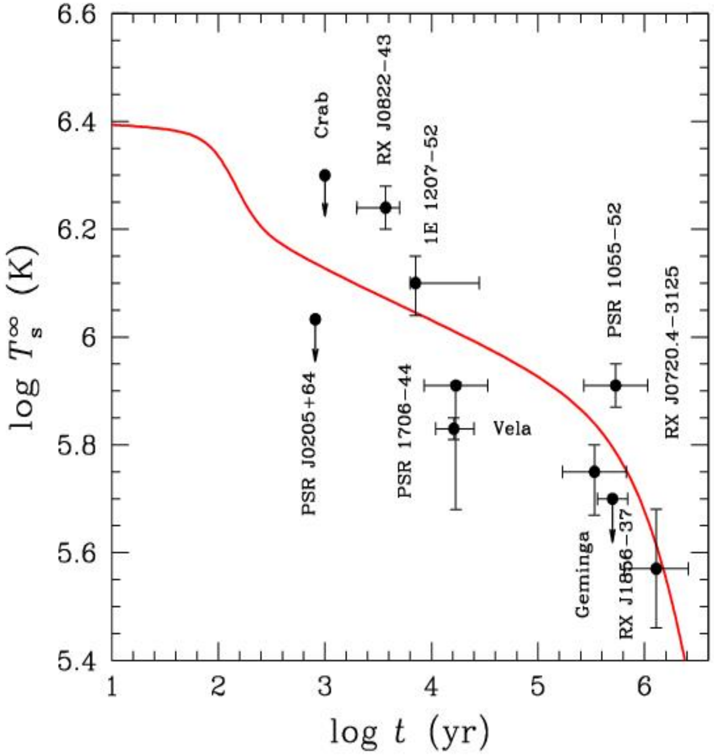


Stellar mass–radius relation for different EOSs

[from **Haensel, Potekhin, & Yakovlev,** ***Neutron Stars. 1. Equation of State and Structure***
(Springer-Kluwer, to be published)]

Thermal evolution

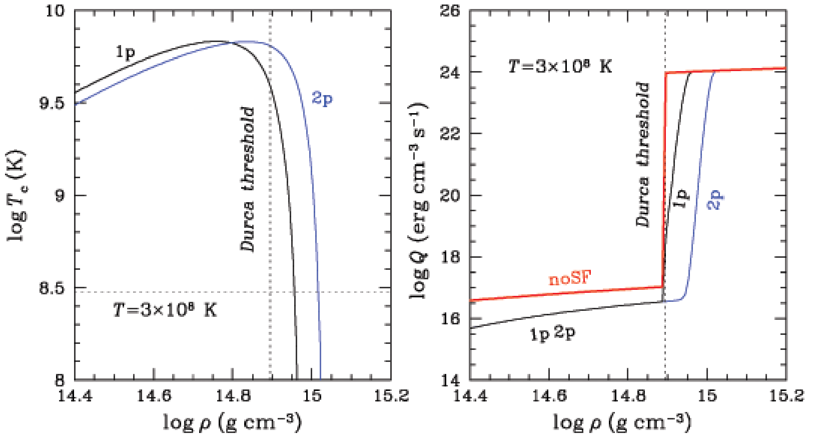
“Basic cooling curve” of a neutron star (no superfluidity, no exotica)

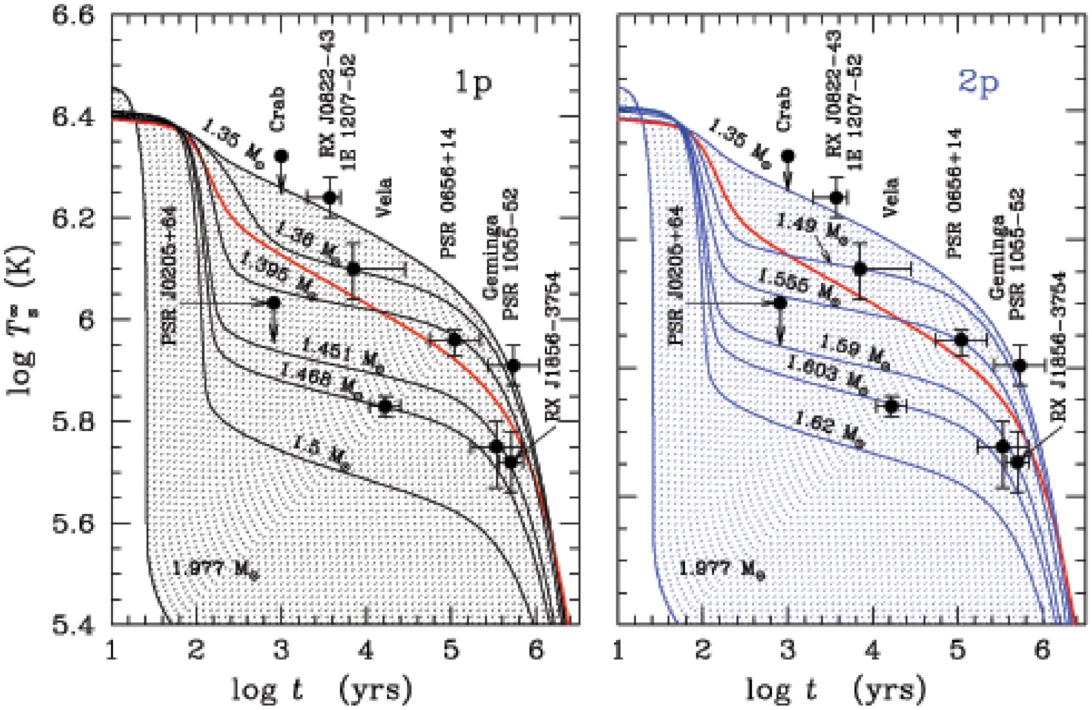


Neutron star cooling

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

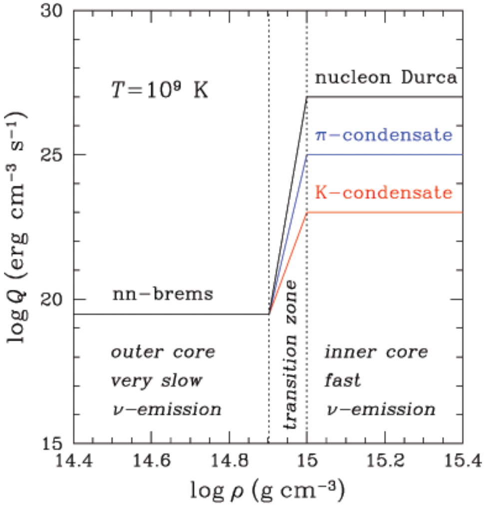
Cooling of neutron stars with proton superfluidity in the cores

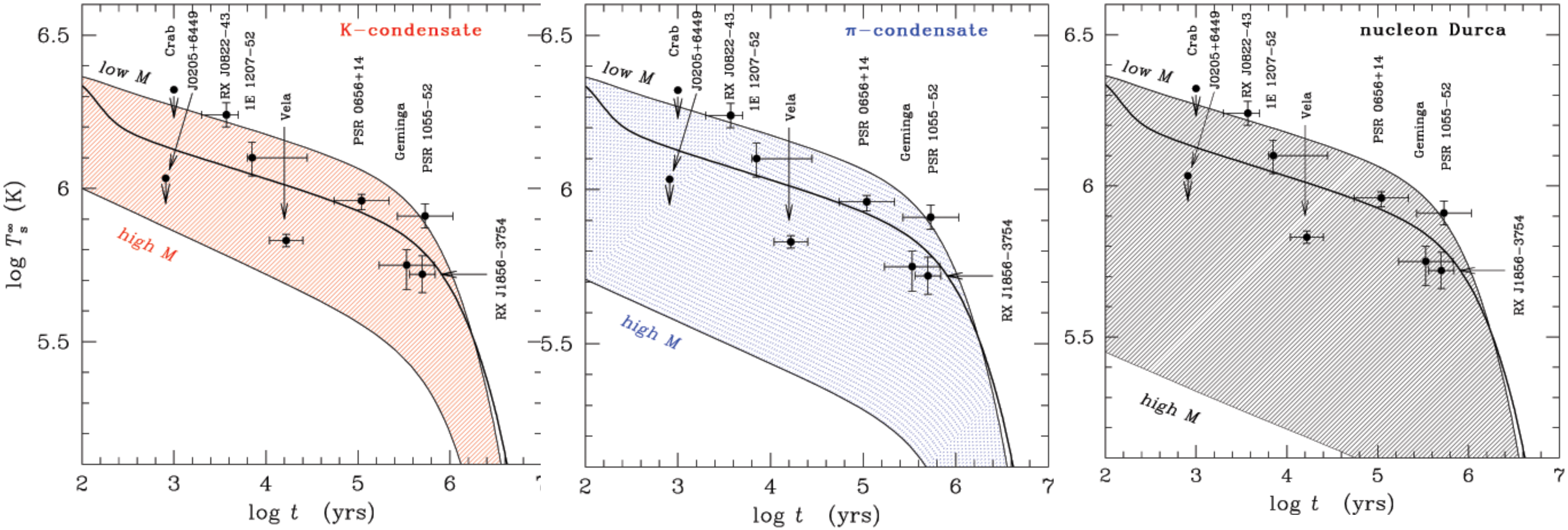




Cooling of neutron stars with nucleon and exotic cores

[based on Yakovlev *et al.* (2005)
Nucl. Phys. A **752**, 590c]





What is required for interpretation of observed thermal radiation from neutron stars

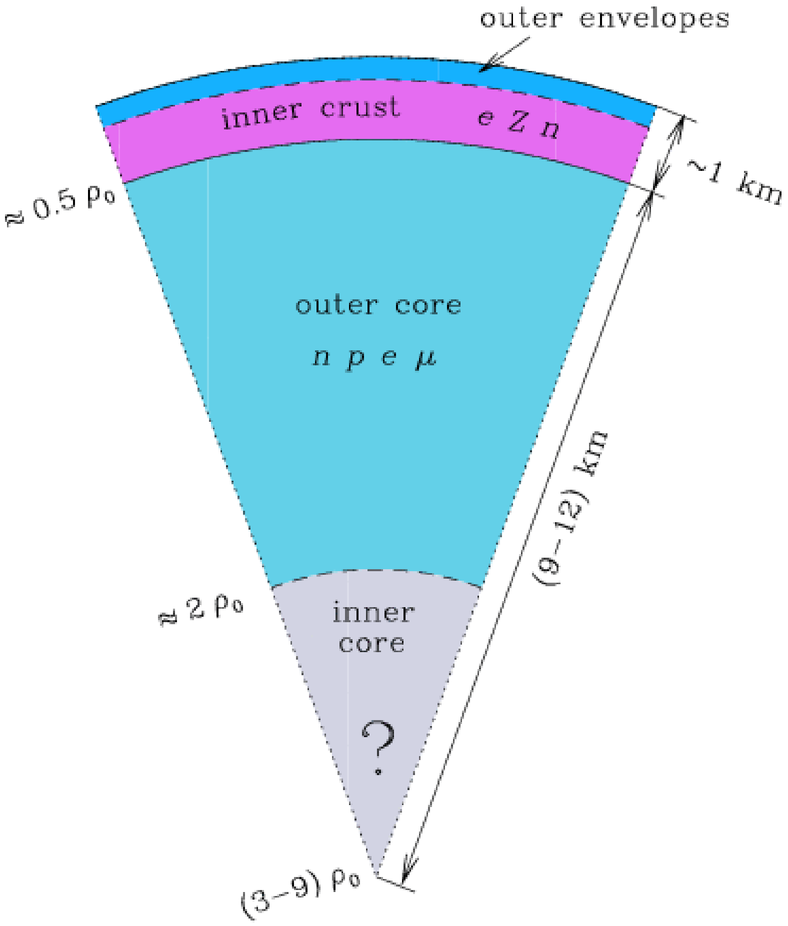
- Relation between ***internal*** (core) temperature and ***effective temperature*** (surface luminosity)
  - requires studying **thermal conduction** and **temperature profiles** in heat-blanketing envelopes
- Knowledge of the shape and features of the ***radiation spectrum*** at given effective temperature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

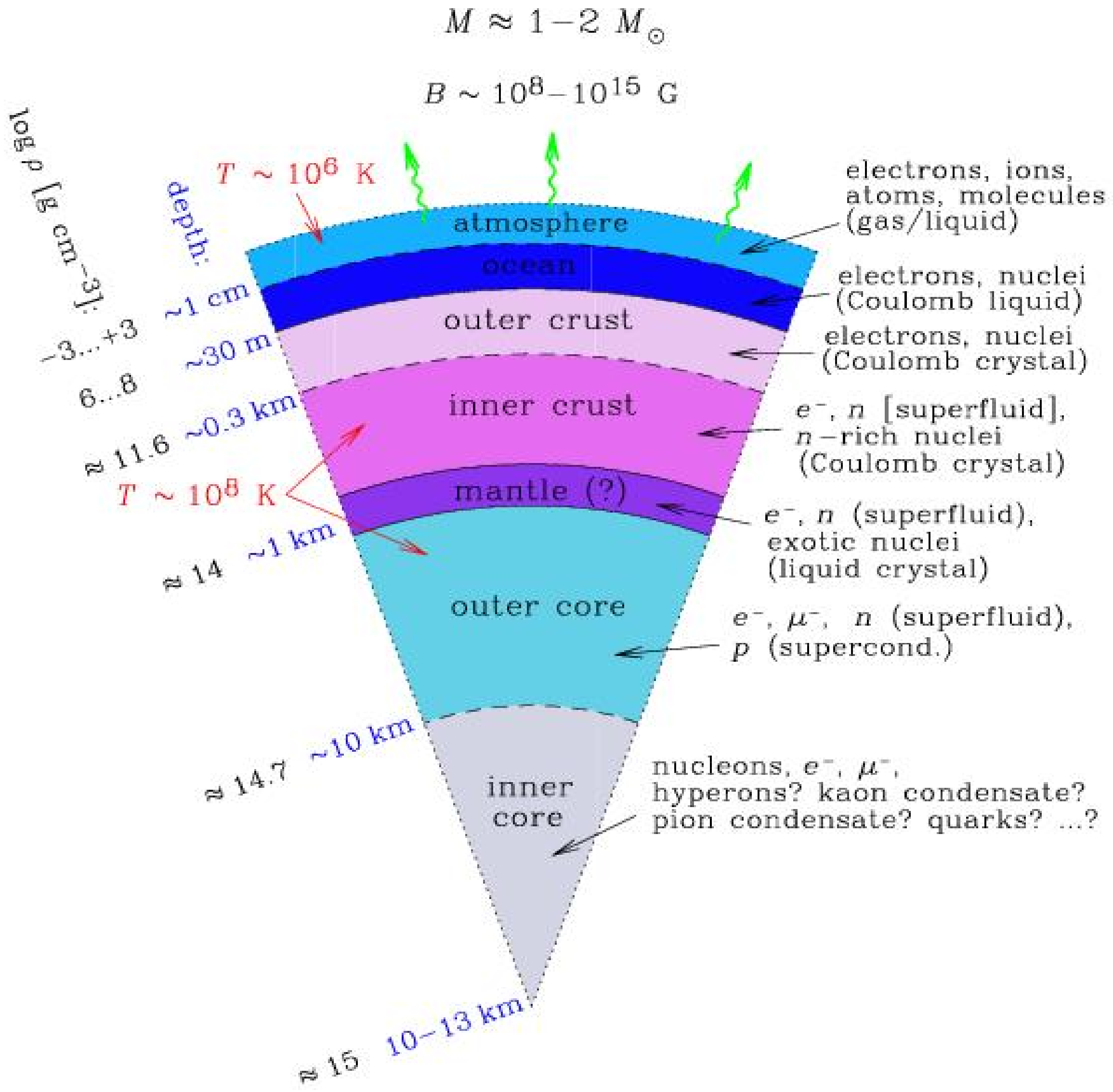
Neutron-star envelopes

Neutron star structure



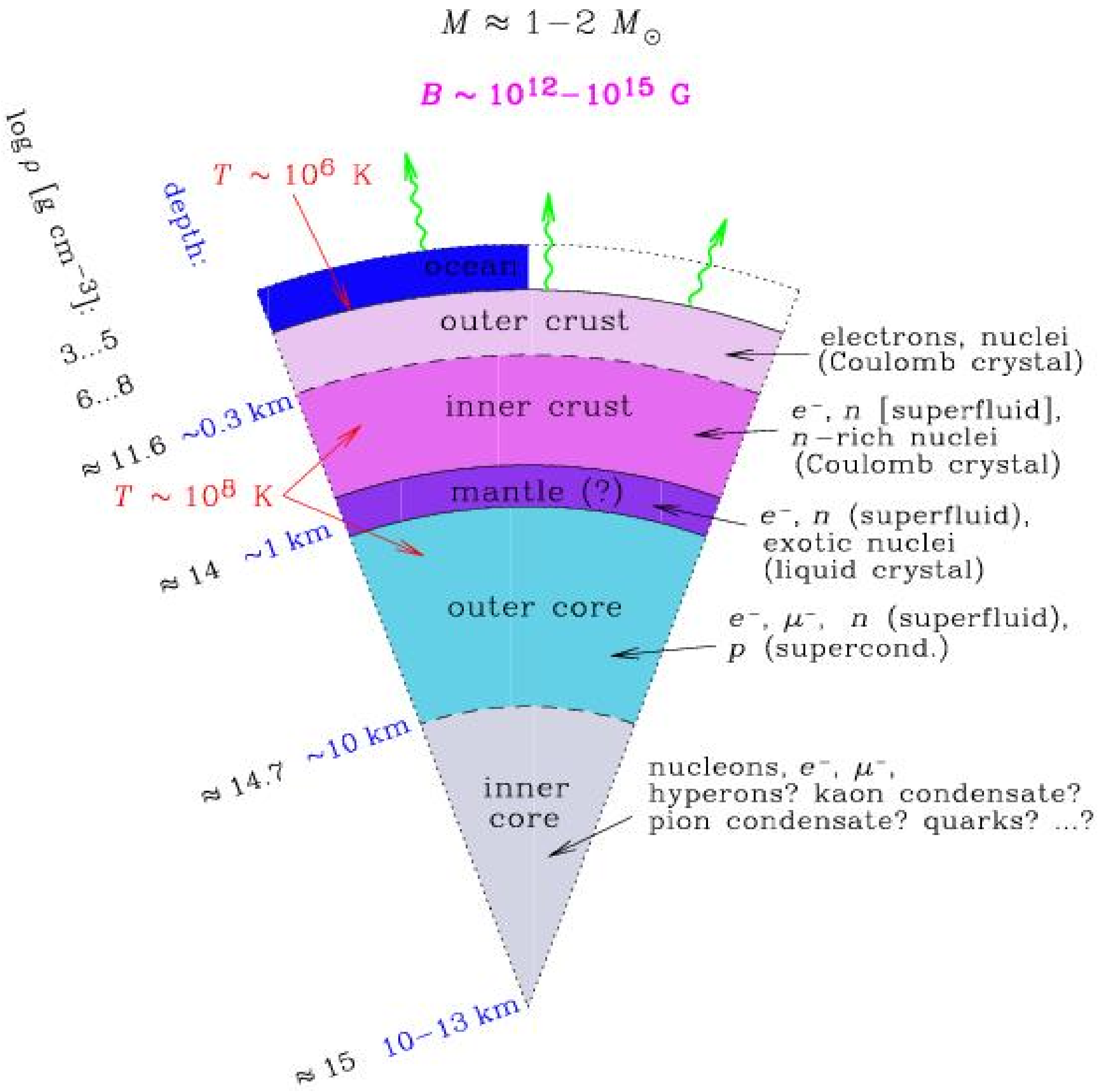
Neutron-star envelopes

Neutron star structure in greater detail



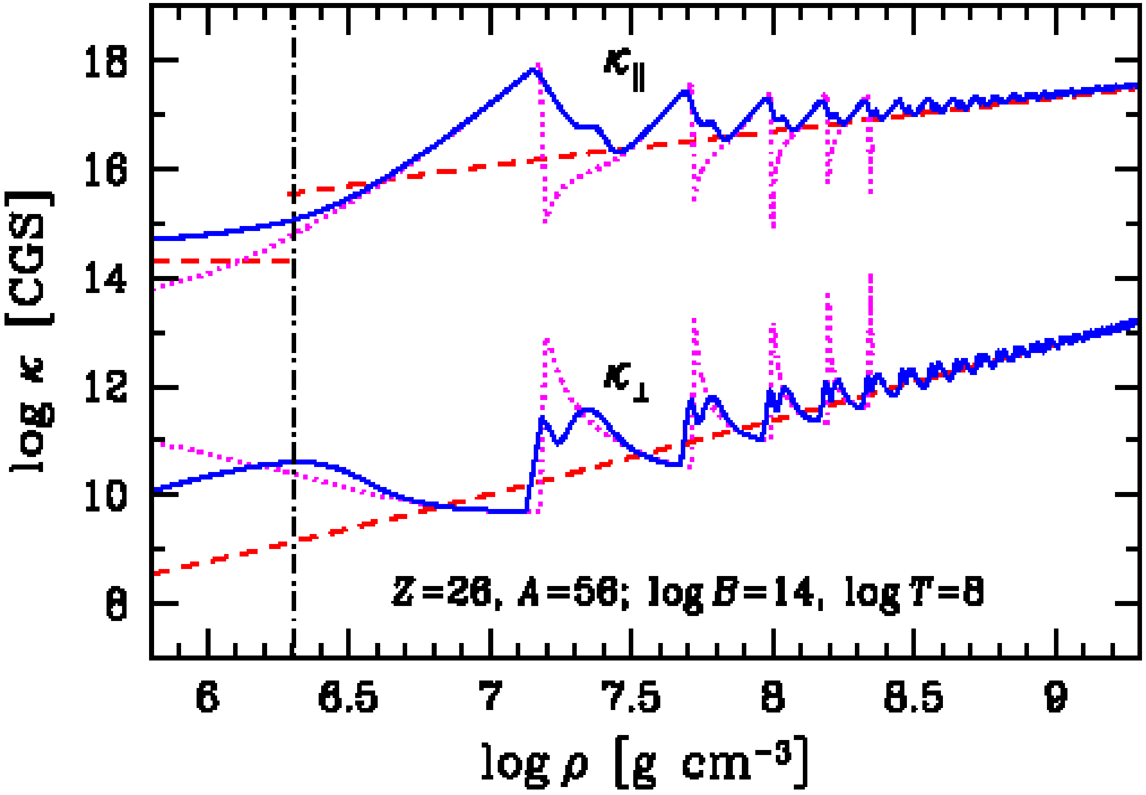
Neutron-star envelopes

Neutron star without atmosphere: possible result of a phase transition



Thermal conductivities in a strongly magnetized envelope

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

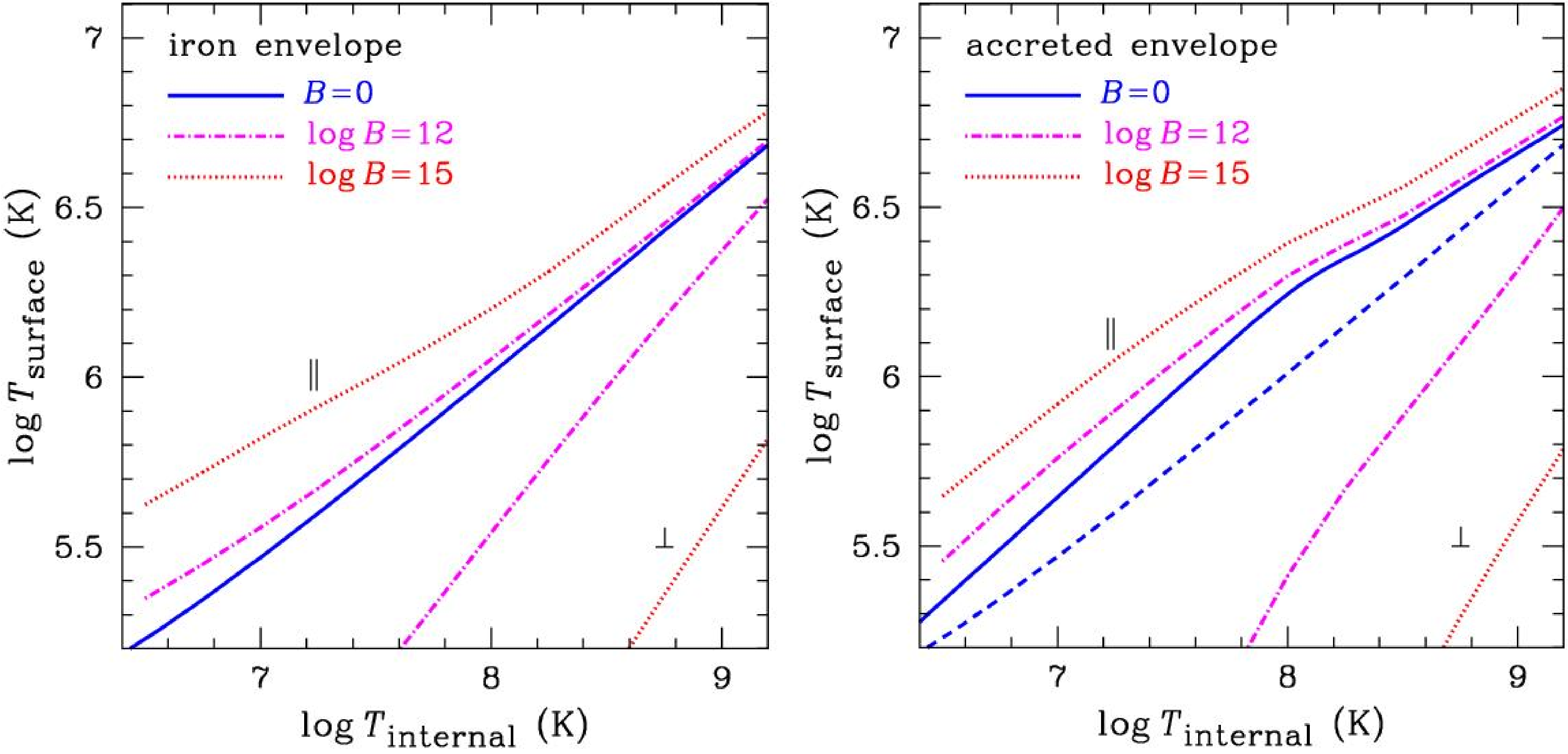


Solid – exact, dots – without *T*-integration, dashes – magnetically non-quantized

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

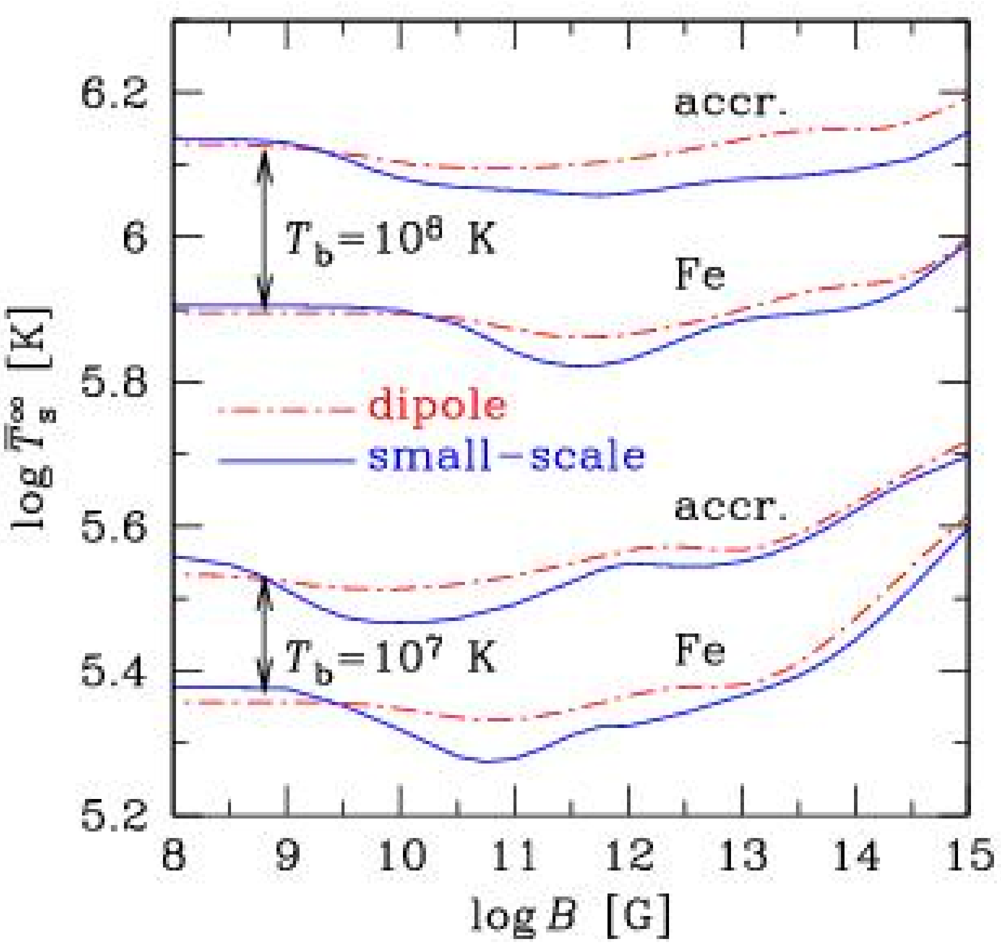
Heat flux: $\boldsymbol{F} = -\kappa_\parallel \nabla_\parallel T - \kappa_\perp \nabla_\perp T - \kappa_\wedge \boldsymbol{b} \times \nabla T, \quad \boldsymbol{b} = \frac{\boldsymbol{B}}{B}$

Temperature drops in magnetized envelopes of neutron stars



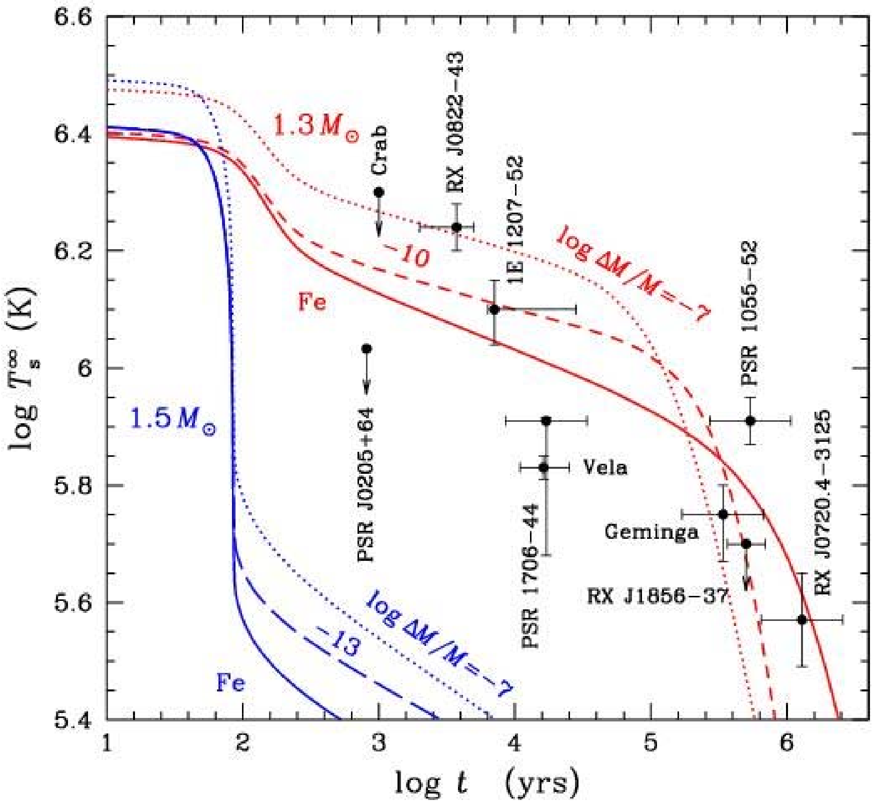
[based on Potekhin *et al.* (2003) *ApJ* **594**, 404]

Configuration of the surface field does <u>not</u> strongly affect luminosity

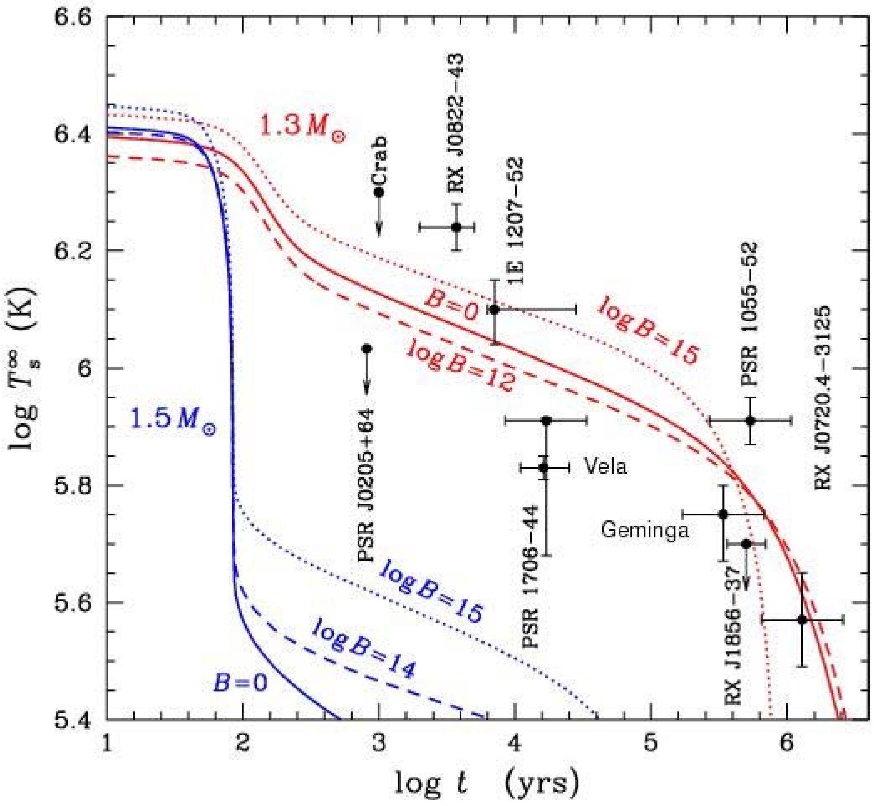


Dependence of the mean effective temperature on the magnetic field strength.
for the light-element ("accr.") and iron ("Fe") envelopes.
Dot-dashed lines – dipole field; solid lines – stochastic field.
[Potekhin, Urpin, & Chabrier (2005) *A&A* **443**, 1025]

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

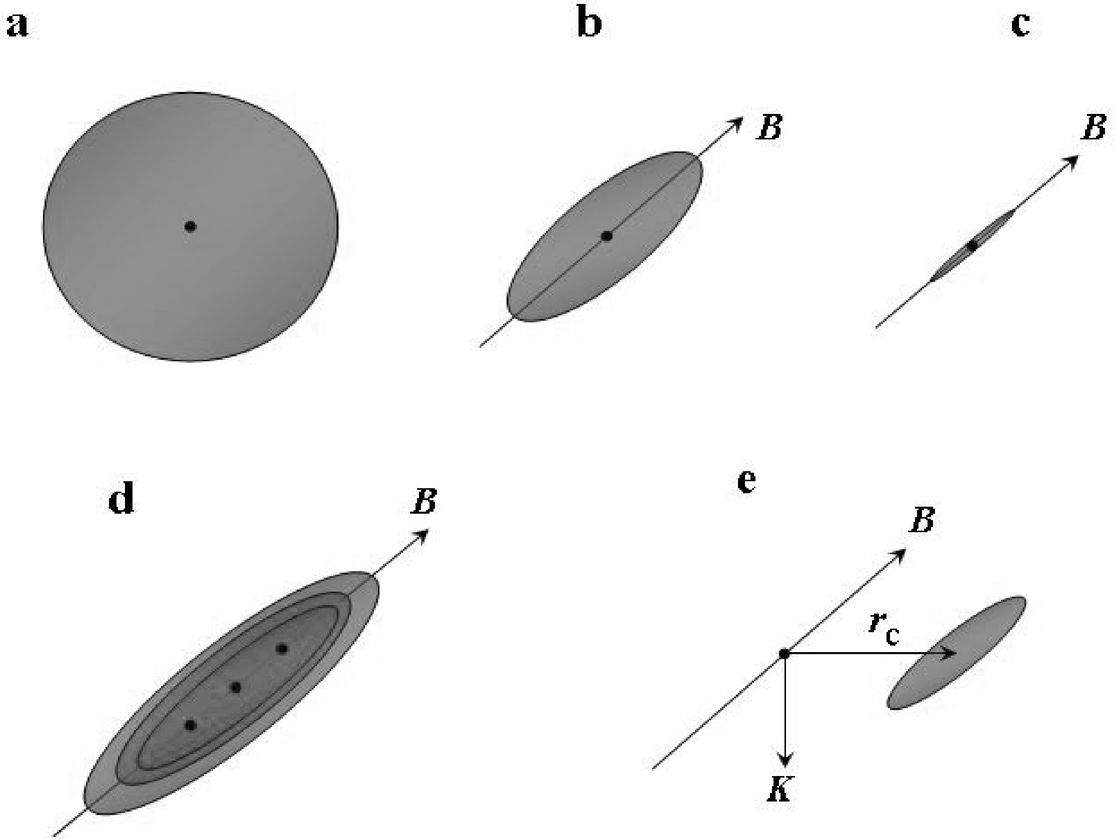


Cooling of neutron stars with ***magnetized envelopes***



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

Modeling neutron-star atmospheres:
Bound species in a strong magnetic field

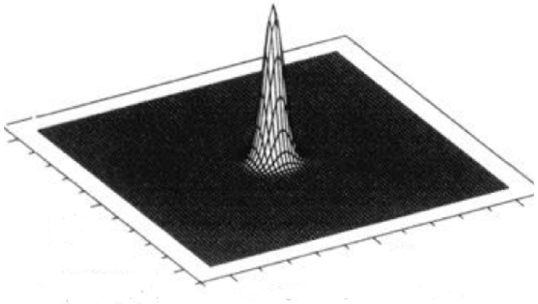


The effects of a strong magnetic field on the atoms and molecules.
a–c: H atom in the ground state (**a**: $B \ll 10^9$ G, **b**: $B \sim 10^{10}$ G, **c**: $B \sim 10^{12}$ G).
d: The field stabilizes the molecular chains (H_3 is shown).
e: H atom moving across the field becomes decentered.

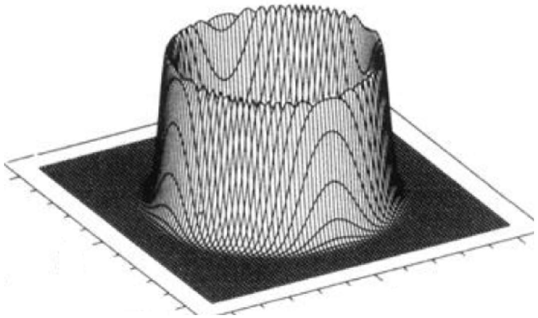
Modeling neutron-star atmospheres:
Bound species in a strong magnetic field

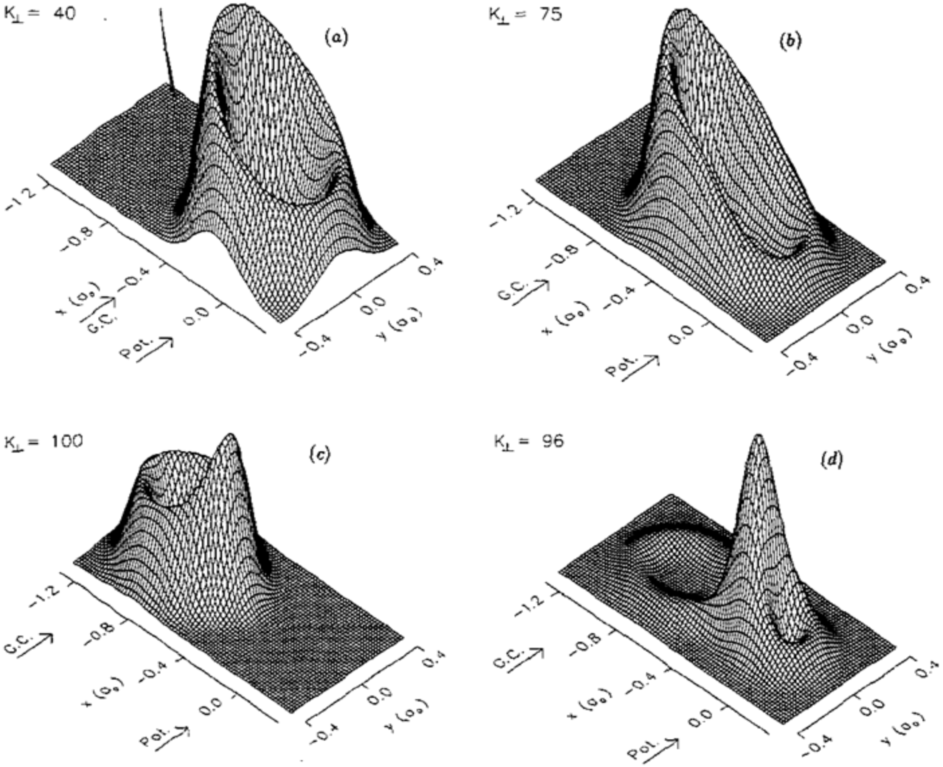
an excited state (m=–5) + center-of-mass motion
(“motional Stark effect”)

the ground state



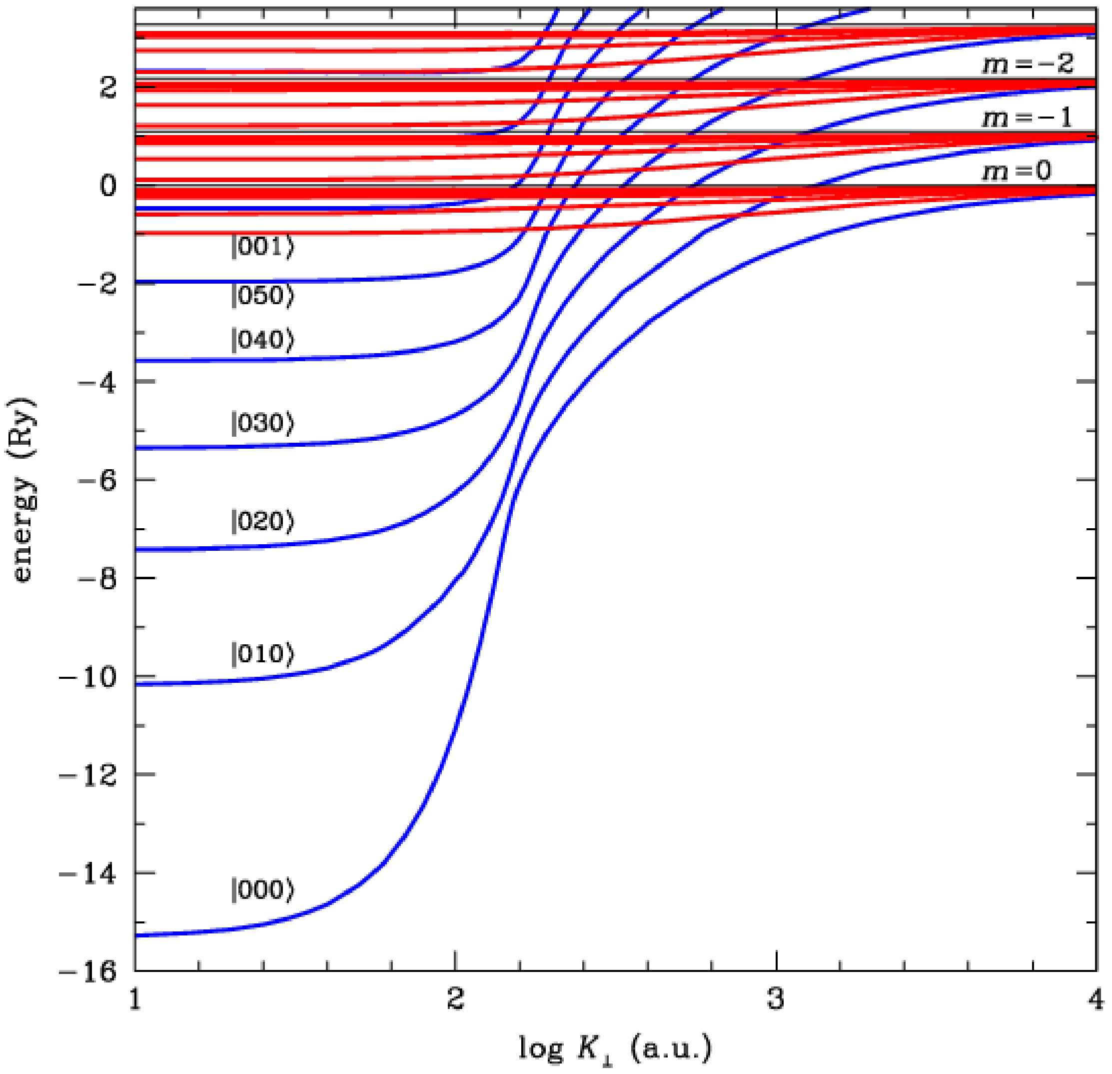
an excited state





Squared moduli of the wave functions of a hydrogen atom at B=2.35x10^{11} G

[Vincke *et al.* (1992) *J.Phys.B: At. Mol. Opt.Phys.* **25**, 2787]



Binding energies of the hydrogen atom in the magnetic field B=2.35×10^{12} G as functions of its state of motion across the field

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

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

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

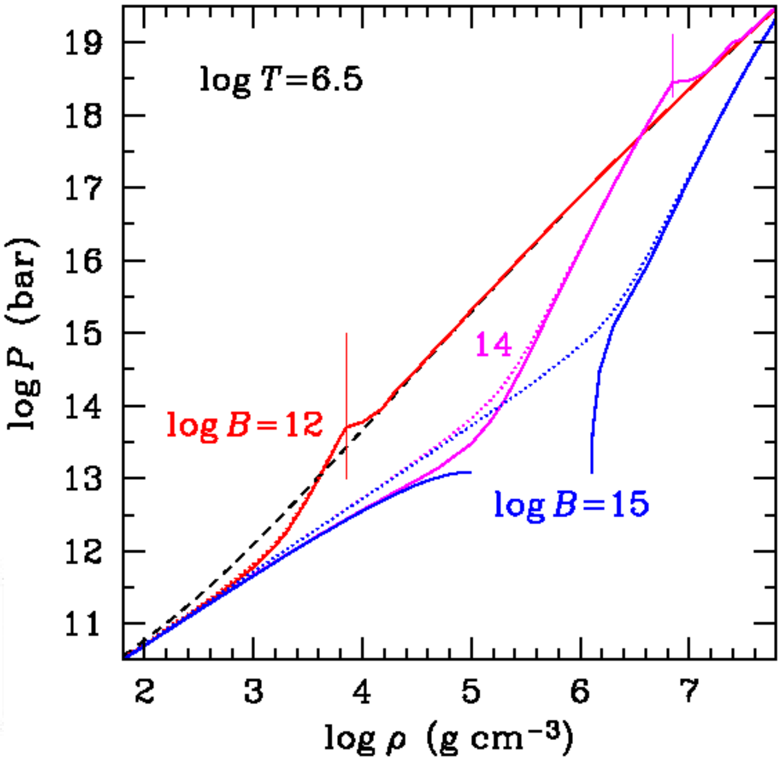
$$F = F_{\rm id}^{\rm e} + F_{\rm id}^{\rm p} + F_{\rm id}^{\rm neu} + F_{\rm ex}^{\rm C} + F_{\rm ex}^{\rm neu}$$

$$F_{\rm id}^{\rm e} = \mu_{\rm e} N_{\rm e} - P_{\rm e} V; \qquad F_{\rm ex}^{\rm C} = F_{\rm pp} + F_{\rm ee} + F_{\rm pe}$$

$$F_{\rm id}^{\rm p}/N_{\rm p} k_{\rm B} T = \ln(2\pi a_{\rm m}^2 \lambda_{\rm p} n_{\rm p}) + \ln\left(1 - {\rm e}^{-\beta_{\rm p}}\right) - 1 + \beta_{\rm p}/2 - \ln\left[2\cosh(g_{\rm p}\beta_{\rm p}/4)\right]$$

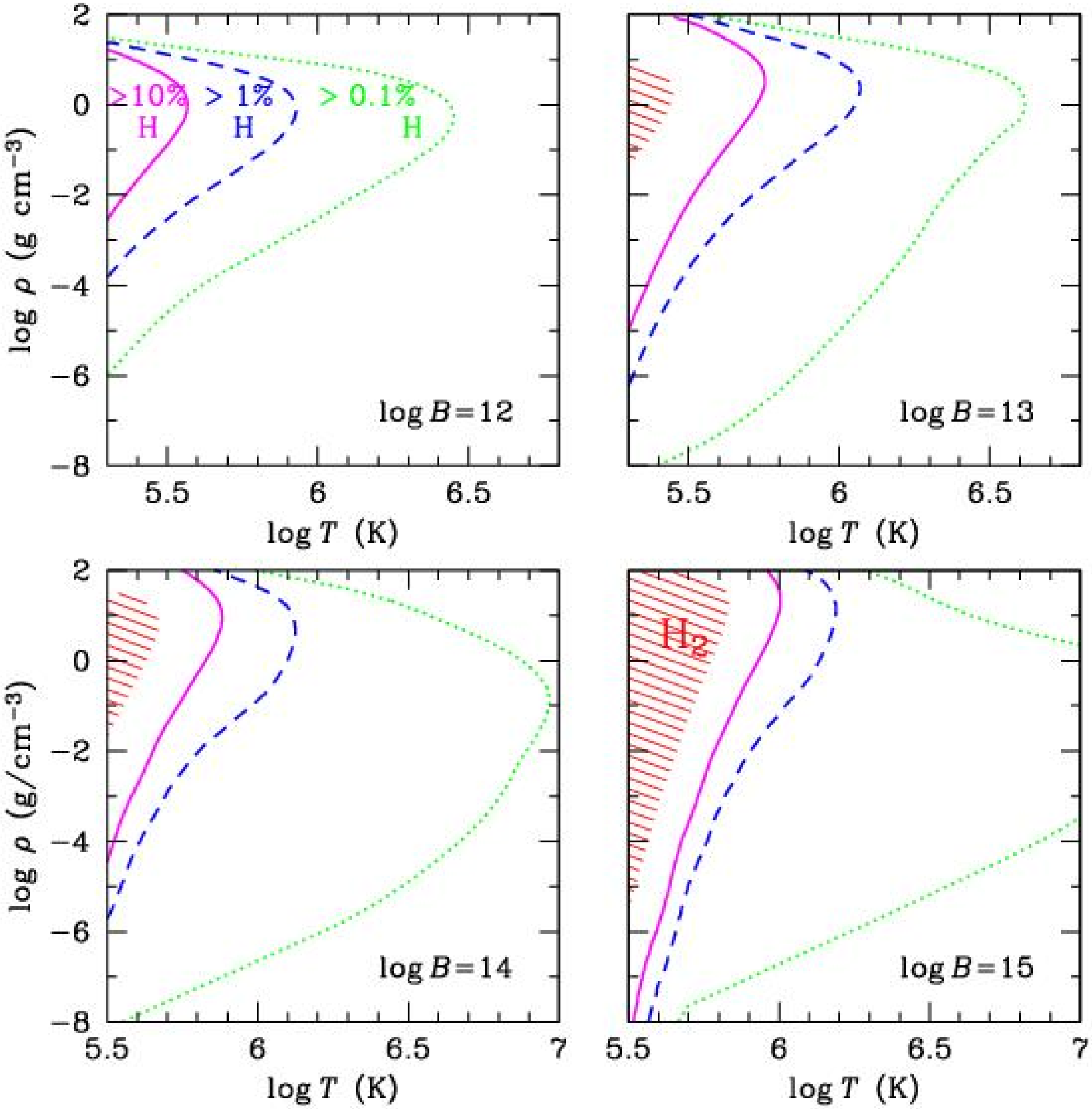
$$\beta_{\rm p} = E_{cp}/k_{\rm B}T \approx 0.0732\, B_{12}/T_6$$

$$F_{\rm id}^{\rm H} = k_{\rm B}T \sum_{s\nu} N_{s\nu} \int \left\{ \ln\left[N_{s\nu}\lambda_{\rm H}\frac{(2\pi\hbar)^2}{V} p_{s\nu}(K_\perp)\right] - 1 - \epsilon_{s\nu}(K_\perp)/(k_{\rm B}T)\right\} p_{s\nu}(K_\perp)\, {\rm d}^2K_\perp + N_{\rm H} k_{\rm B} T \left\{\beta_{\rm p}/2 - \ln\left[2\cosh(g_{\rm p}\beta_{\rm p}/4)\right]\right\}$$

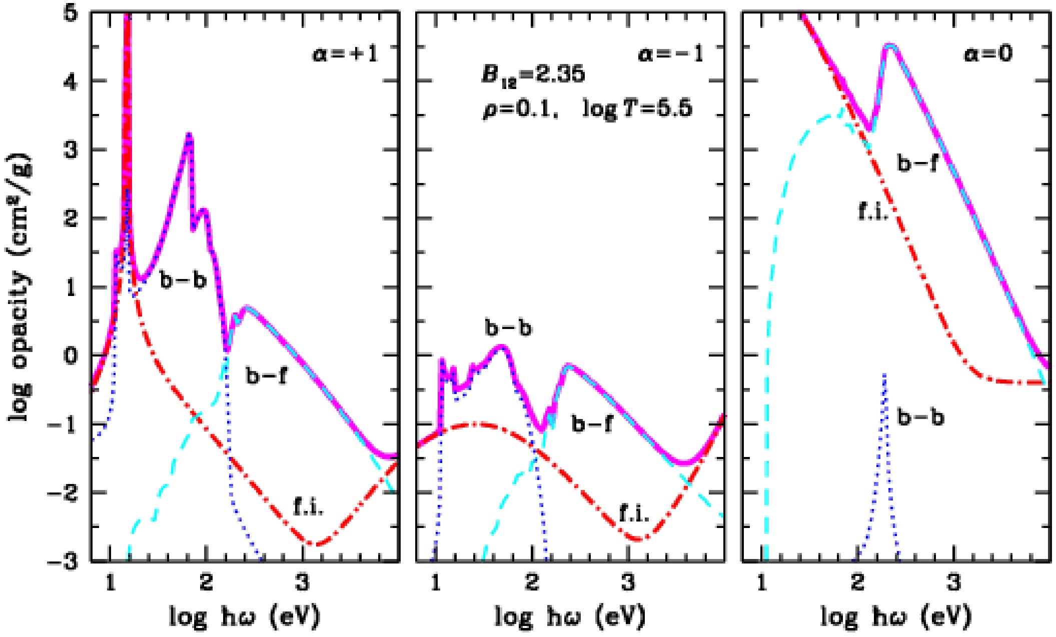


EOS of ideal (dotted lines) and nonideal (solid lines) H plasmas at various field strengths
[Potekhin & Chabrier (2004) *ApJ* **600**, 317]

Partial ionization/recombination in hydrogen plasmas with strong magnetic fields



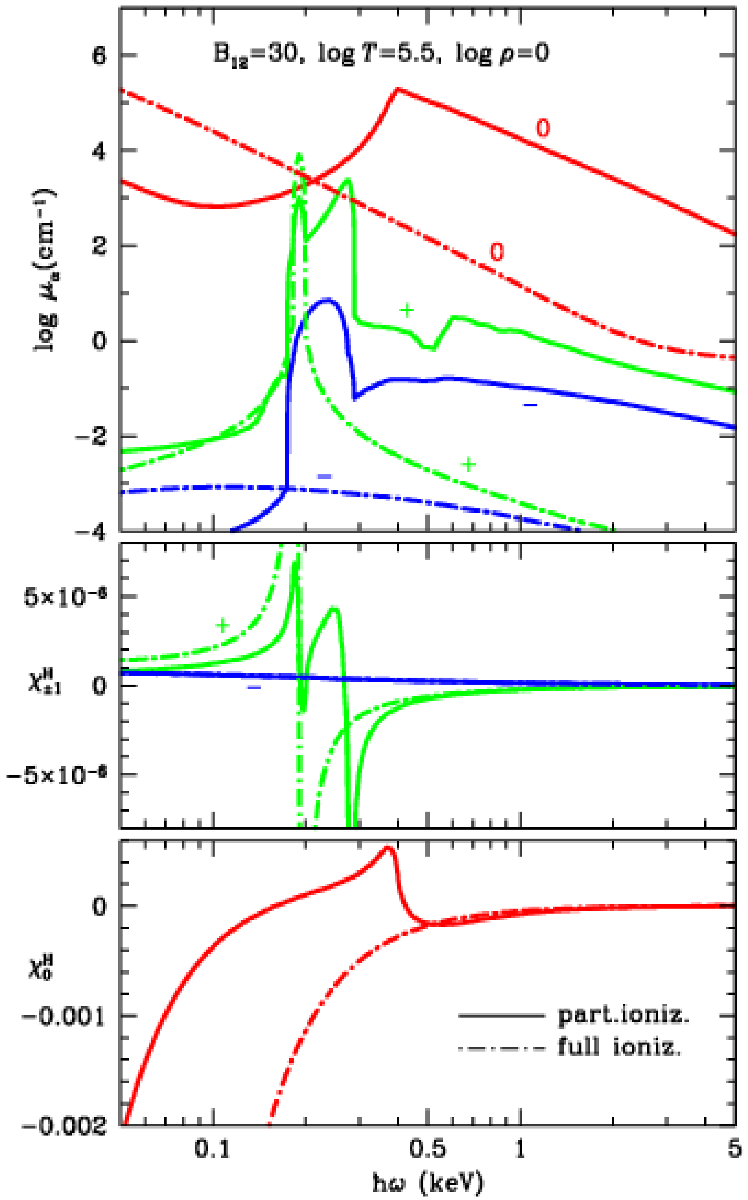
Plasma absorption and polarizabilities in strong magnetic fields: The effects of nonideality and partial ionization



Spectral opacities for 3 basic polarizations.

Solid lines – taking into account bound states, dot-dashes –full ionization

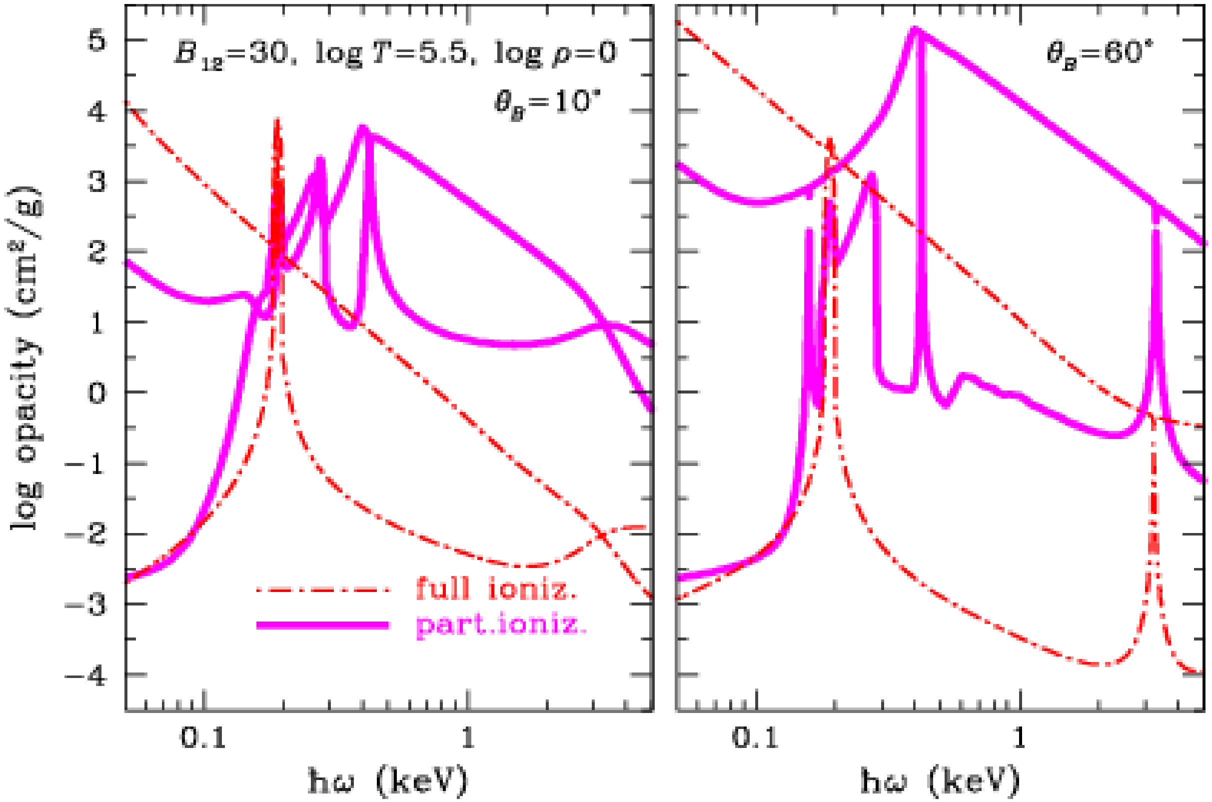
[Potekhin & Chabrier (2003) *ApJ* **585**, 955]



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

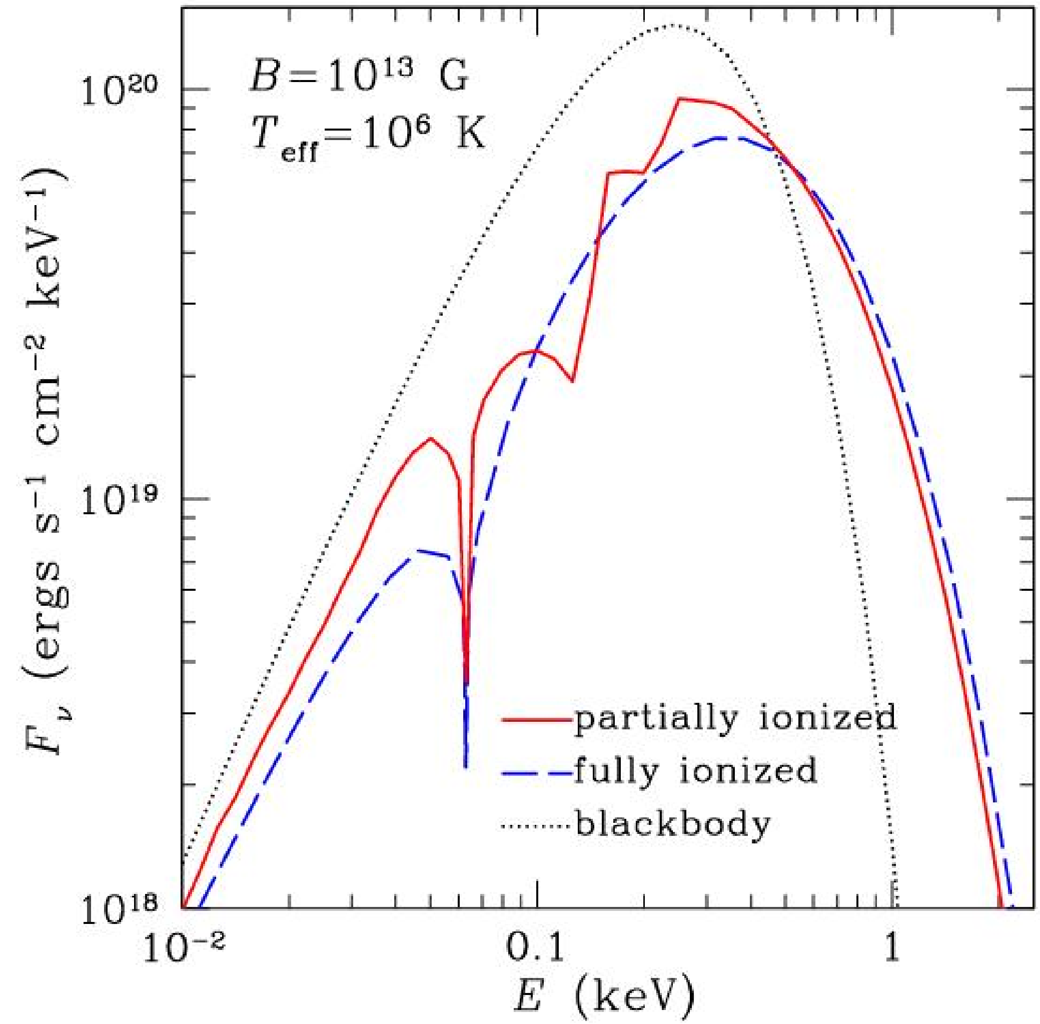
at the magnetic field strength B=3×10^{13} G, density 1 g/cc, and temperature 3.16×10^5 K**.**

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]

Result: the spectrum



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

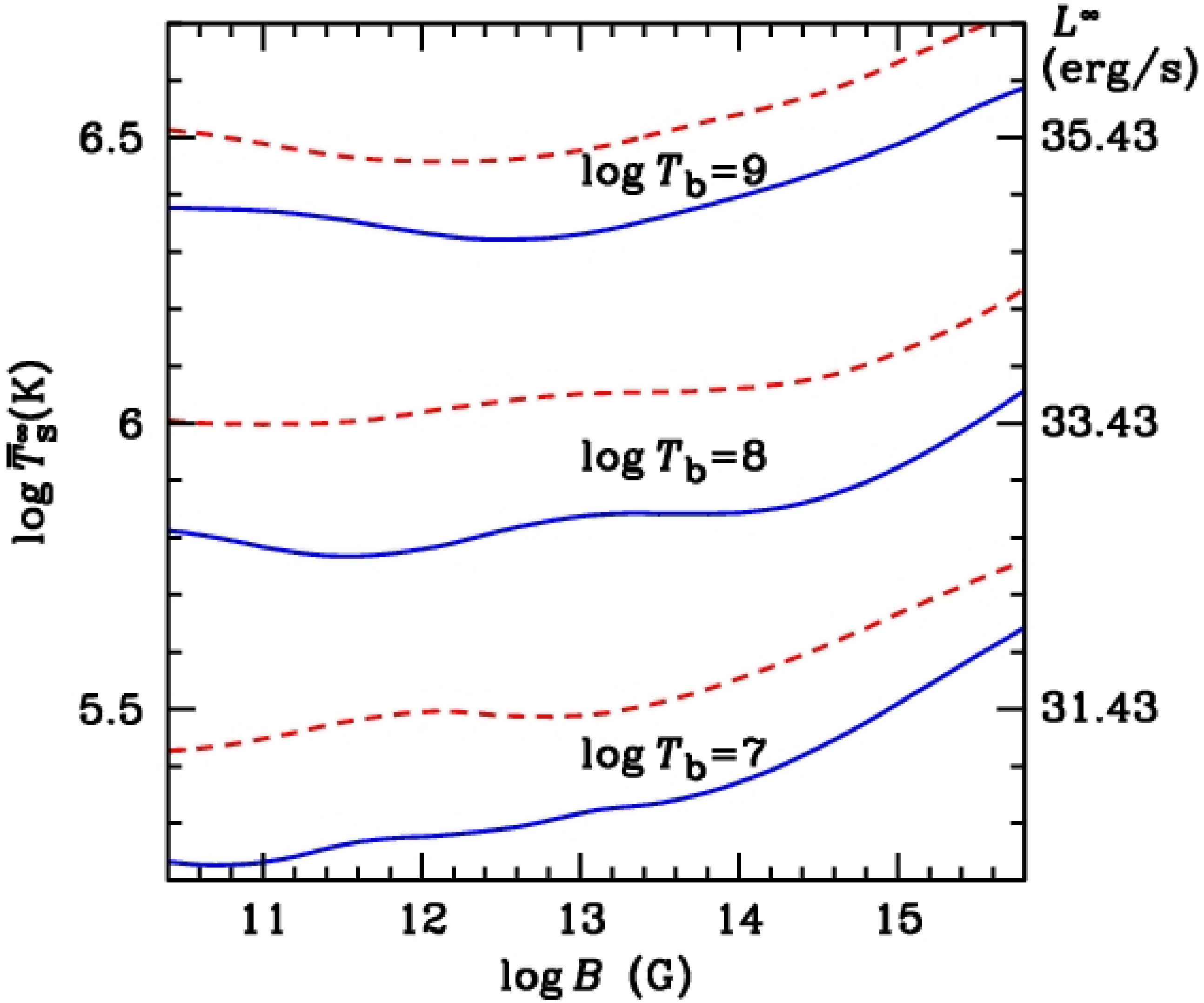
(the field is normal to the surface, the radiation flux is angle-averaged)

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

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

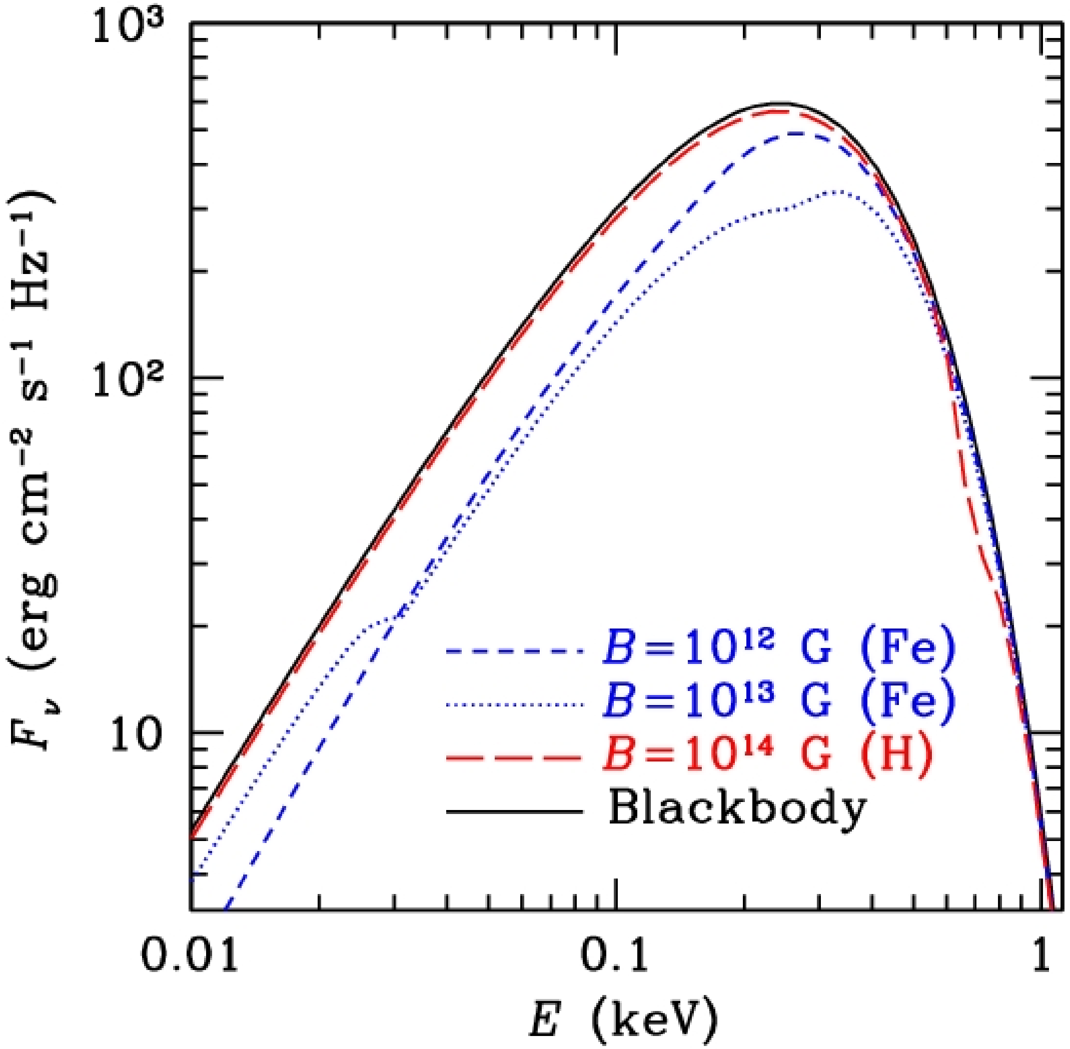
1. ***Thermal structure: field affects luminosity***
2. ***Surface layers: molecules, chains, and magnetic condensation***
3. ***Radiative transfer: vacuum polarization and mode conversion***
4. ***Energy transport below the plasma frequency***
5. ***Non-LTE distribution of ions over Landau levels***

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.

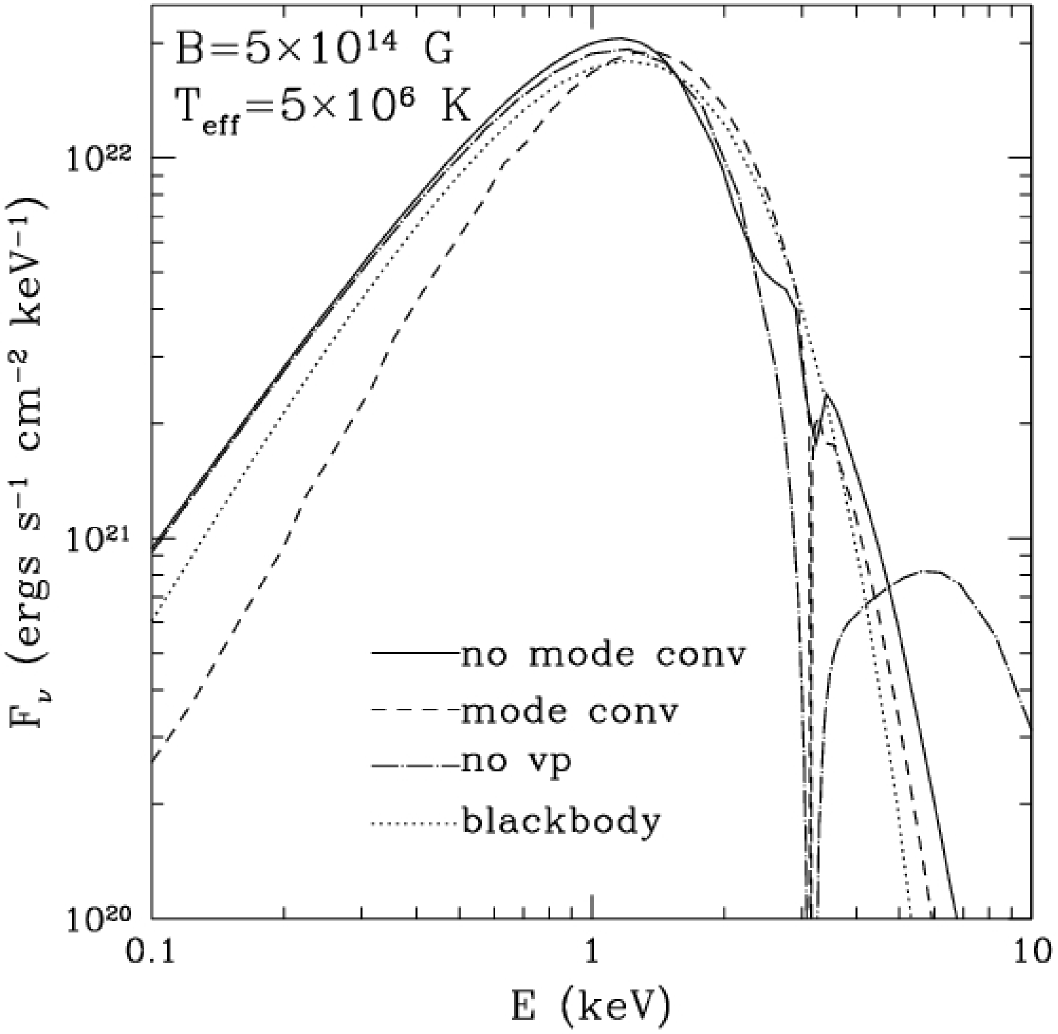
Radiation from condensed surface



Monochromatic flux from the condensed surface in various cases

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

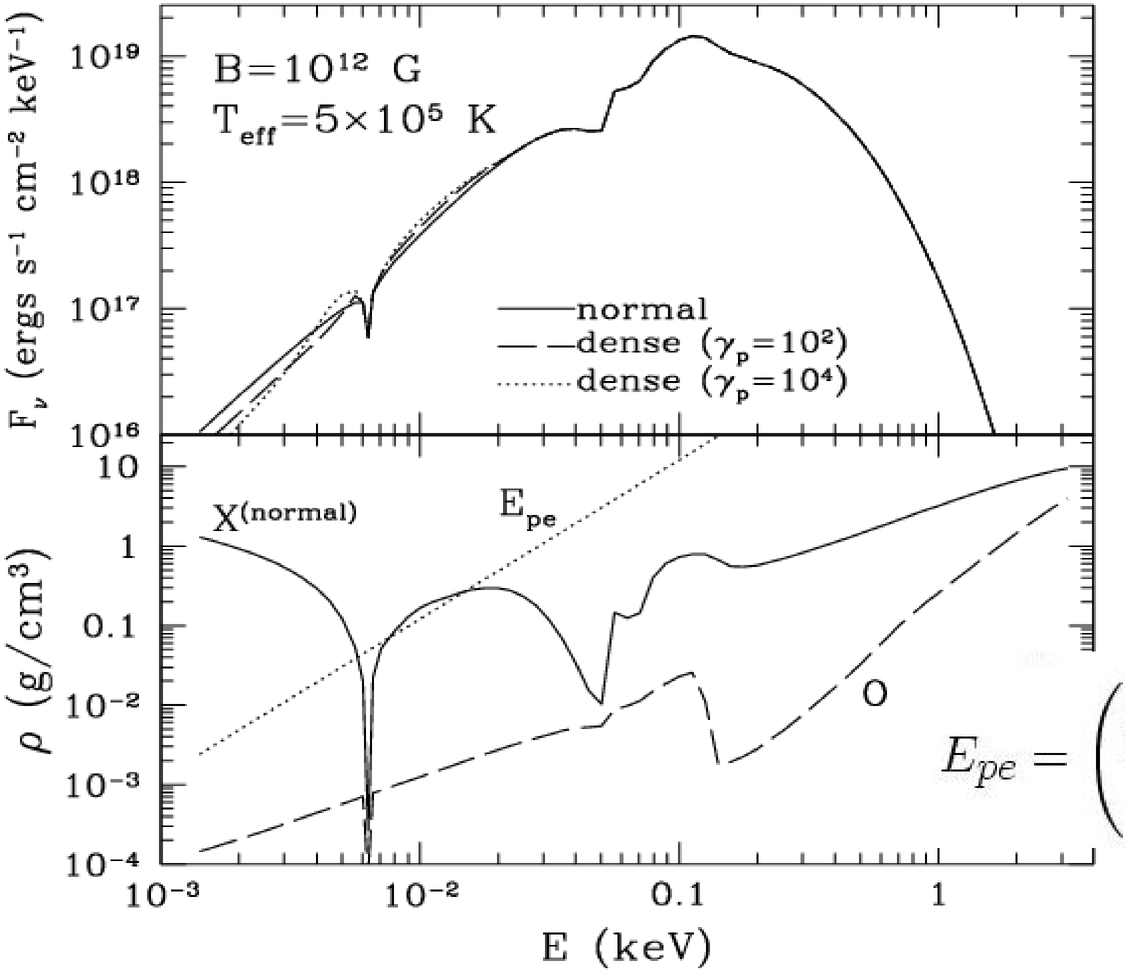
The effect of vacuum polarization



Spectra of fully ionized H atmospheres in a superstrong magnetic field.

The solid line and dashed line are the atmospheres with vacuum polarization but no mode conversion and complete mode conversion; the dot-dashed line is the atmosphere without vacuum polarization, and the dotted line is for a blackbody [Ho *et al.* (2003) *ApJ* **599**, 1293]

Energy transport below the plasma frequency may affect the spectrum

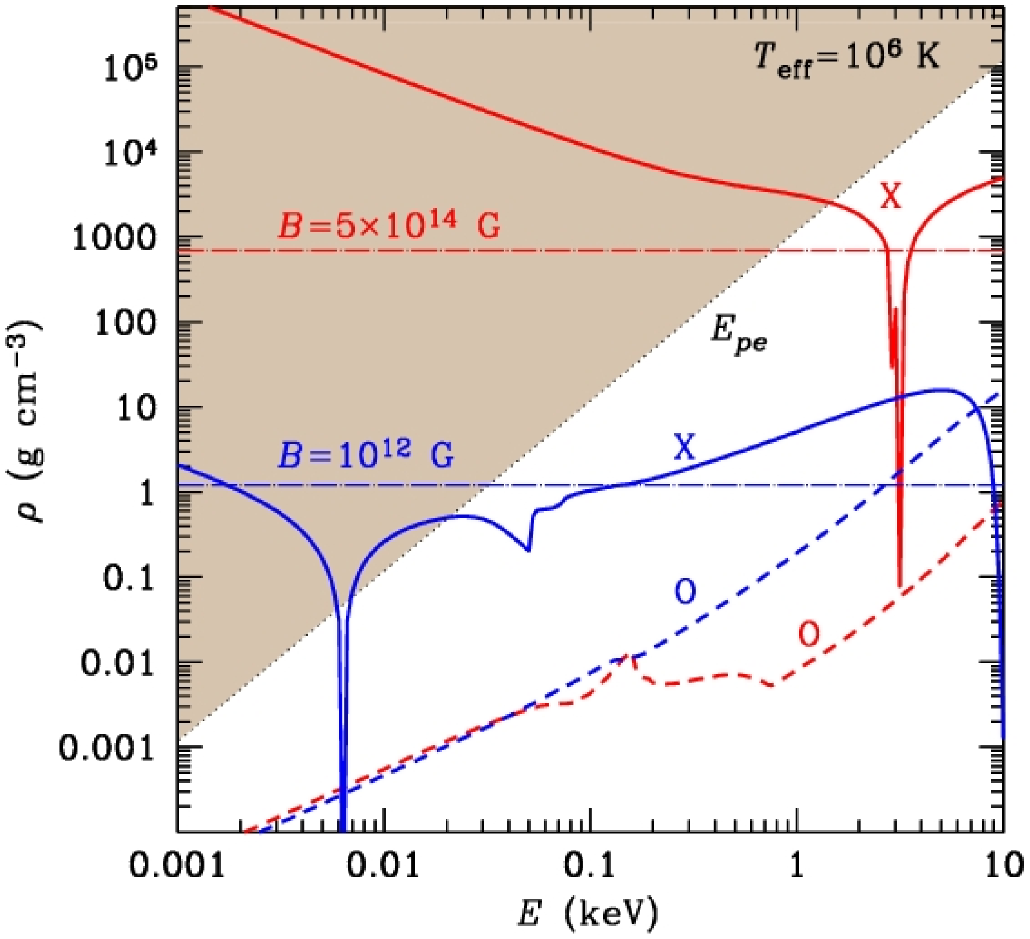


$$E_{pe} = \left(\frac{4\pi\hbar^2 e^2 n_e}{m_e}\right)^{1/2} \approx 28.7\,\rho^{1/2}\ \mathrm{eV}$$

Spectra (upper panel) and photon-decoupling densities for X- and O-modes (lower panel) for a partially ionized H atmosphere.

The suppression of radiation below the plasma energy E_{pe} is approximately modeled by dashed and dotted lines in the upper panel [Ho *et al.* (2003) *ApJ* **599**, 1293]

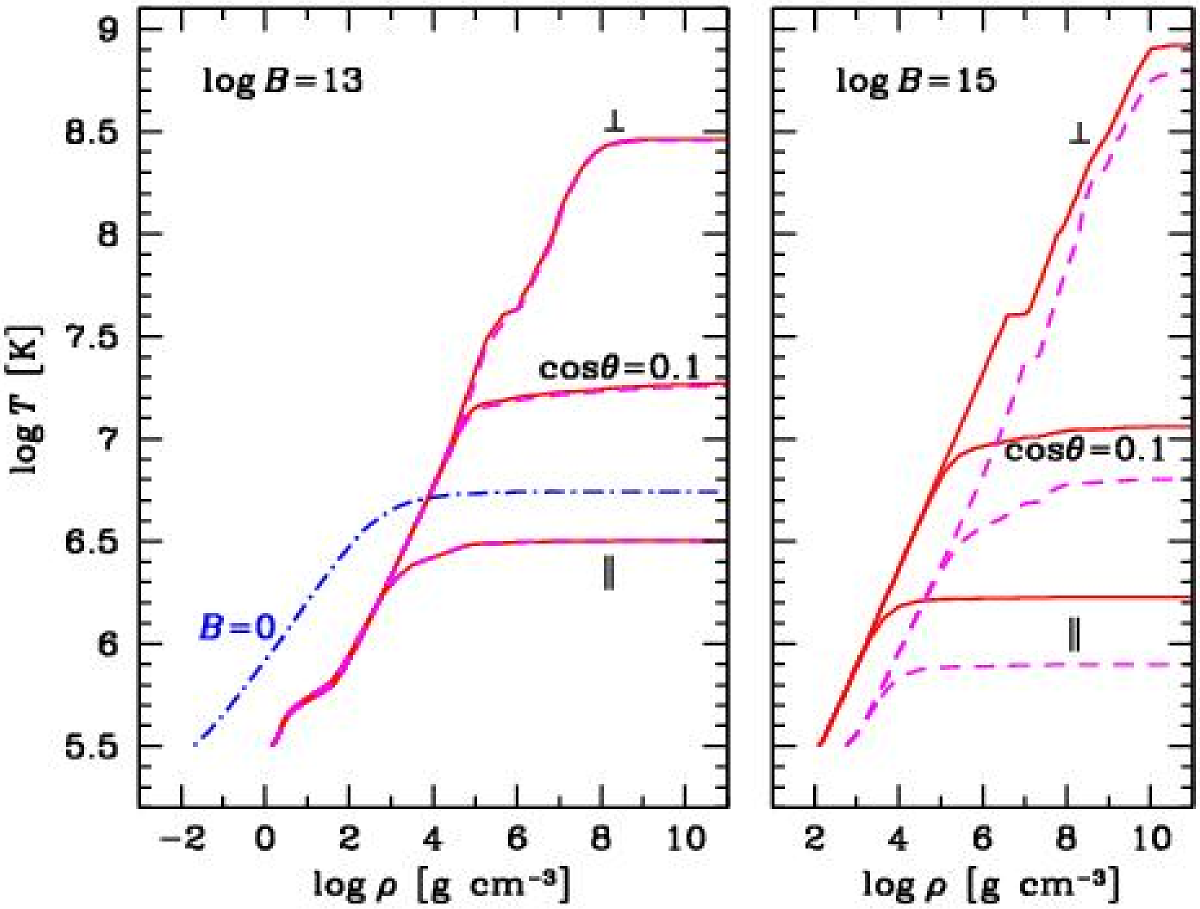
Energy transport below the plasma frequency can be important



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).

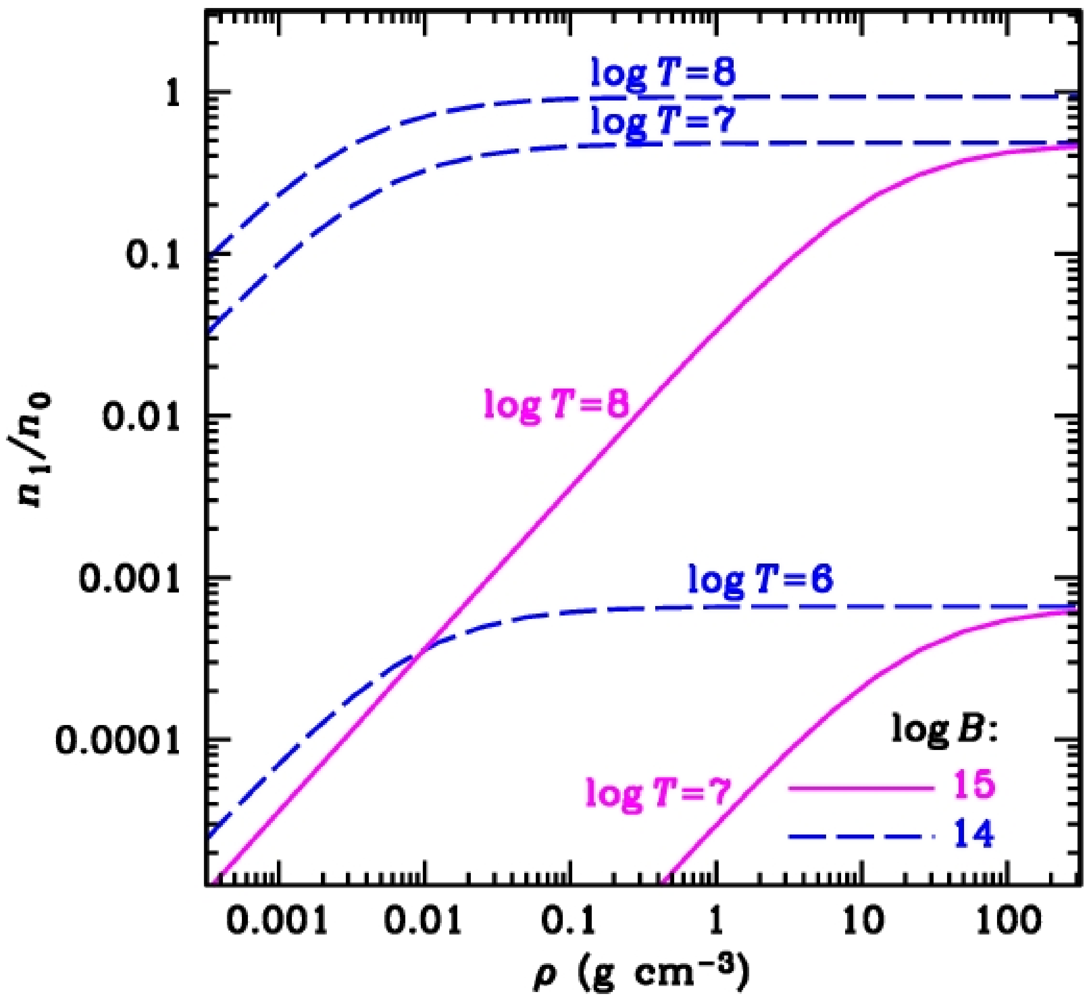
Dot-dashed lines correspond to the radiative surface, the shadowed region corresponds to $E < E_{pl}$.

Energy transport below the plasma frequency may affect the temperature profile and T_s



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]

Superstrong field may lead to non-LTE effects



Population of proton Landau level N=1 relative to N=0 as function of mass density for different values of B and T [Lai & Potekhin, *in* preparation]

Conclusions

- In order to link neutron-star observations with theoretical models of ultradense matter, one needs to model ***heat diffusion*** and formation of thermal radiation ***spectrum***, which requires knowledge of ***thermodynamic*** and ***kinetic*** properties of nonideal, strongly magnetized plasmas in neutron star envelopes.
- Practical models of the ***electron conductivities***, *EOS*, and ***opacities*** of strongly magnetized plasmas, applicable to neutron stars, are developed in recent years. This allows us to model neutron-star thermal spectra which can be used for interpretation of observations.
- Magnetic fields of ***ordinary pulsars*** are ***not*** very important for the ***cooling***, regardless of the field scale at the surface. However, they can be ***important*** for modeling the ***spectrum*** and evaluation of the effective ***temperature*** from observations.
- A ***superstrong*** magnetic field (1) accelerates cooling at late epochs and (2) leads to theoretical uncertainties in modeled spectra, which require further study.