Dense matter in neutron stars and their envelopes

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in collaboration with
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- Introduction: Neutron stars and their importance for fundamental physics
- Neutron-star envelopes – link between the superdense core and observations
- Conductivities and thermal structure of neutron star envelopes
- Atmospheres and thermal radiation spectra of neutron stars with magnetic fields

Neutron stars – the densest stars in the Universe

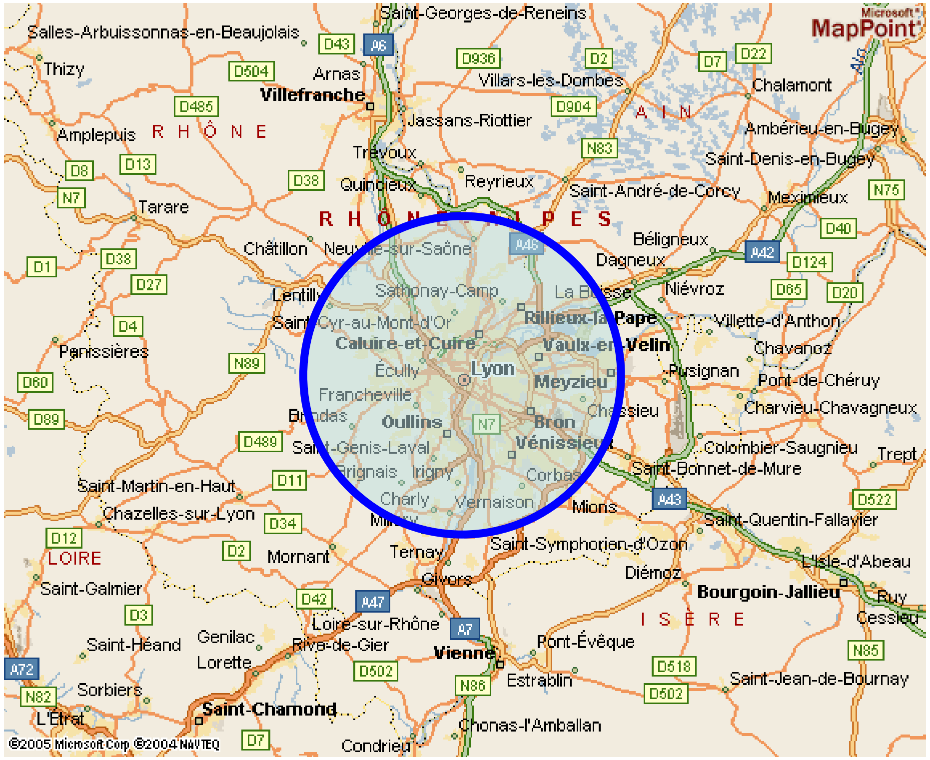
Mass and radius:

$$M \sim 1.4\, M_\odot, \quad R \sim 10 \text{ km}$$

$$(M_\odot = 1.989 \times 10^{33} \text{ g}, \quad R_\odot = 6.96 \times 10^5 \text{ km})$$

Gravitational energy:

$$U_g \sim GM^2/R \sim 5 \times 10^{53} \text{ erg} \sim 0.2\, Mc^2,$$



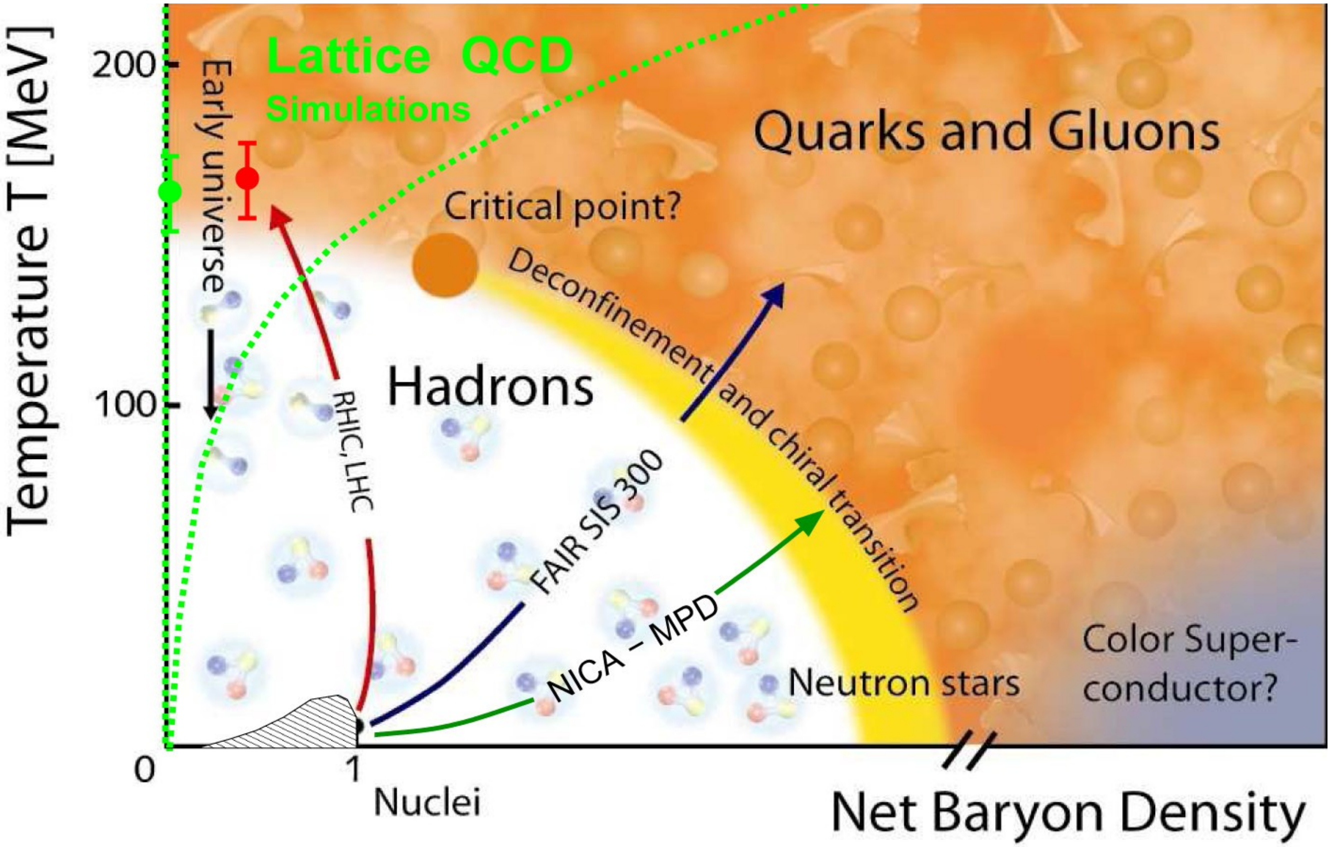
average density:

$$\bar{\rho} \simeq 3M/(4\pi R^3) \simeq 7 \times 10^{14} \text{ g cm}^{-3}$$

$$\sim (2-3)\, \rho_0$$

$$(\rho_0 = 2.8 \times 10^{14} \text{ g cm}^{-3})$$

Neutron stars on the density – temperature diagram



Phase diagram of dense matter.
Courtesy of ***David Blaschke***

GR effects

Gravitational radius $r_g = 2GM/c^2 \approx 2.95\, M/M_\odot$ km

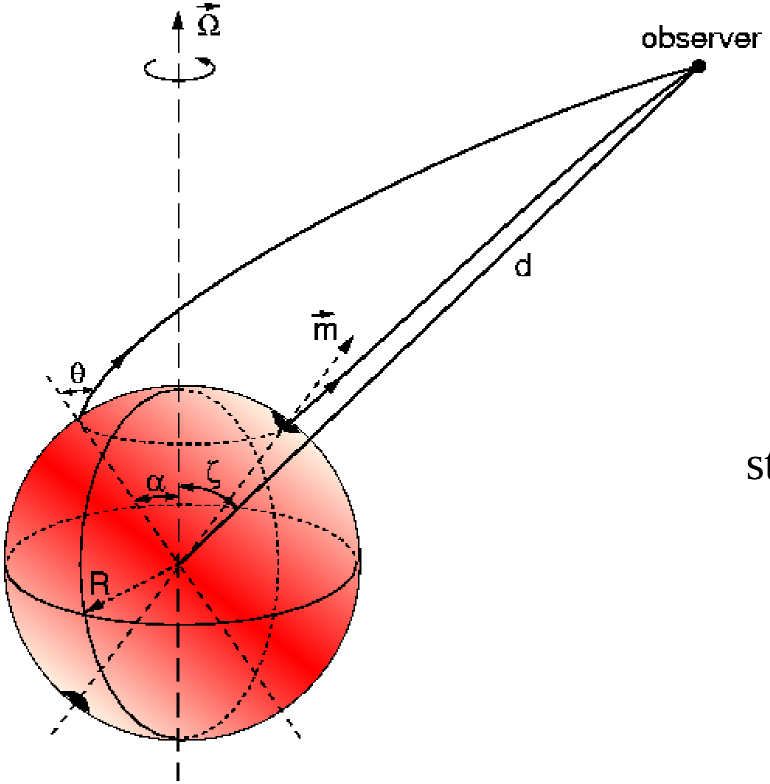
$$\omega_\infty = \omega_{\rm surf}\sqrt{1 - r_g/R}$$

Redshift z_g: $1 + z_g = \dfrac{1}{\sqrt{1-u}}$

"compactness parameter" $u = r_g/R$ ~ 0.3–0.4

"Observed" temperature $T_\infty = T_{\rm eff}\sqrt{1 - r_g/R}$ $= T_{\rm eff}/(1+z_g)$

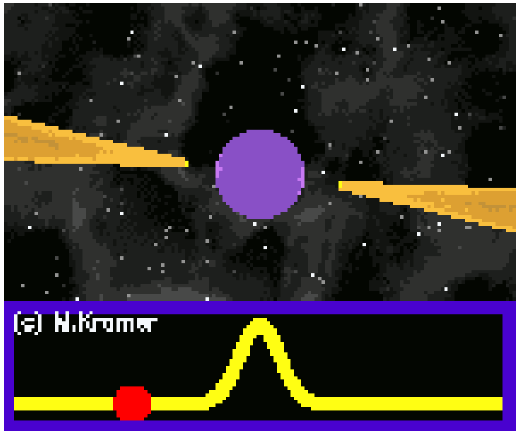
gravity $g = (1+z_g)\,GM/R^2 \approx 1.328\times10^{14}\,(1+z_g)\,(M/M_\odot)\,(R/10\ {\rm km})^{-2}$ cm s^{-2}



Light rays are bending near the stellar surface, thus allowing one to "look behind the horizon".

"Apparent" radius $R^\infty = R(1+z_g)$

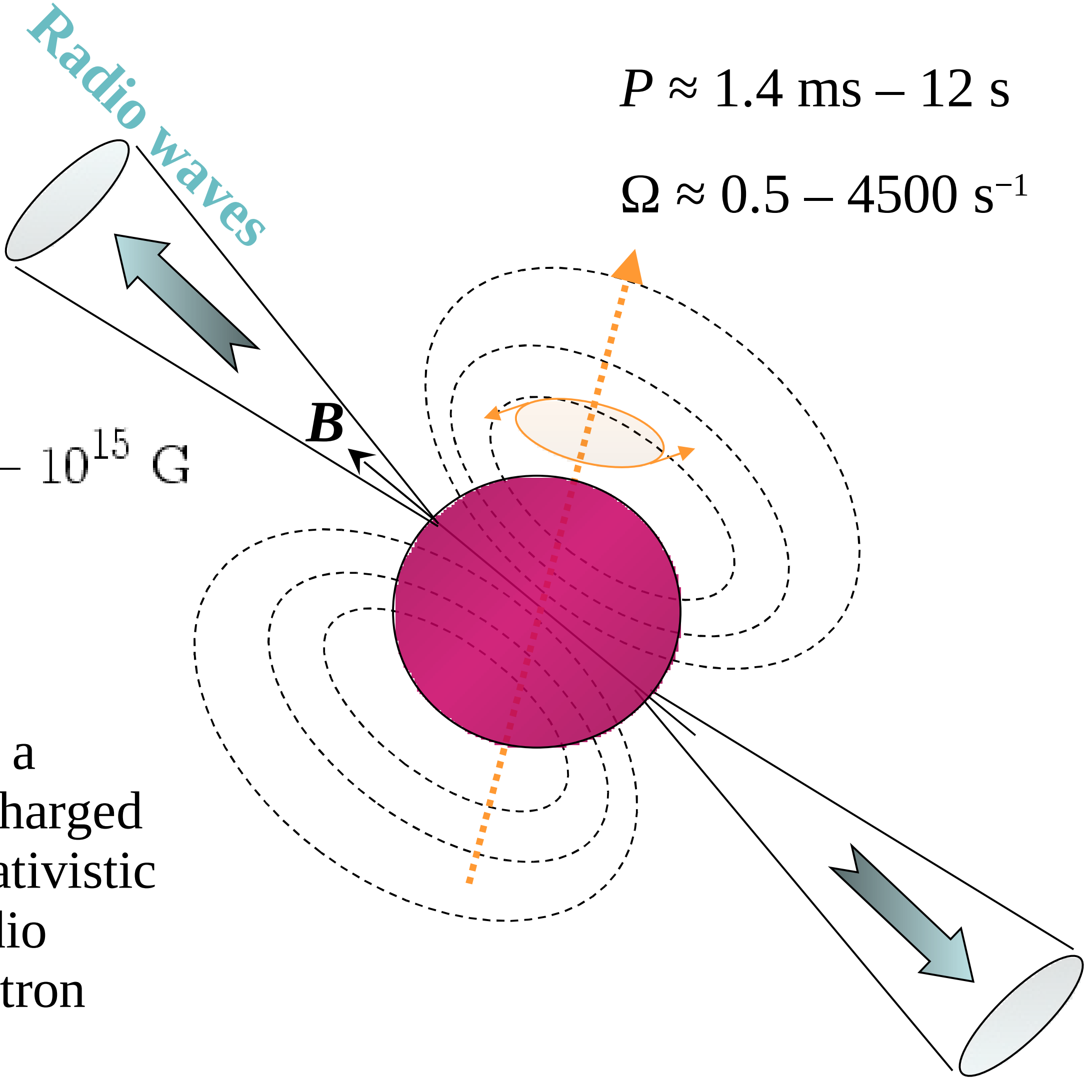
Neutron stars – the stars with the strongest magnetic field



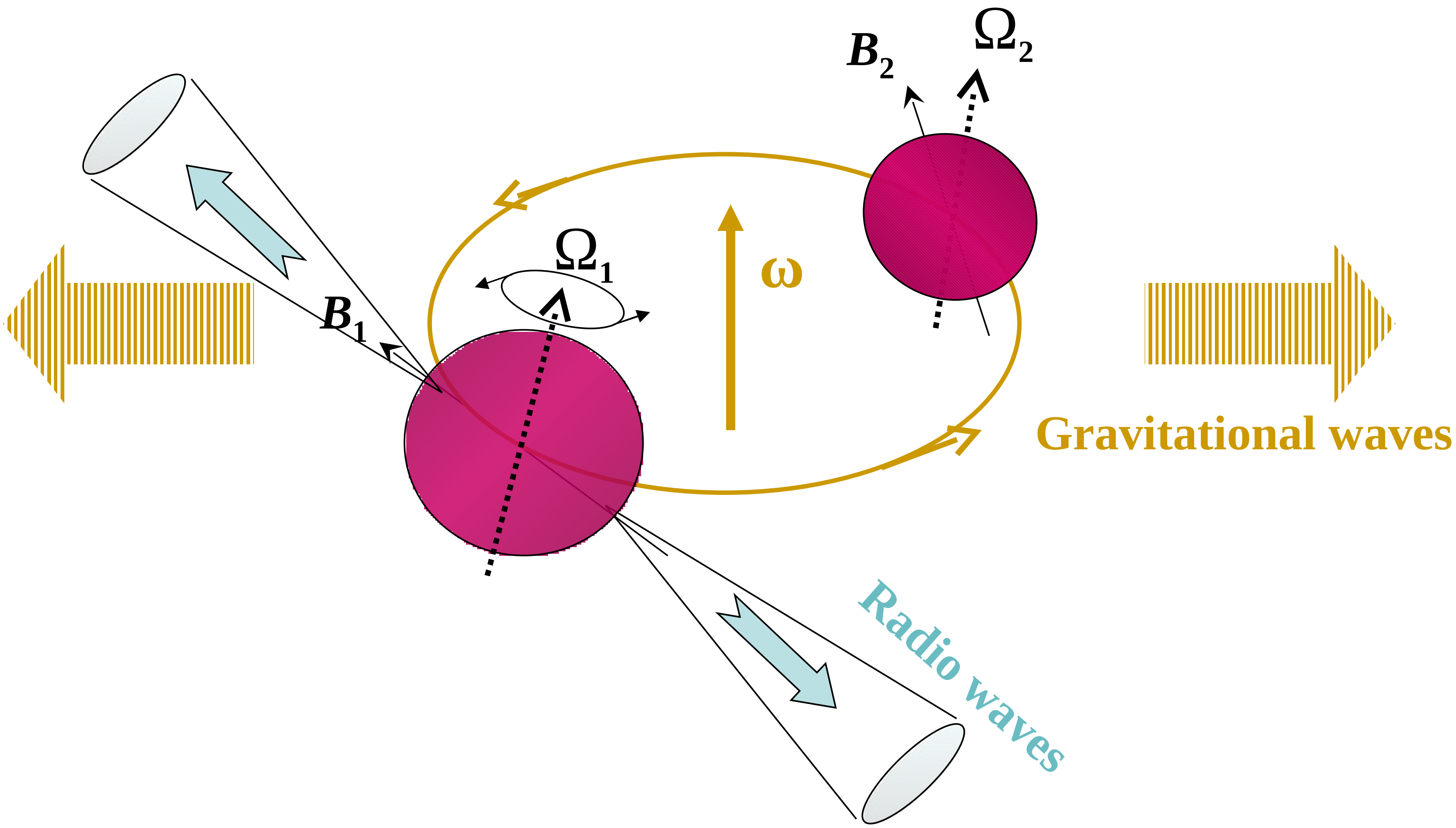
$$B \sim 10^8 - \underline{\mathbf{10^{12} - 10^{14}}} - 10^{15}\ \mathrm{G}$$

$P \approx 1.4$ ms – 12 s

$\Omega \approx 0.5$ – 4500 s^{-1}



In the strong magnetic field of a rapidly rotating neutron star, charged particles are accelerated to relativistic energies, creating coherent radio emission. Therefore many neutron stars are observed as ***pulsars***.



Binary neutron stars emit **gravitational waves** (losing the angular momentum) and undergo relativistic precession.

Prediction

- L.D.Landau (1931) – ***anticipation*** [L.D.Landau, “On the theory of stars,” *Physikalische Zs. Sowjetunion* **1** (1932) 285]: for stars with $M>1.5M_{\odot}$ “density of matter becomes so great that atomic nuclei come in close contact, foming **one gigantic nucleus**’’.
- J.Chadwick – ***discovery of a neutron*** [*Nature*, Feb.27, 1932]
- W.Baade & F.Zwicky (1933) – ***prediction of neutron stars*** [“Supernovae and cosmic rays,” *Phys. Rev.* **45** (1934) 138; “On super-novae,” *Proc. Nat. Acad. Sci.* **20** (1934) 254]: “…supernovae represent the transitions from ordinary stars to *neutron stars*, which in their final stages consist of extremely closely packed neutrons”; “…possess a very small radius and an extremely high density.”

Crab nebula – remnant of the supernova, which exploded on July 4, 1054 (according to Chinese chronicles).

Discovered in 1731 by amateur astronomer John Bavis.

Link between the nebula and the archival Chinese “Guest star” was supposed by K.Lundmark in 1921.

Confirmed as the supernova type I remnant in 1942 (Dyuvendak; Mayall & Oort; Baade; Minkowski).

In 1968, the ***Crab pulsar*** was discovered near the center of the nebula (in radio and X-rays).

Theory before the discovery

- T.E.Sterne (1933) – first model EOS (equation of state) of nuclear matter; prediction of the ***neutronization*** with increasing density.
- F.Zwicky ["On collapsed neutron stars," *Astrophys. J.* **88** (1938) 522]
  – estimate of the maximum ***binding energy*** of a neutron star;
  – difference between M_b and M;
  – "enormous *gravitational red shifts*"
- R.C.Tolman; J.R.Oppenheimer & G.M.Volkoff (*Phys. Rev.*, 3.01. – 15.02.1939)
  – ***"TOV equation"*** (hydrostatic equilibrium of a spherically symmetric star).
  O.&V.: ***maximum mass*** of a neutron star (in the model of non-interacting neutrons $M_{\max} = 0.71\ M_{\odot} < \mathrm{M}_{\max}(\mathrm{WD}) = 1.44\ M_{\odot}$).
- ***EOS for dense matter***. J.A.Wheeler, B.K.Harrison, *et al.* (1950s).
  A.G.W.Cameron (1959) – nuclear forces ($\mathrm{M}_{\max} \sim 2\ M_{\odot}$); hyperons.
  Ya.B.Zeldovich (1961) – maximally stiff EOS model.
- ***Superfluidity***. BCS: J.Bardeen, L.N.Cooper, & J.R.Schrieffer (1957).
  A.Bohr, B.R.Mottelson, & D.Pines, "Possible analog between the excitation spectra of nuclei and those of superconducting metal state," [*Phys. Rev.* **110** (1958) 936].
  A.B.Migdal (1959), V.L.Ginzburg & D.A.Kirzhnits (1964):
  $T_c \sim 10^{10}$ K, $\rho \sim 10^{13} – 10^{15}$ g/cc.
- ***Neutrino emission***. H.-Y.Chiu & E.E.Salpeter (1964); J.N.Bahcall & R.A.Wolf (1965).
- ***Cooling***. R.Stabler (1960, PhD); Chiu (1964); Chiu & Salpeter (1964); D.C.Morton (1964), Bahcall & Wolf; S.Tsuruta & A.G.W.Cameron (1966).

Search and discovery

- ***Search in X-rays***. *T* ~ 10^6 K => X-rays => space observations.

R.Giacconi et al. (1962): discovery of Sco X-1 (Nobel Prize of 2002 to Giacconi for outstanding contribution to X-ray astronomy) .

I.S.Shklovsky (1967): Sco X-1 – “a neutron star in a state of accretion” (correct, *but* unnoticed).

- ***Plerion pulsar nebulae.*** S.Bowyer et al. (1964): X-ray source in the Crab nebula ~ 10^{13} km (=> *not* a neutron star).

N.S.Kardashev (1964), F.Pacini (1967): models of a nebula around a rapidly rotating strongly magnetized neutron star. Pacini – ***pulsar model***.

- ***Radio observations***. 1962, 1965 (A.Hewish) – pulsar in the Crab nebula, *but* unexplained and unnoticed.

6.08 – 28.11.1967: Jocelyn Bell, Anthony Hewish

– discovery of pulsars

(Nobel prize of 1974 to Hewish)

By 1969 it has become clear that pulsars are rapidly rotating neutron stars with strong magnetic fields (Thomas Gold, 1968).

Neutron stars from a hypothesis turned into reality.

Jocelyn Bell and the telescope in Cambridge, England, used to discover pulsars in 1967–68.

Image Credit: *Jocelyn Bell Burnell*

6.08 – 28.11.1967: Jocelyn Bell, Anthony Hewish
– discovery of pulsars

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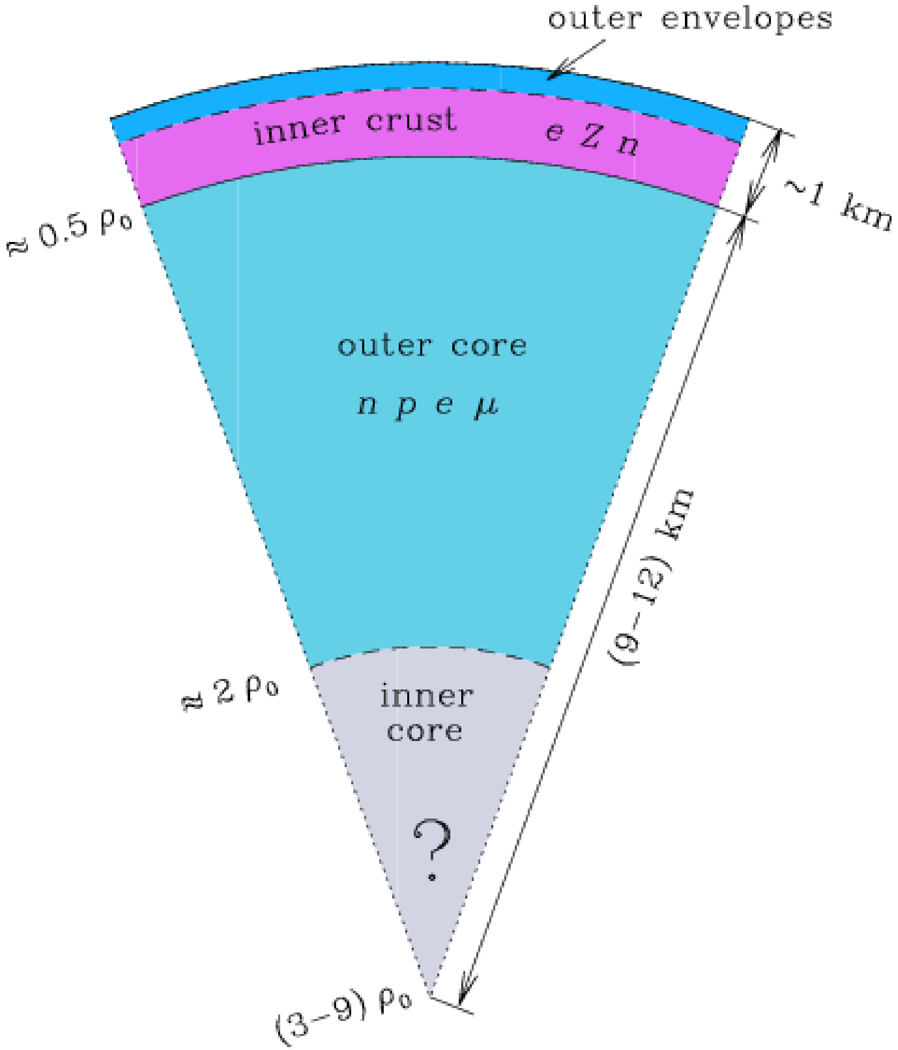
Neutron stars from a hypothesis turned into reality.

Neutron-star structure



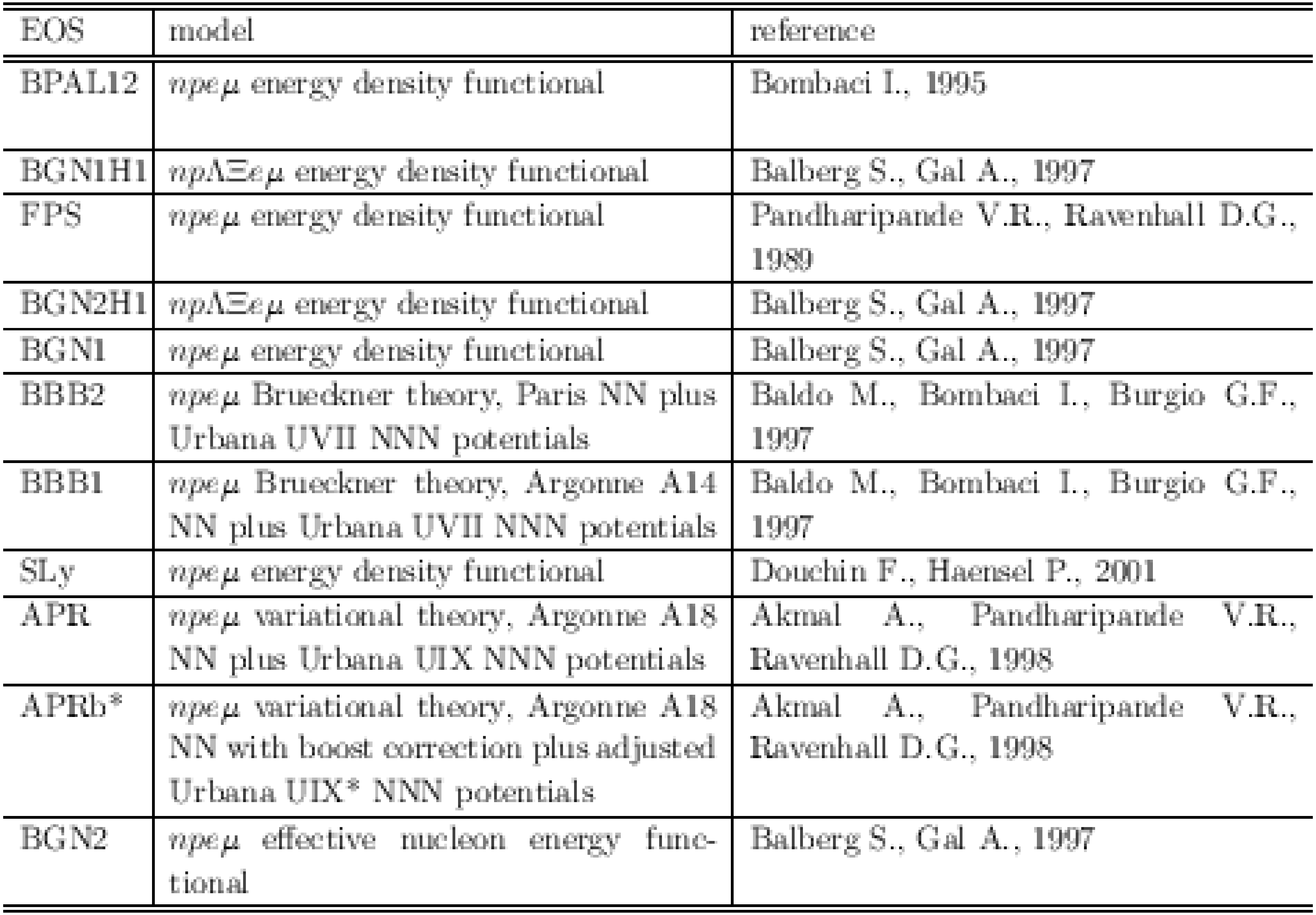
Hypotheses about the inner core

- ***Hyperonization*** – appearance of hyperons, first of all Λ и Σ^-.
- ***Pion condensation*** – Bose-condensation of π-meson-like collective excitations.
- ***Kaon condensation*** (K-meson-like excitations with strangeness)
- ***Phase transition*** to the ***quark matter*** composed of light deconfined u, d, s quarks and small admixture of electrons.

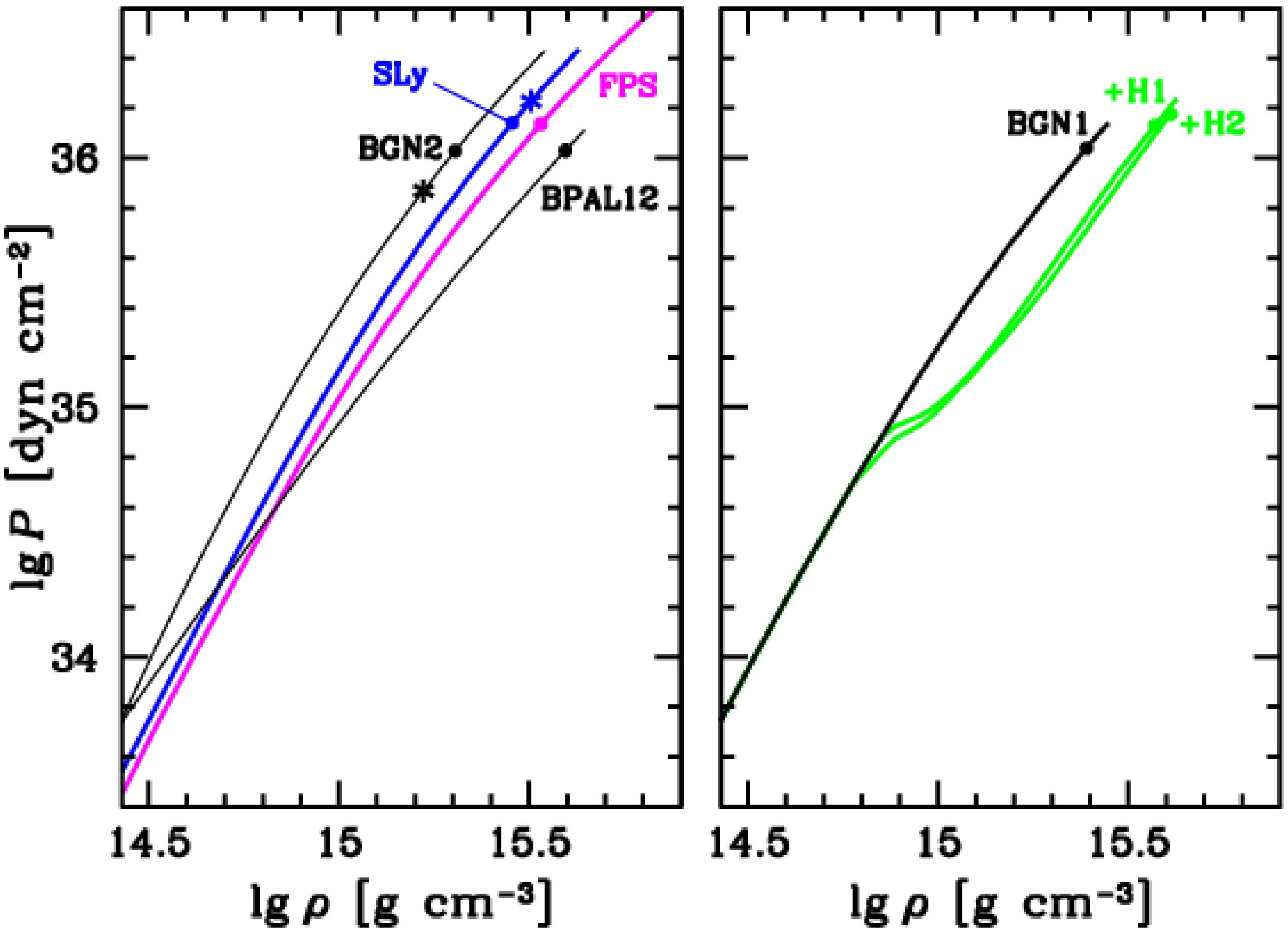
- ✓ Hypotheses 2 – 4 are known as ***exotic models*** *of dense matter*.
- ✓ *Composition* of the inner core affects *EOS* and *neutrino cooling rate.*
- ✓ *Superfluidity* in the core affects *cooling rate* and *mechanical properties*.
- ✓ *Phase transitions* may result in *EOS softening*.

Some modern models of the EOS of superdense matter

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



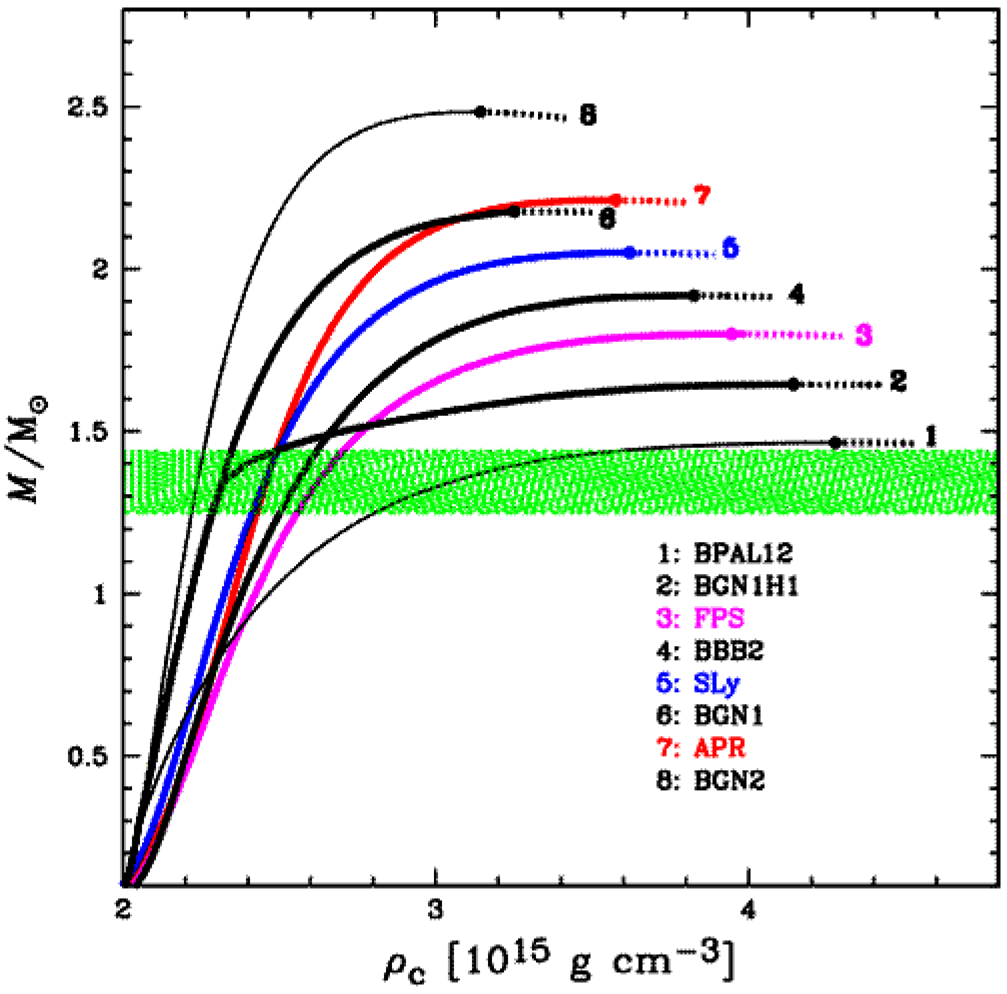
EOS	model	reference
BPAL12	$npe\mu$ energy density functional	Bombaci I., 1995
BGN1H1	$np\Lambda\Xi e\mu$ energy density functional	Balberg S., Gal A., 1997
FPS	$npe\mu$ energy density functional	Pandharipande V.R., Ravenhall D.G., 1989
BGN2H1	$np\Lambda\Xi e\mu$ energy density functional	Balberg S., 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



Examples of EOSs for the neutron star core.

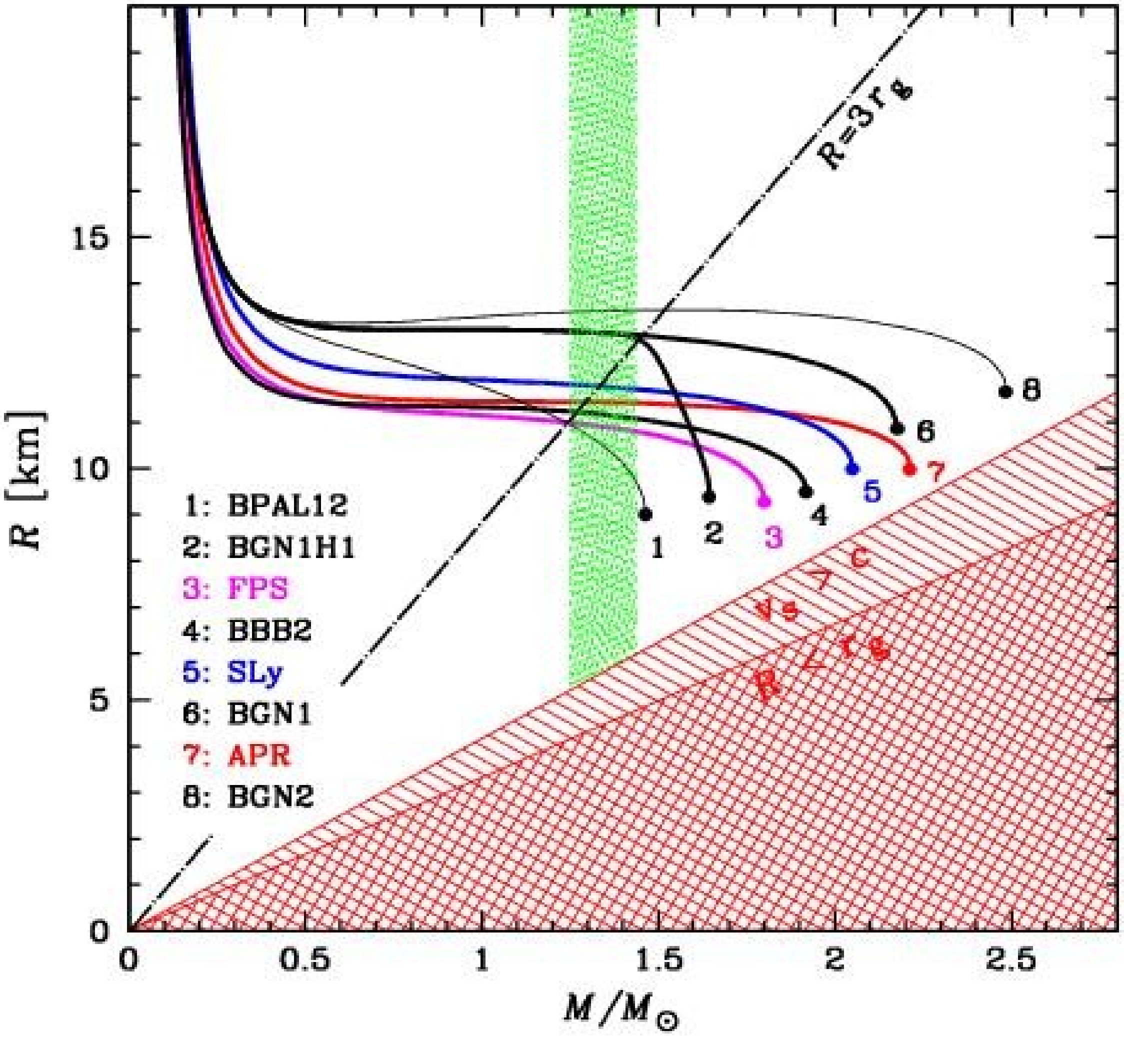
Dots – stellar stability limit, asterisks – causal limit (i.e., where speed of sound = speed of light).

Neutron star models



Dependence of stellar mass on central density for different EOSs

Neutron star models



Stellar mass–radius relation for different EOSs

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

Neutrino emission from neutron stars

D.G.Yakovlev *et al.*, *Phys.Rep.* **354** (2001) 1

Inner cores of massive neutron stars:

Nucleons, hyperons	$n \to p + e + \bar{\nu}_e$ $p + e \to n + \nu_e$	$Q \sim 3\times10^{27} T_9^6 \, \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{46} T_9^6 \, \frac{erg}{s}$
Pion condensates	$\tilde{n} \to \tilde{p} + e + \bar{\nu}_e$ $\tilde{p} + e \to \tilde{n} + \nu_e$	$Q \sim 10^{24-26} T_9^6 \, \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{42-44} T_9^6 \, \frac{erg}{s}$
Kaon condensates	$\tilde{n} \to \tilde{p} + e + \bar{\nu}_e$ $\tilde{p} + e \to \tilde{n} + \nu_e$	$Q \sim 10^{23-24} T_9^6 \, \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{41-42} T_9^6 \, \frac{erg}{s}$
Quark matter	$d \to u + e + \bar{\nu}_e$ $u + e \to d + \nu_e$	$Q \sim 10^{23-24} T_9^6 \, \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{41-42} T_9^6 \, \frac{erg}{s}$

Everywhere in neutron star cores:

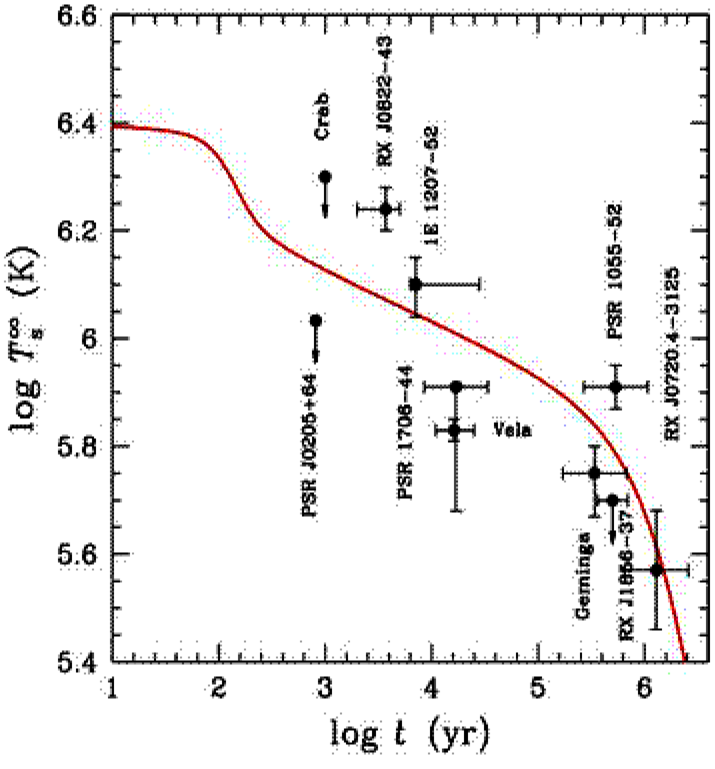
Modified Urca (Murca)	$n + N \to p + e + N + \bar{\nu}_e$ $p + e + N \to n + N + \nu_e$	$Q \sim 10^{20-22} T_9^8 \, \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{38-40} T_9^8 \, \frac{erg}{s}$
Brems-strahlung	$N + N \to N + N + \nu + \bar{\nu}$	$Q \sim 10^{18-20} T_9^8 \, \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{36-38} T_9^8 \, \frac{erg}{s}$

⇩

$\nu_e,\ \nu_\mu,\ \nu_\tau$

Thermal evolution

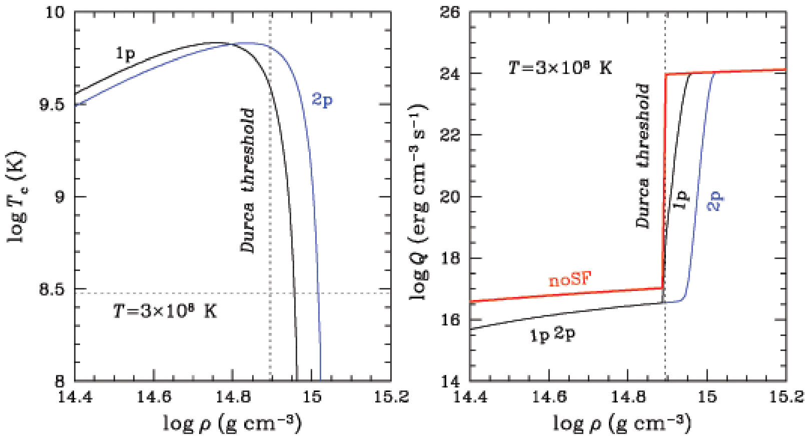
"Basic cooling curve"
of a neutron star
(no superfluidity, no exotica)

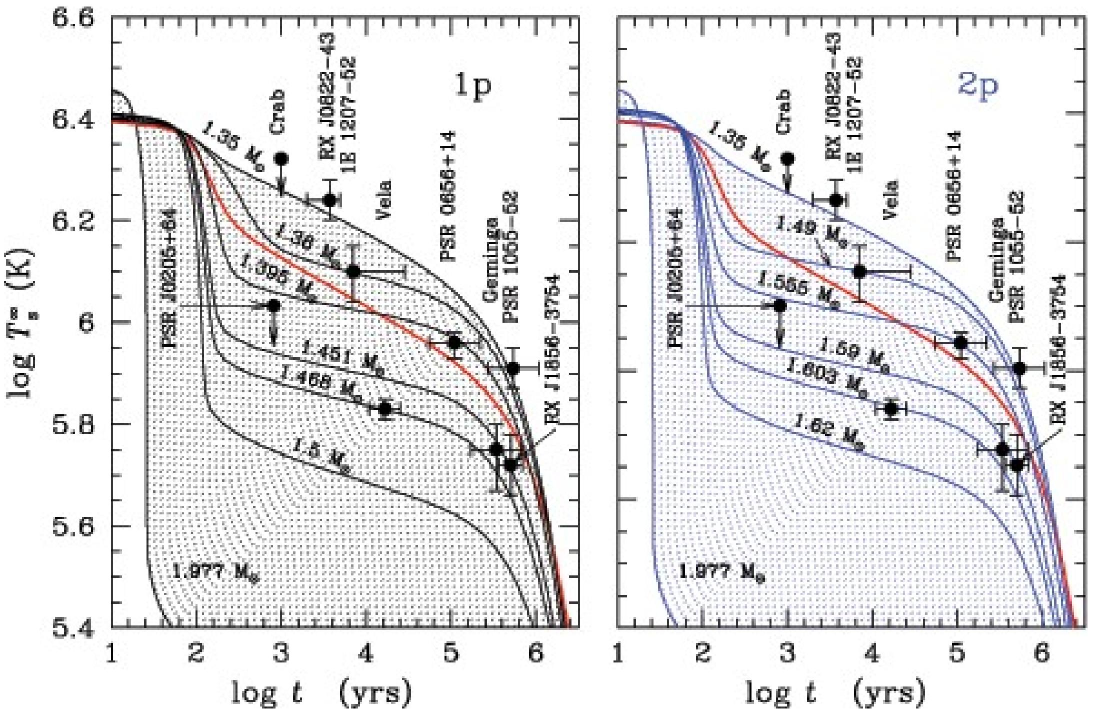


Neutron star cooling

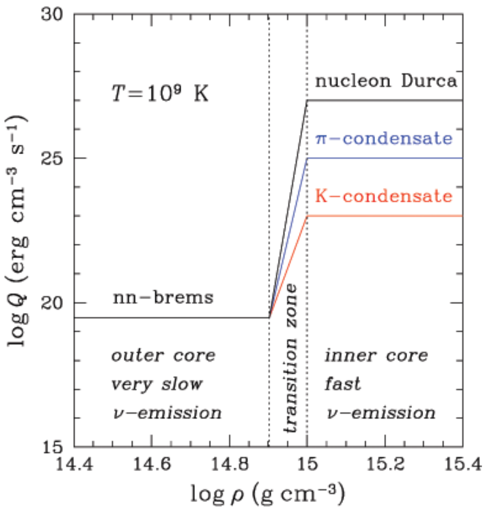
[Yakovlev *et al*. (2005) *Nucl. Phys. A* **752**, 590c]

Cooling of neutron stars
with proton superfluidity in the cores



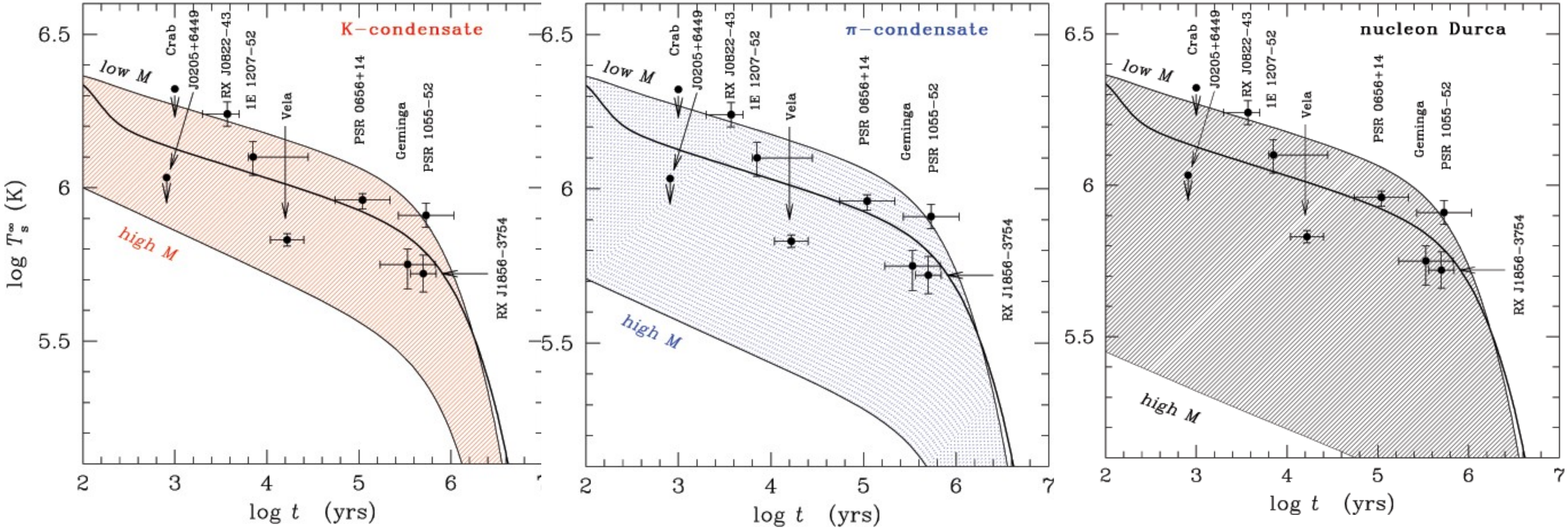


Thermal evolution



Cooling of neutron stars with nucleon and exotic cores

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



Observational instruments

Optical and radio telescopes on the Earth


The Arecibo radio telescope

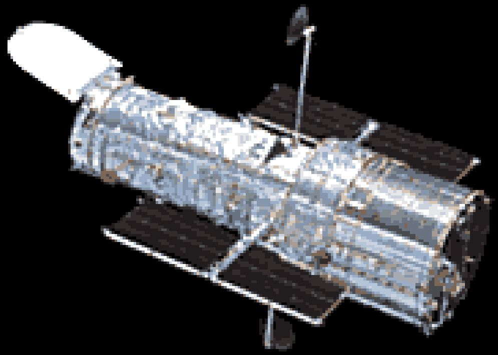

The VLT


The Parkes radio telescope

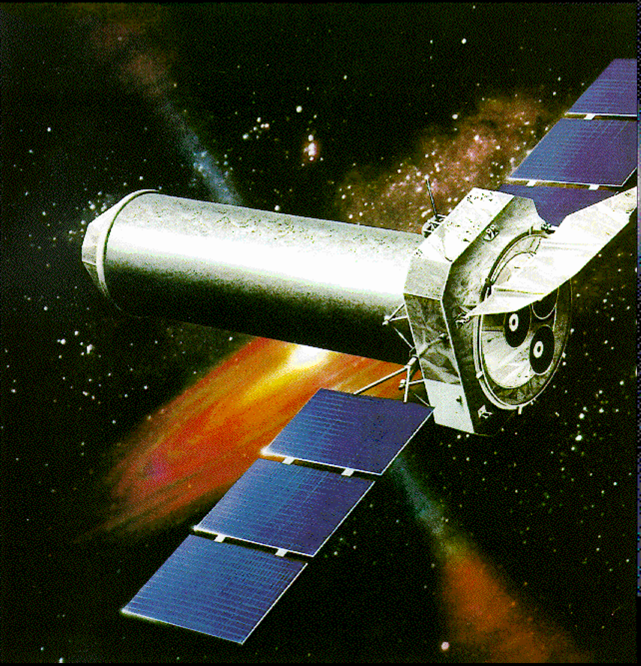

The VLA

Observational instruments

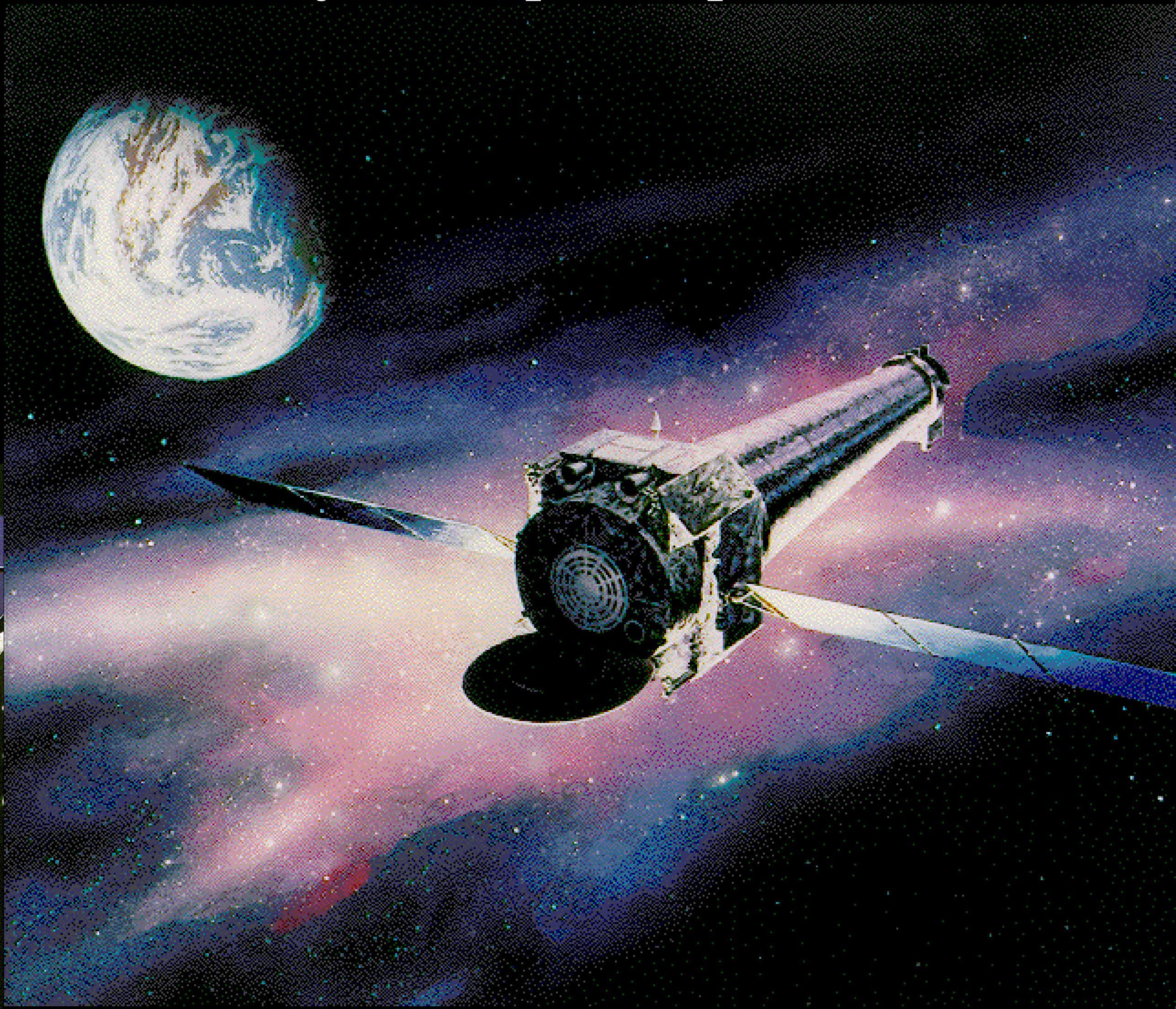
Optical–UV and X-ray telescopes in space



Hubble Space Telescope

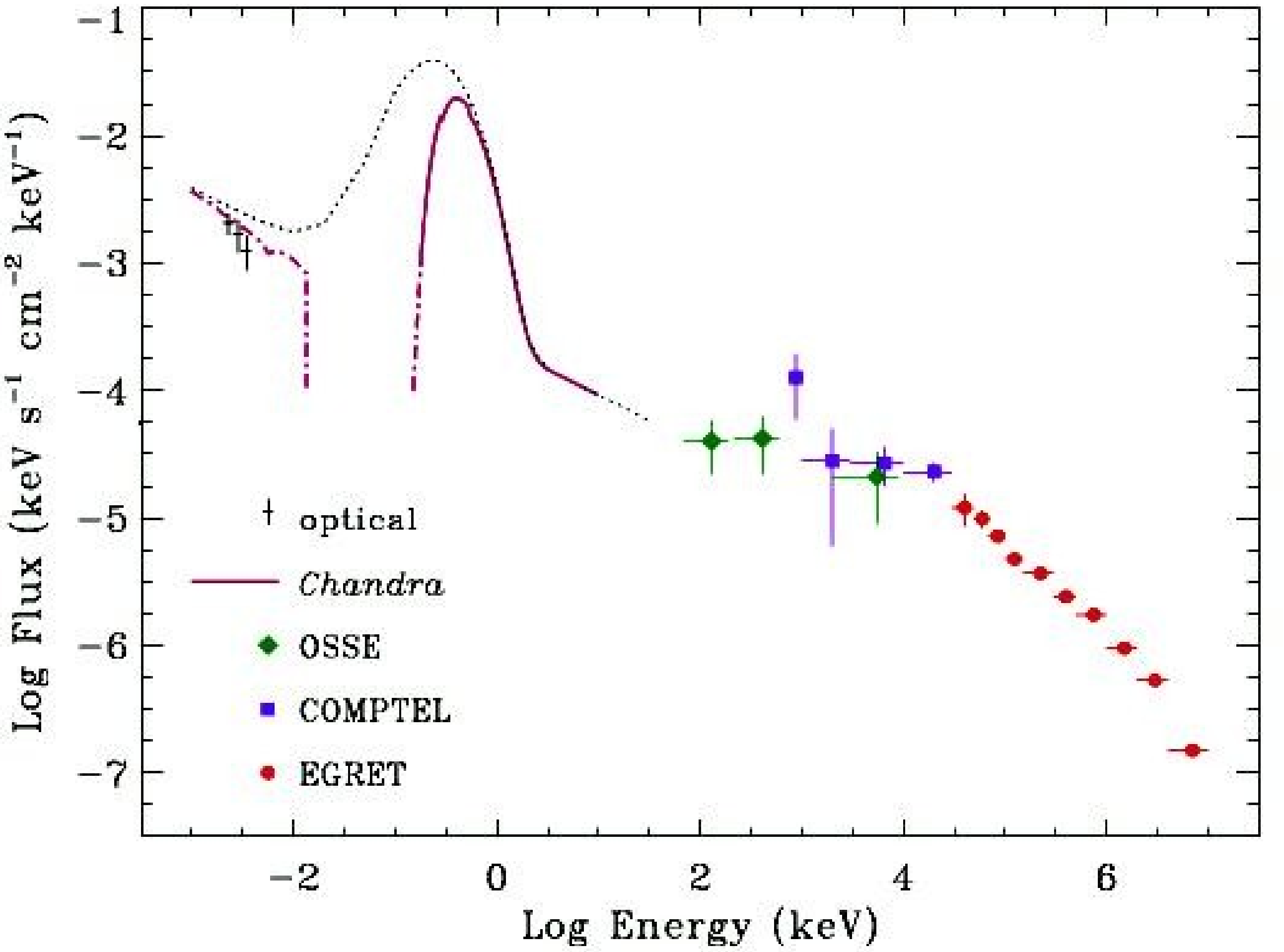


XMM-Newton



Chandra

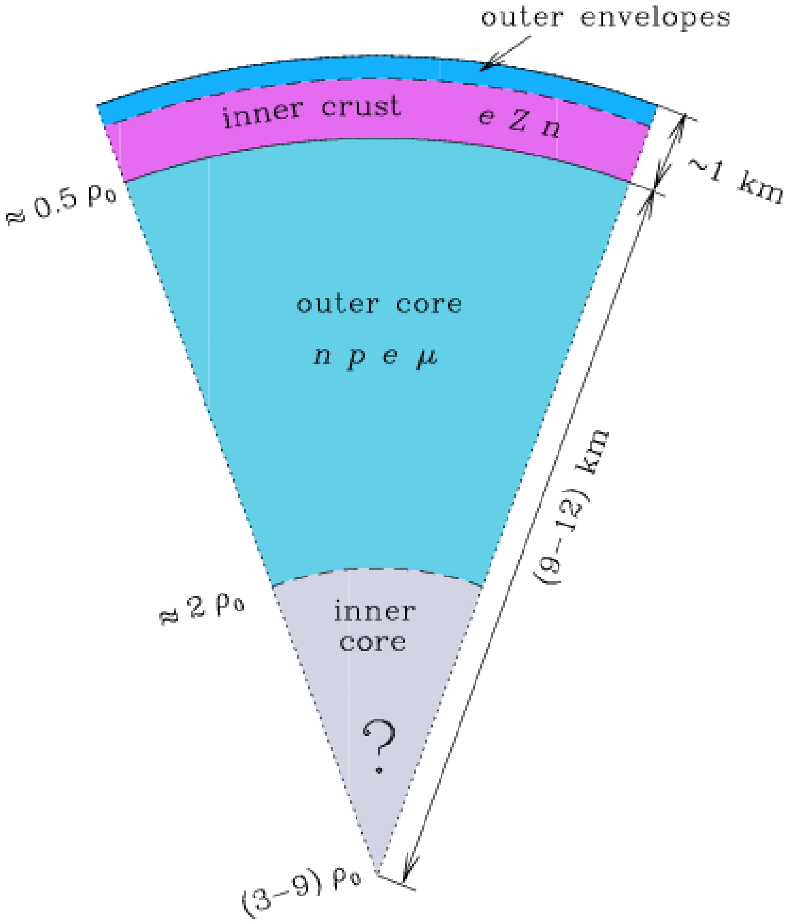
Multiwavelength spectrum of a neutron star



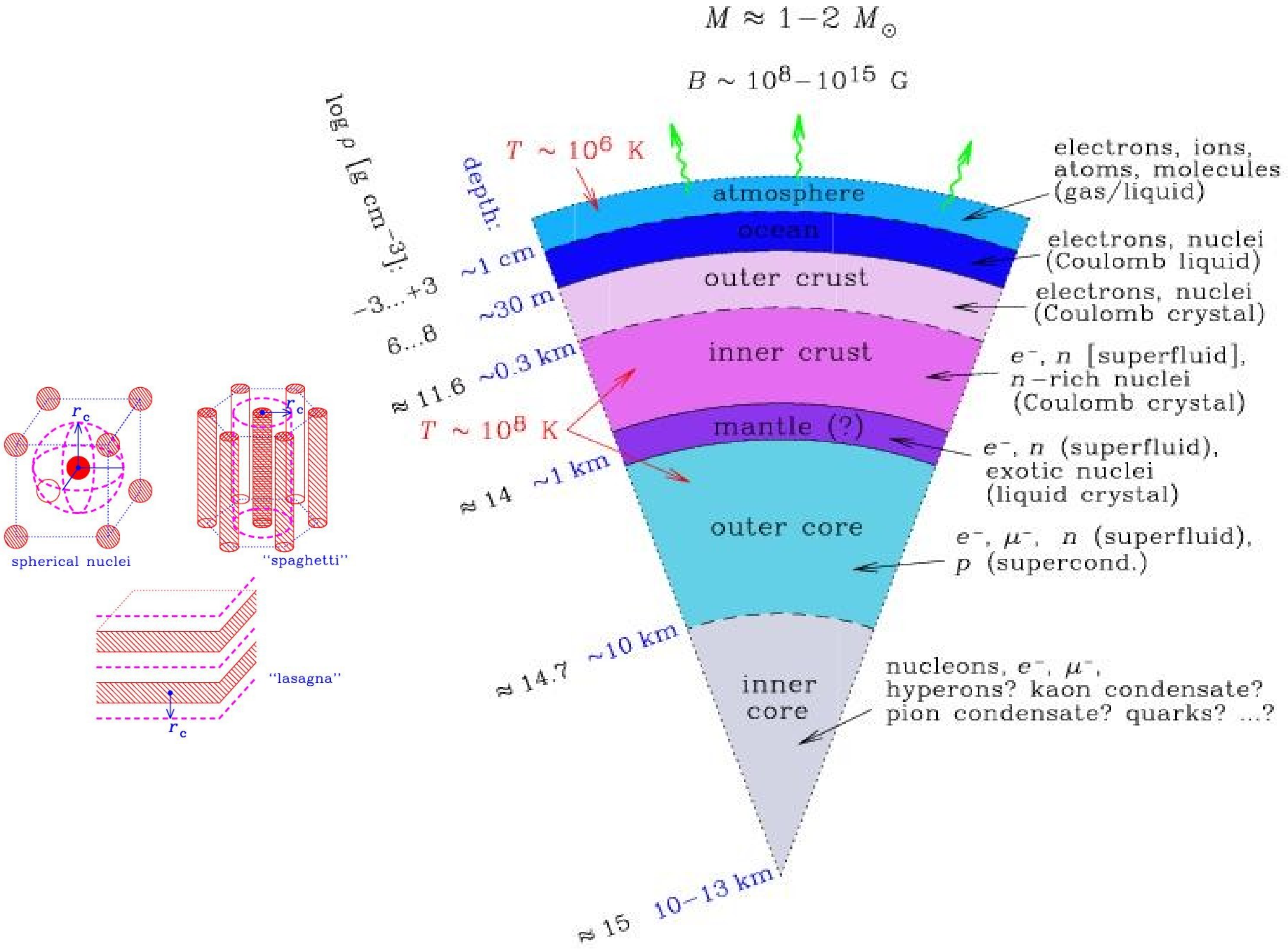
Multiwavelength spectrum of the Vela pulsar

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

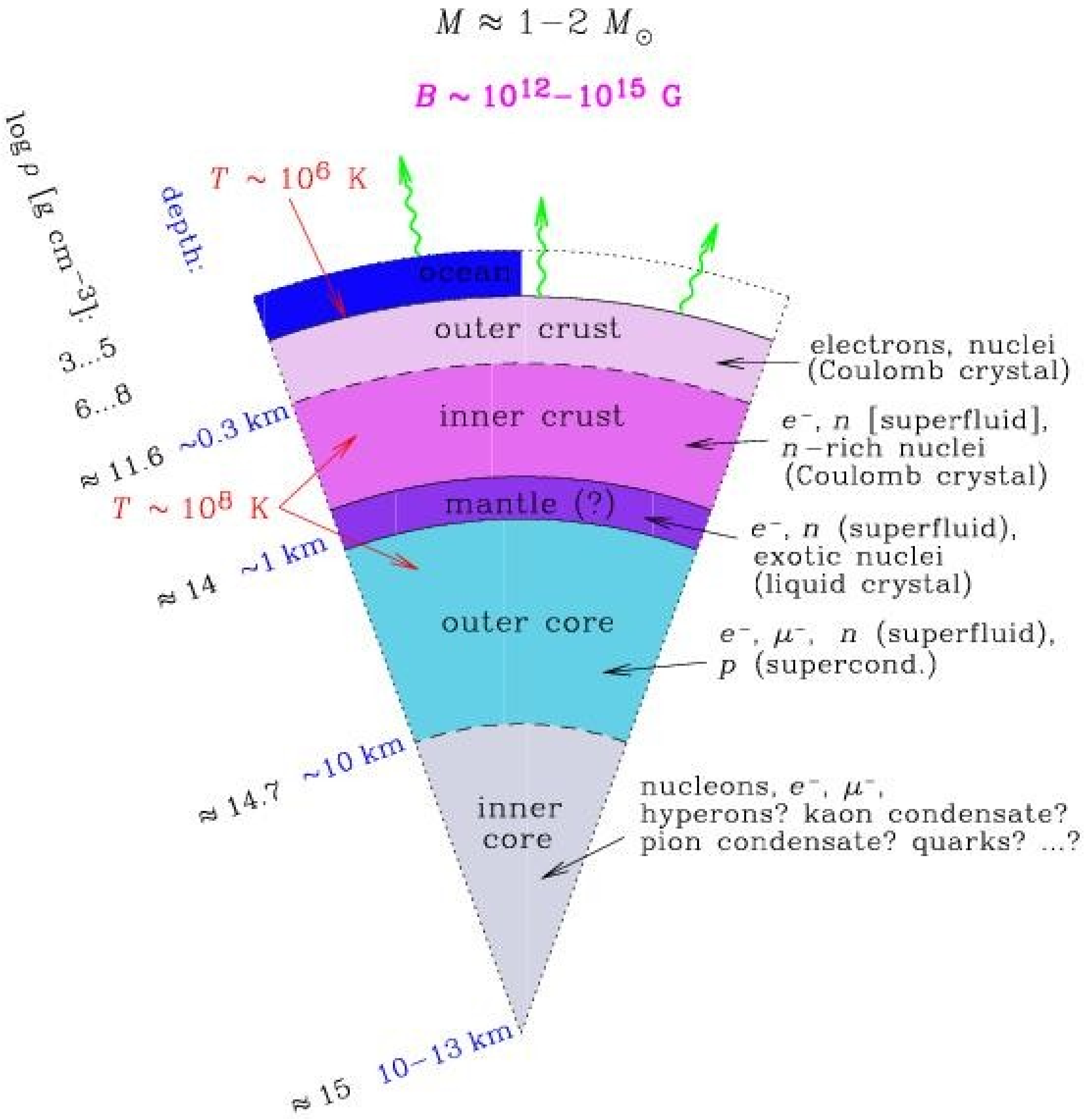
Neutron star structure



Neutron star structure in greater detail



Neutron star without atmosphere: possible result of a phase transition



The role and importance of the envelopes

- 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

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 :

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

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

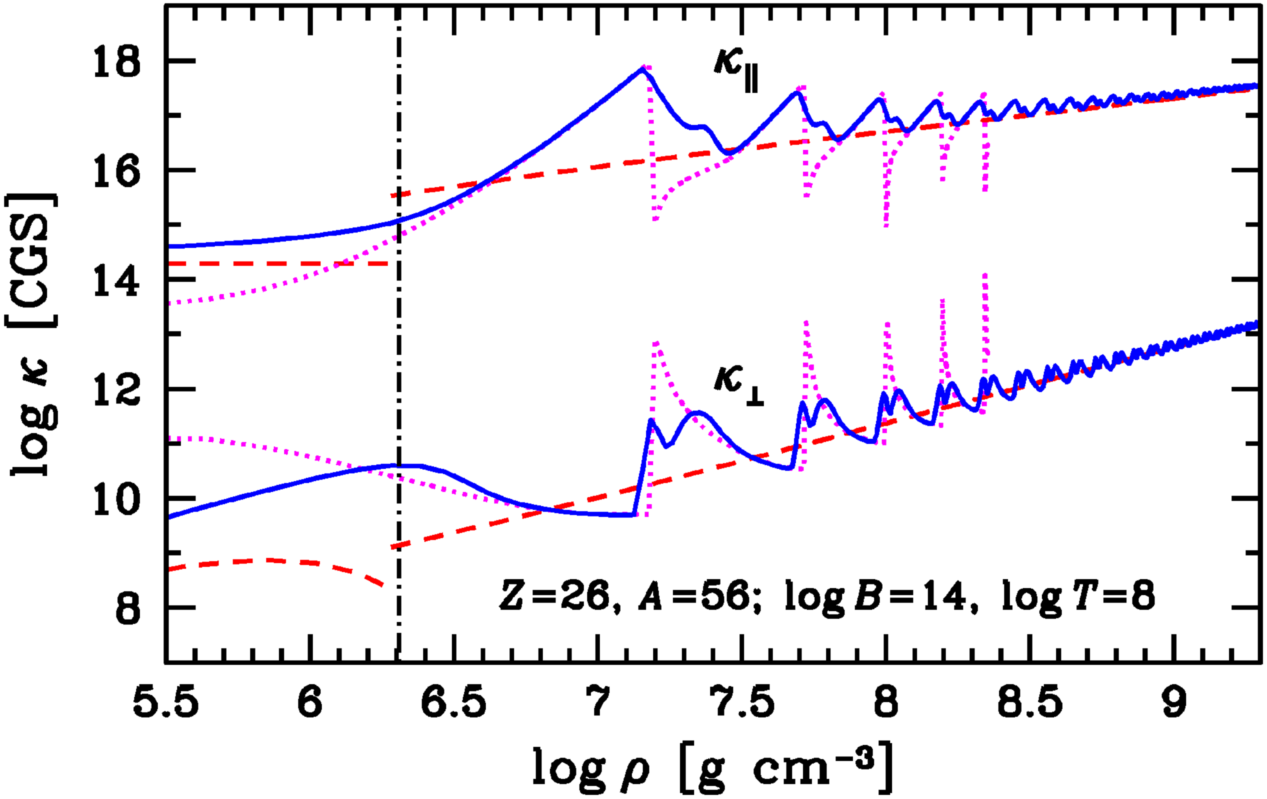
- Strongly quantizing magnetic field :

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

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

Thermal conductivities in a strongly magnetized envelope

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



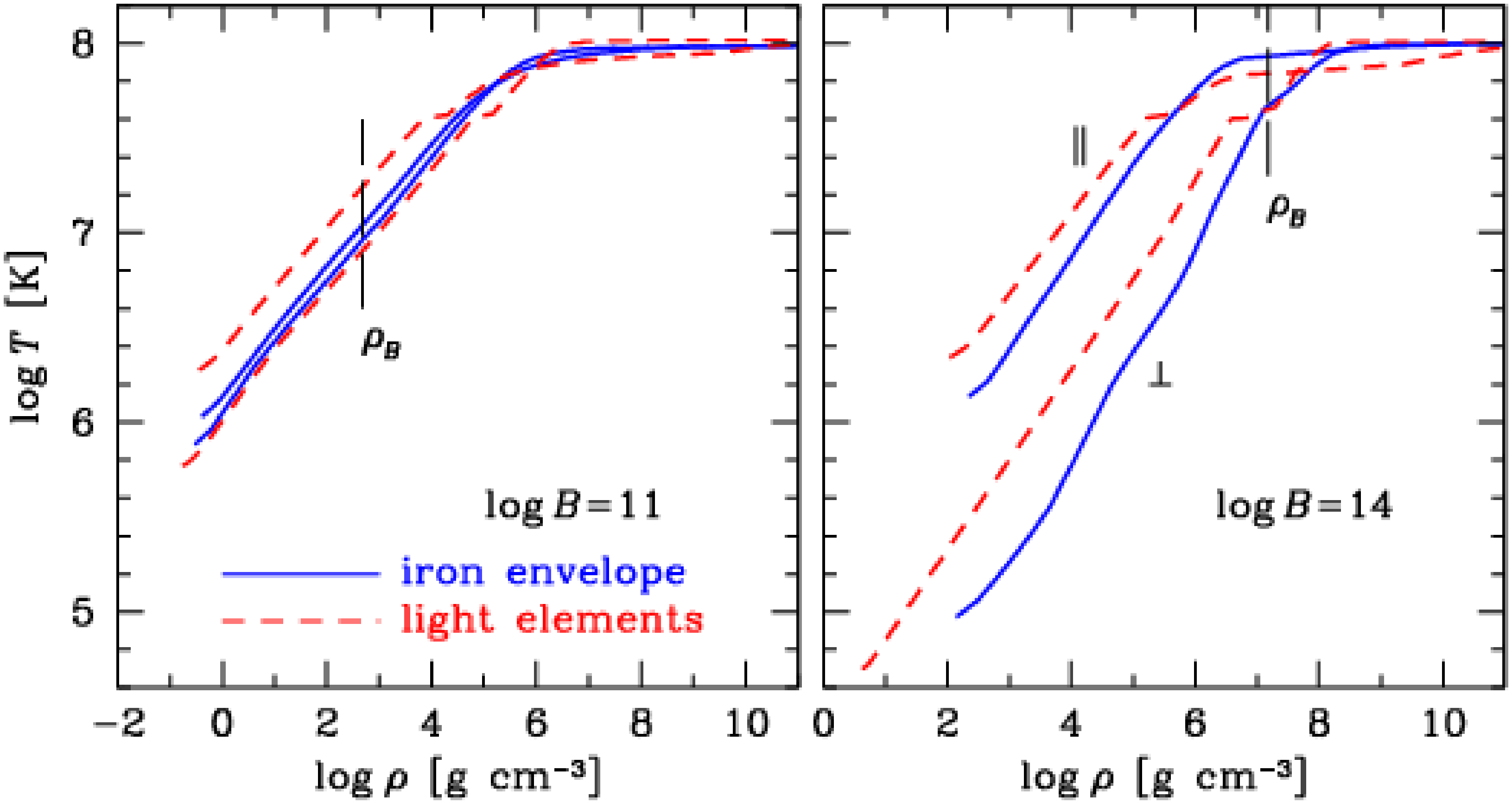
Solid – exact, dots – without *T*-integration, dashes – magnetically non-quantized

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

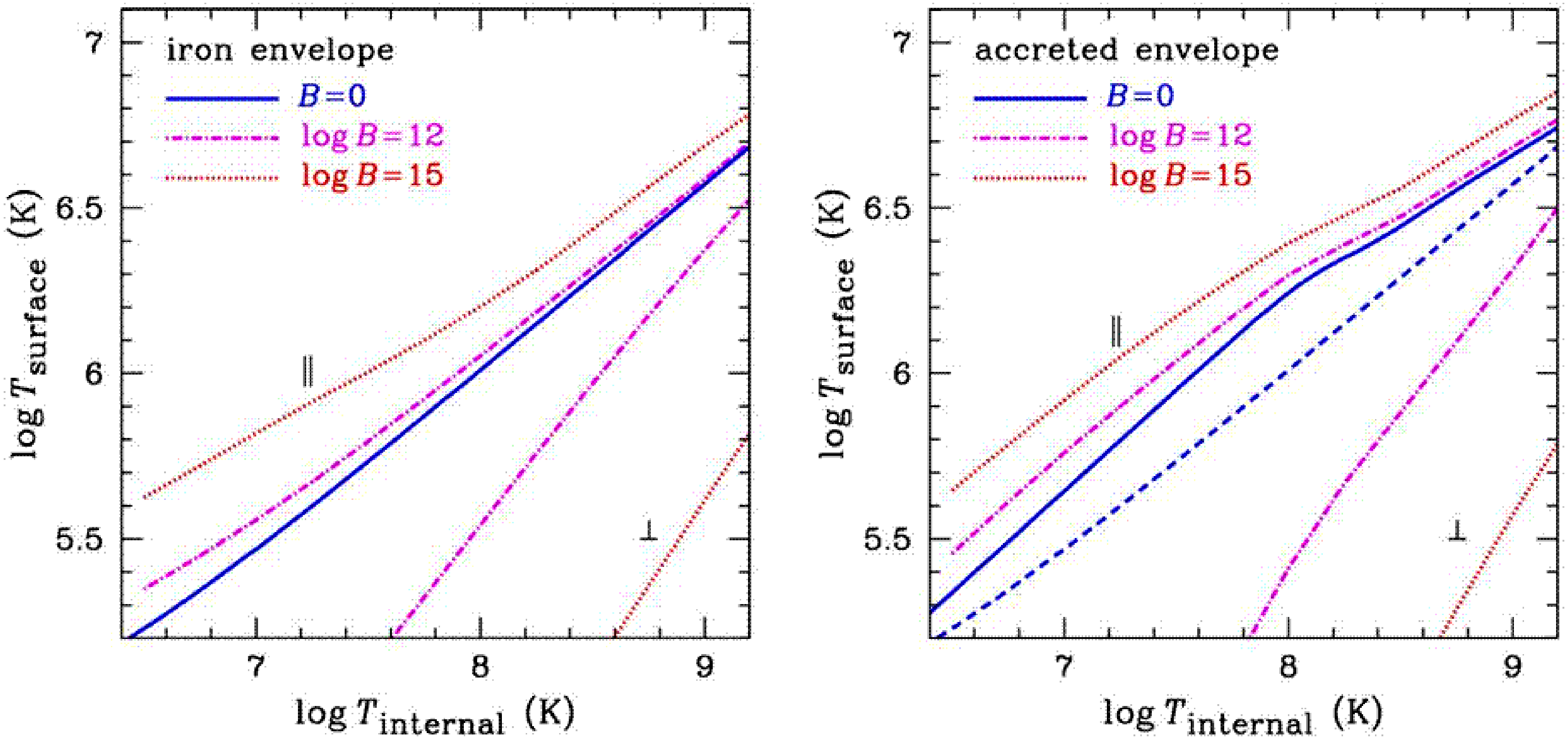
Heat flux: $\boldsymbol{F} = -\kappa_\parallel \nabla_\parallel T - \kappa_\perp \nabla_\perp T - \kappa_\wedge \boldsymbol{b} \times \nabla T, \quad \boldsymbol{b} = \frac{\boldsymbol{B}}{B}$

Temperature profiles in envelopes of neutron stars with strong magnetic fields



$T_s - T_b$

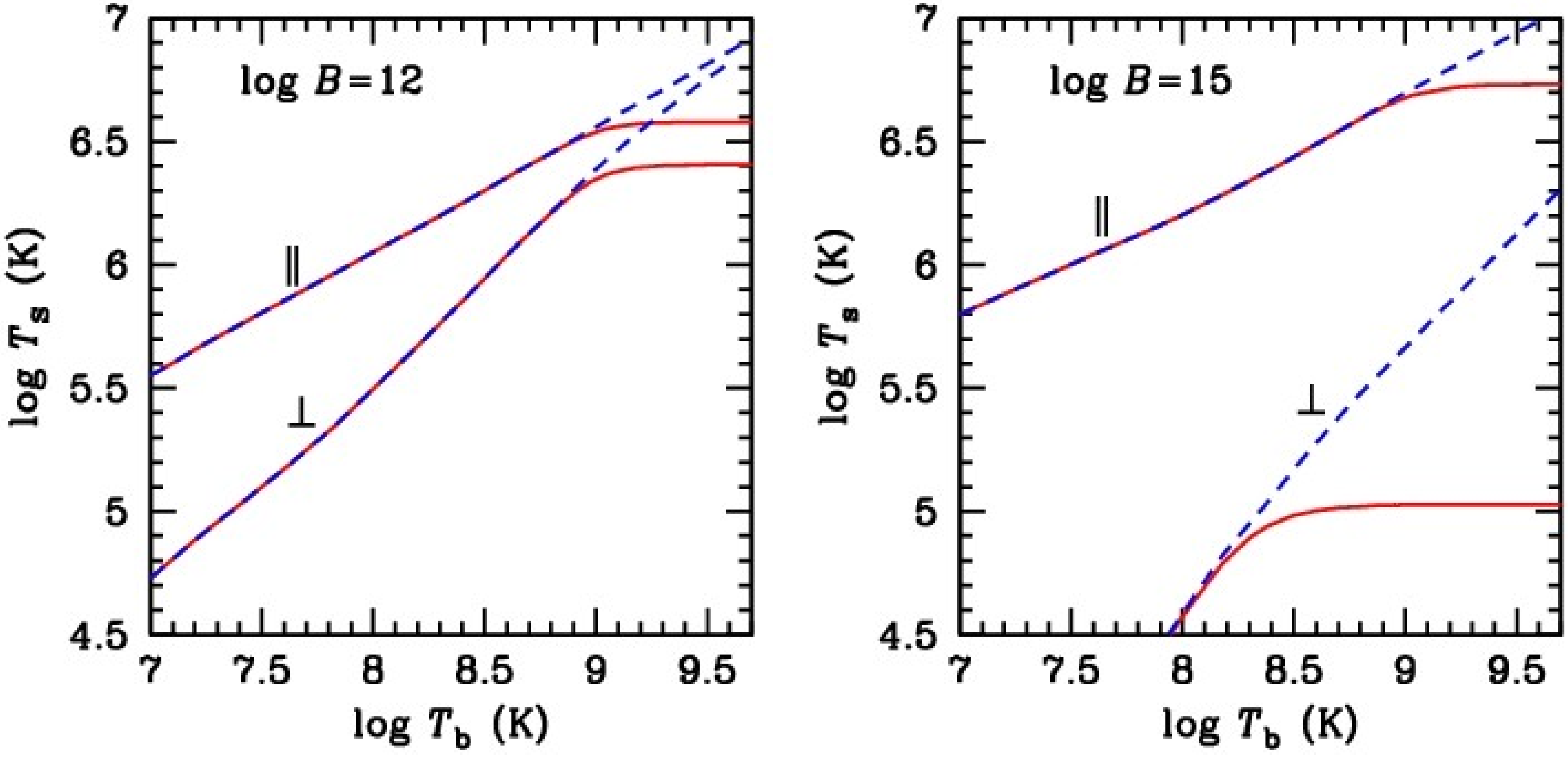
Temperature drops in magnetized envelopes of neutron stars



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

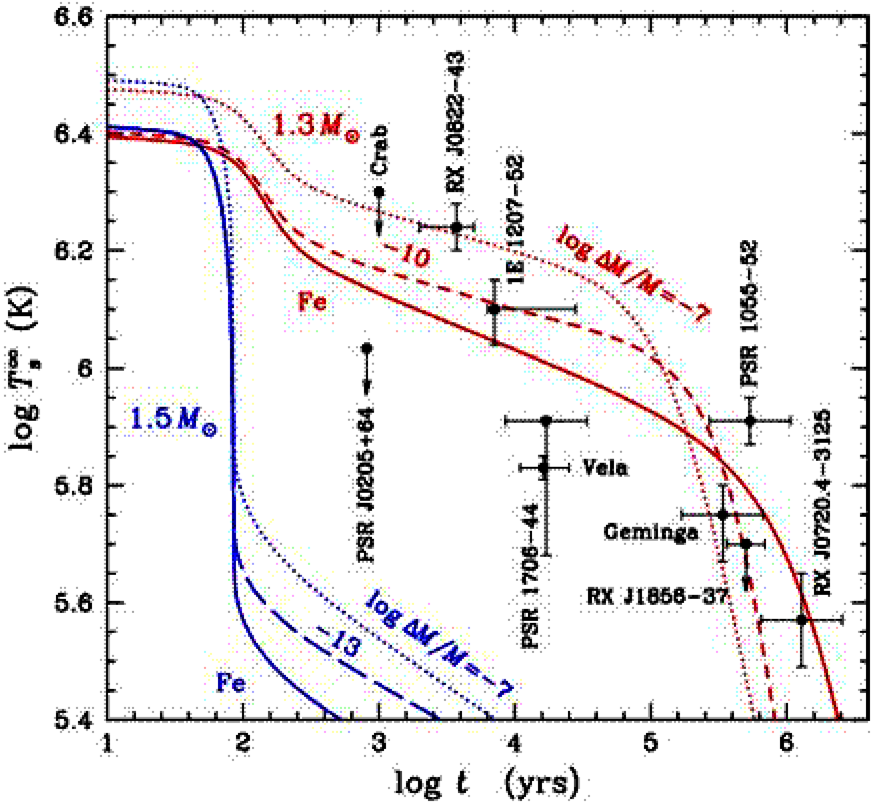
$T_s – T_b$

The effect of neutrino emission in the outer envelope

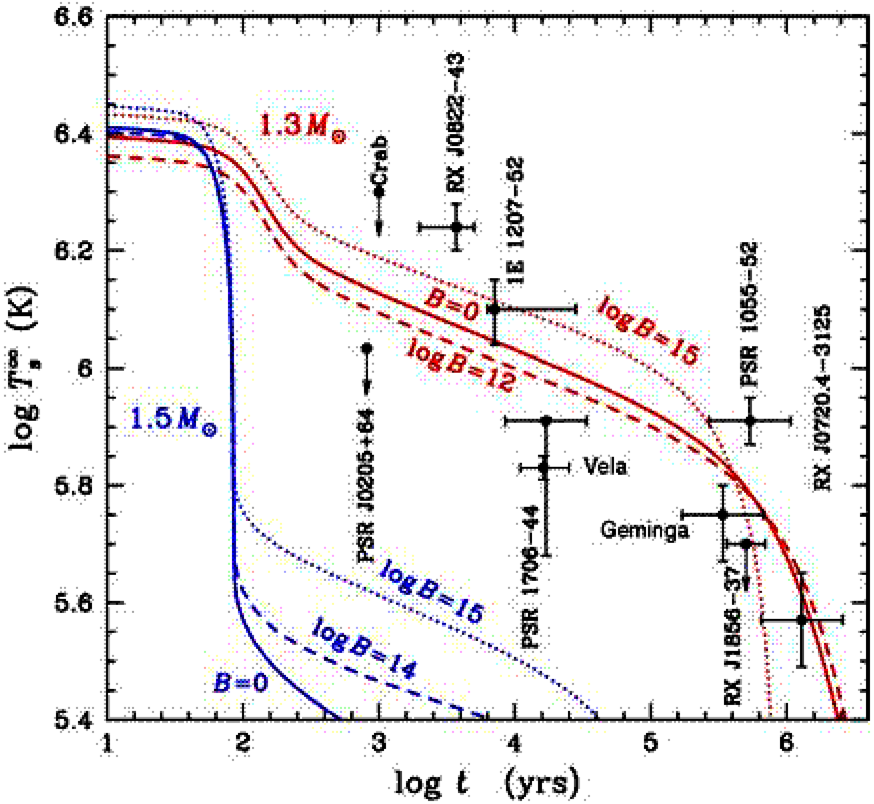


Effective temperature of the surface as a function of the internal temperature with account of the neutrino emission

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



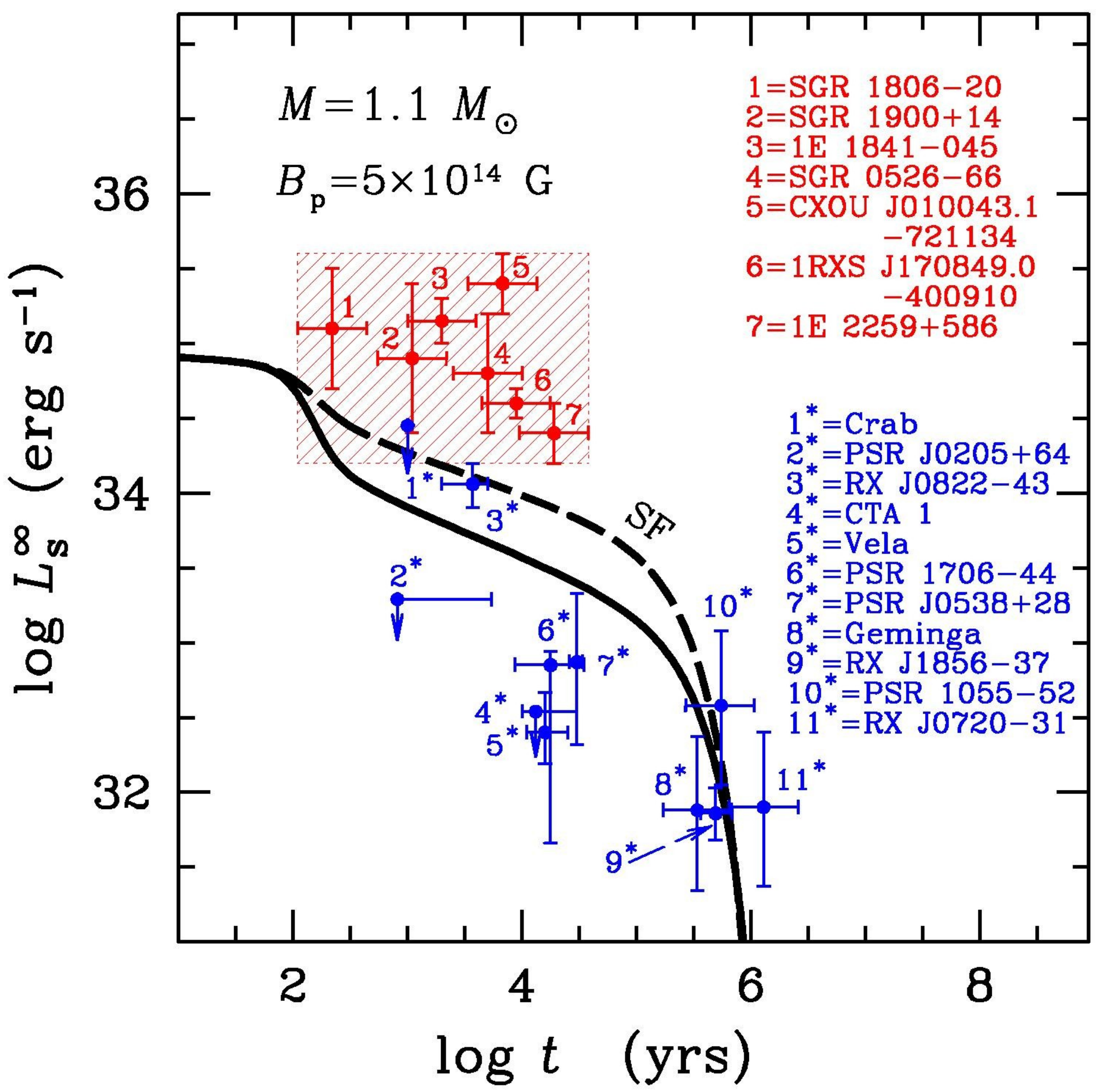
Cooling of neutron stars with ***magnetized envelopes***



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

Magnetars versus ordinary neutron stars

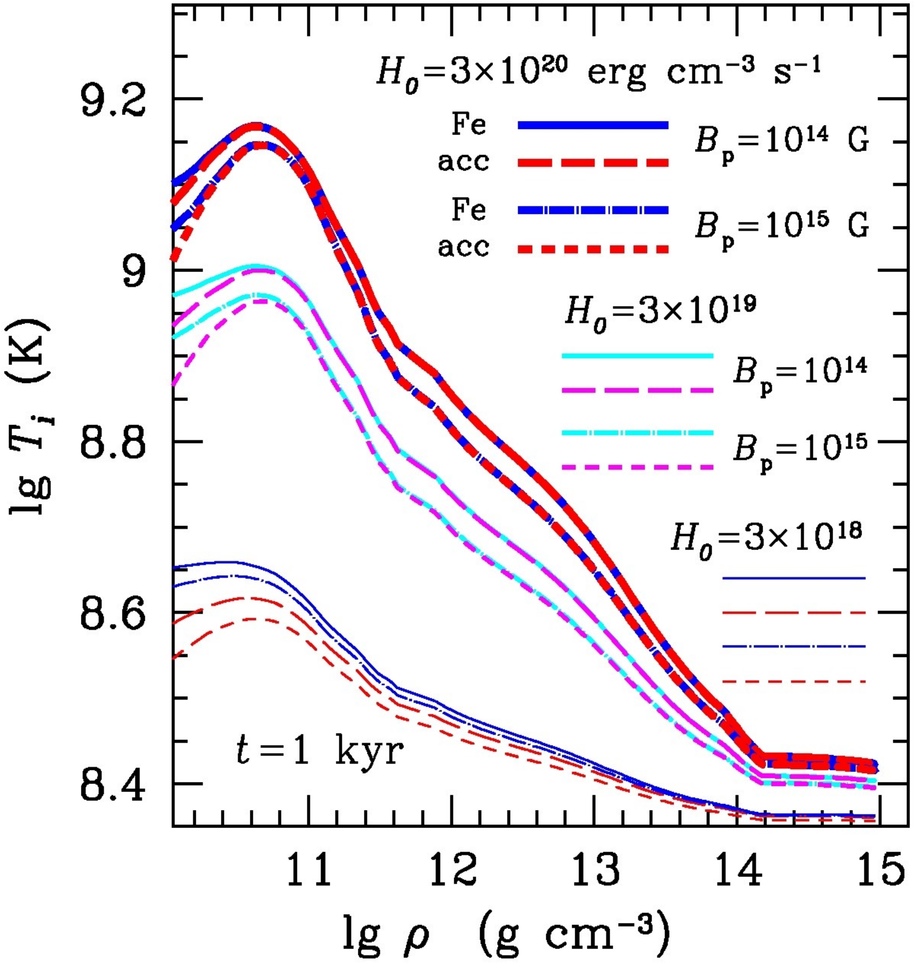
The need for heating



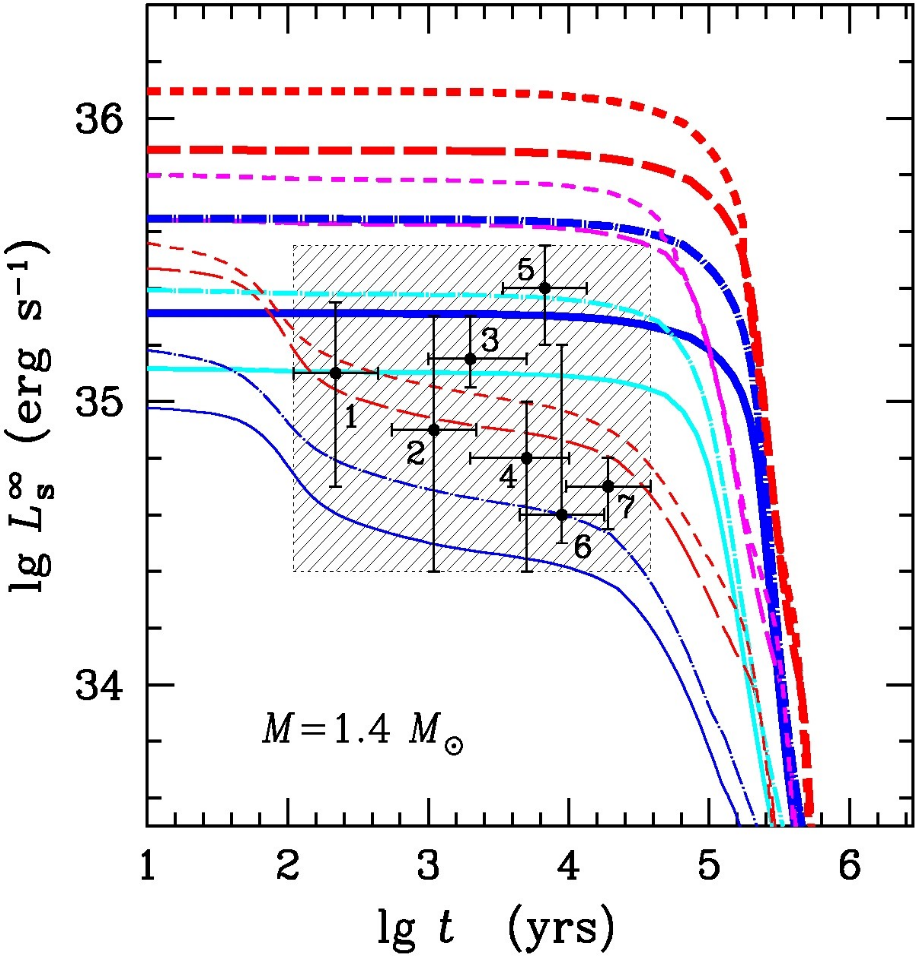
Thermal structure and cooling of magnetars

Different heating intensities, magnetic field strengths, envelope compositions

Thermal structure

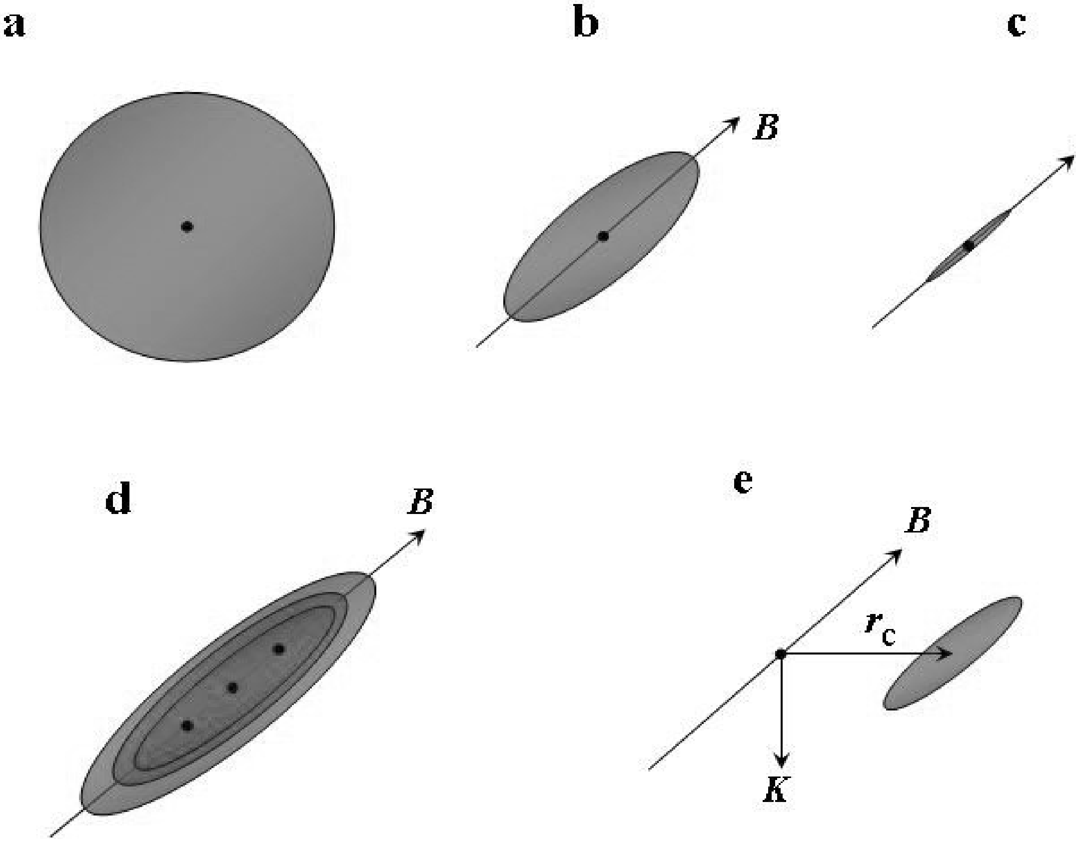


Cooling curves



A.D.Kaminker, A.Y.Potekhin, D.G.Yakovlev, & G.Chabrier, *Mon. Not. R. astr. Soc*. **395**, 2257 (2009)

Bound species in a strong magnetic field



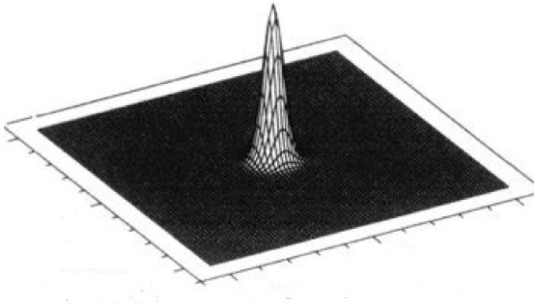
The effects of a strong magnetic field on the atoms and molecules.
a–c: H atom in the ground state (**a**: $B \ll 10^9$ G, **b**: $B \sim 10^{10}$ G, **c**: $B \sim 10^{12}$ G).

d: The field stabilizes the molecular chains (H_3 is shown).

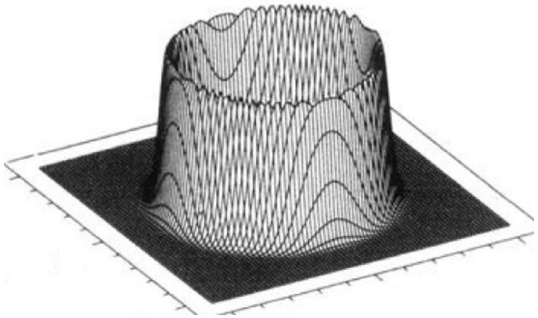
e: H atom moving across the field becomes decentered.

Bound species in a strong magnetic field

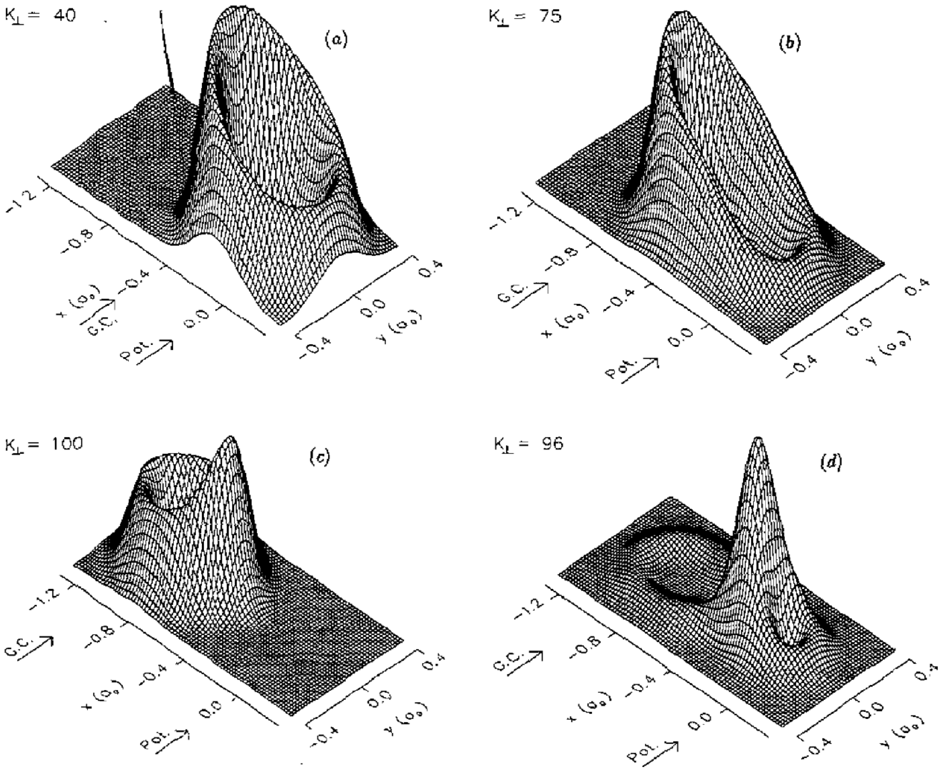
the ground state



an excited state

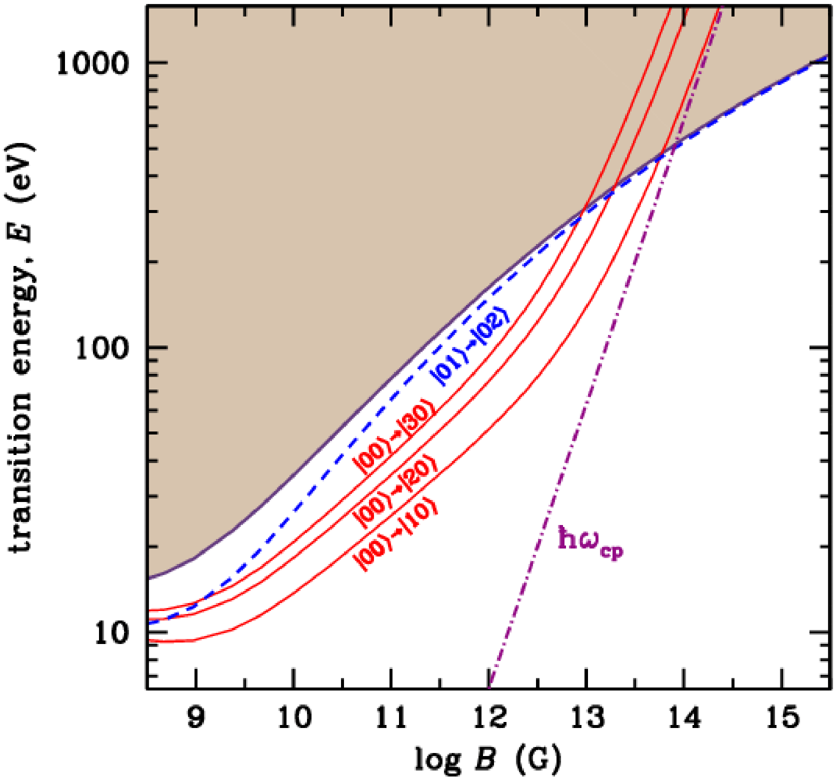


an excited state (m=–5) + center-of-mass motion
(“motional Stark effect”)

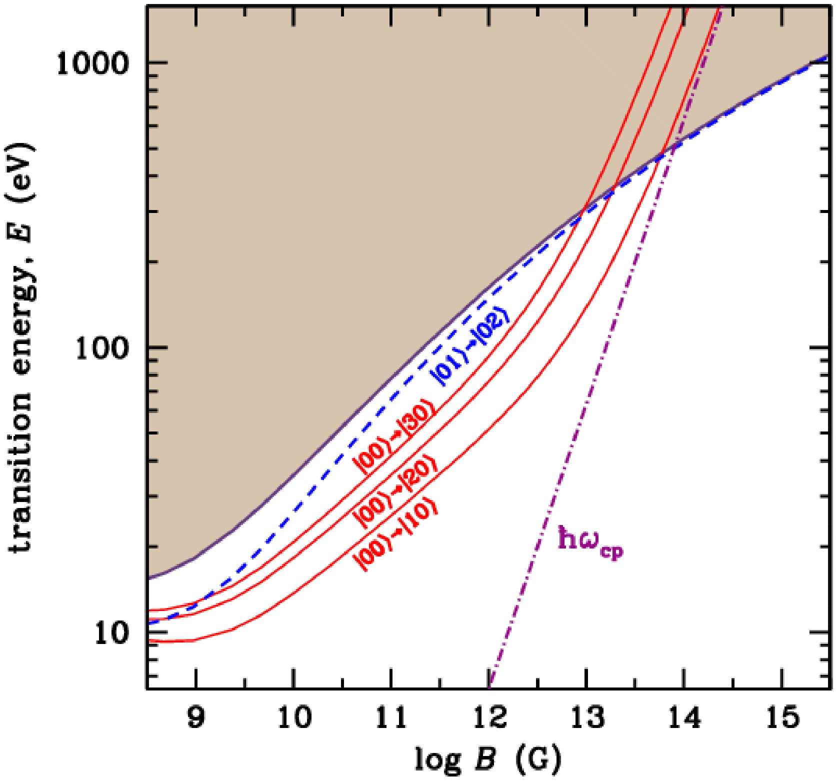


Squared moduli of the wave functions of a hydrogen atom at B=2.35×10^{11} G

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



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



Main transition energies of the hydrogen atom in a magnetic field
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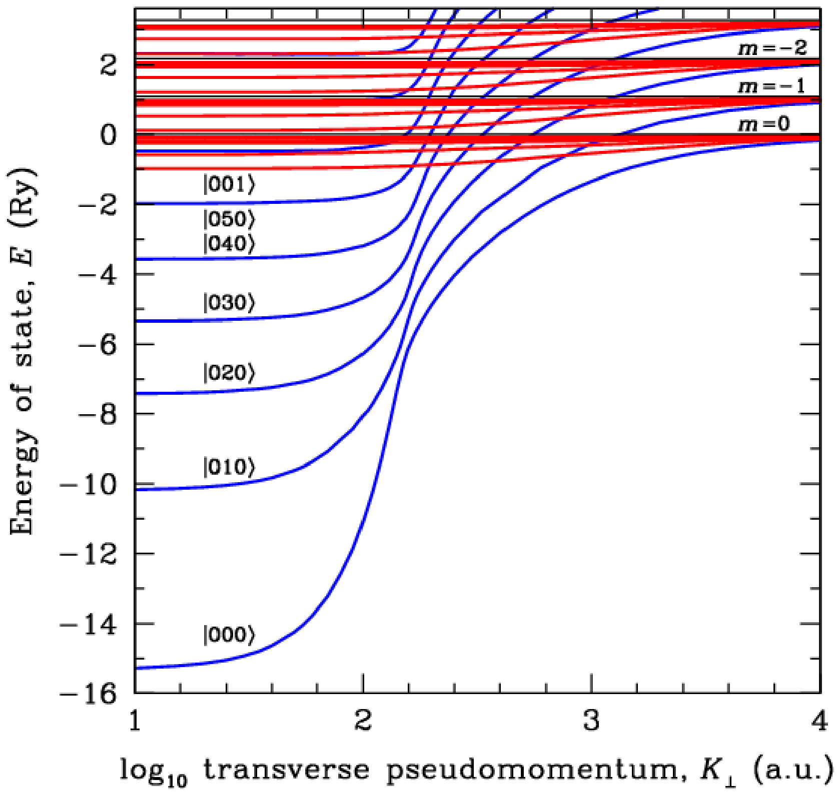


Binding energies of the hydrogen atom in the magnetic field B=2.35x10^{12} G as functions of its state of motion across the field
[Potekhin (1994) *J.Phys.B: At. Mol. Opt. Phys.* **27**, 1073]

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

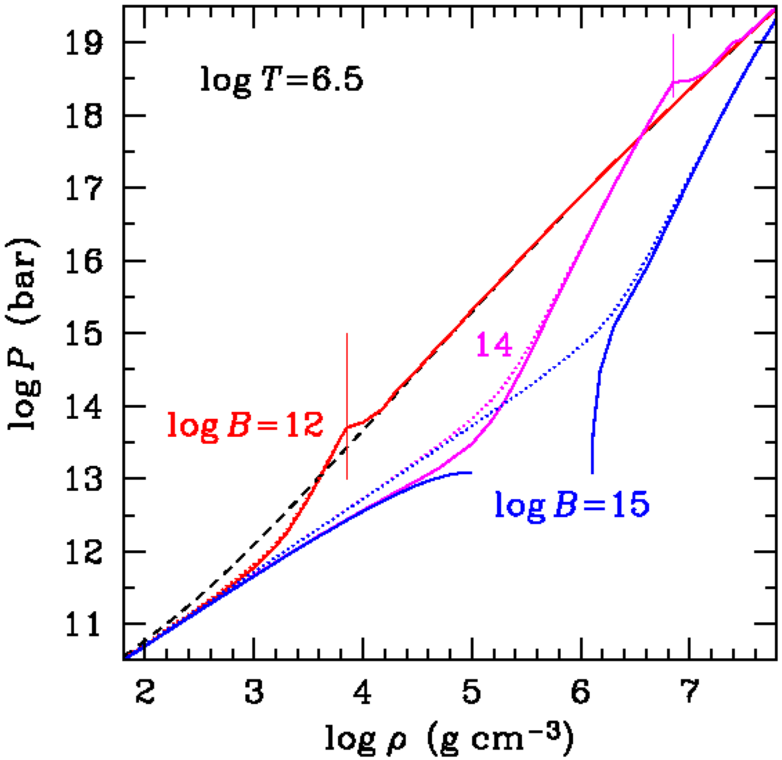
$$F = F_{\mathrm{id}}^{\mathrm{e}} + F_{\mathrm{id}}^{\mathrm{p}} + F_{\mathrm{id}}^{\mathrm{neu}} + F_{\mathrm{ex}}^{\mathrm{C}} + F_{\mathrm{ex}}^{\mathrm{neu}}$$

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

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

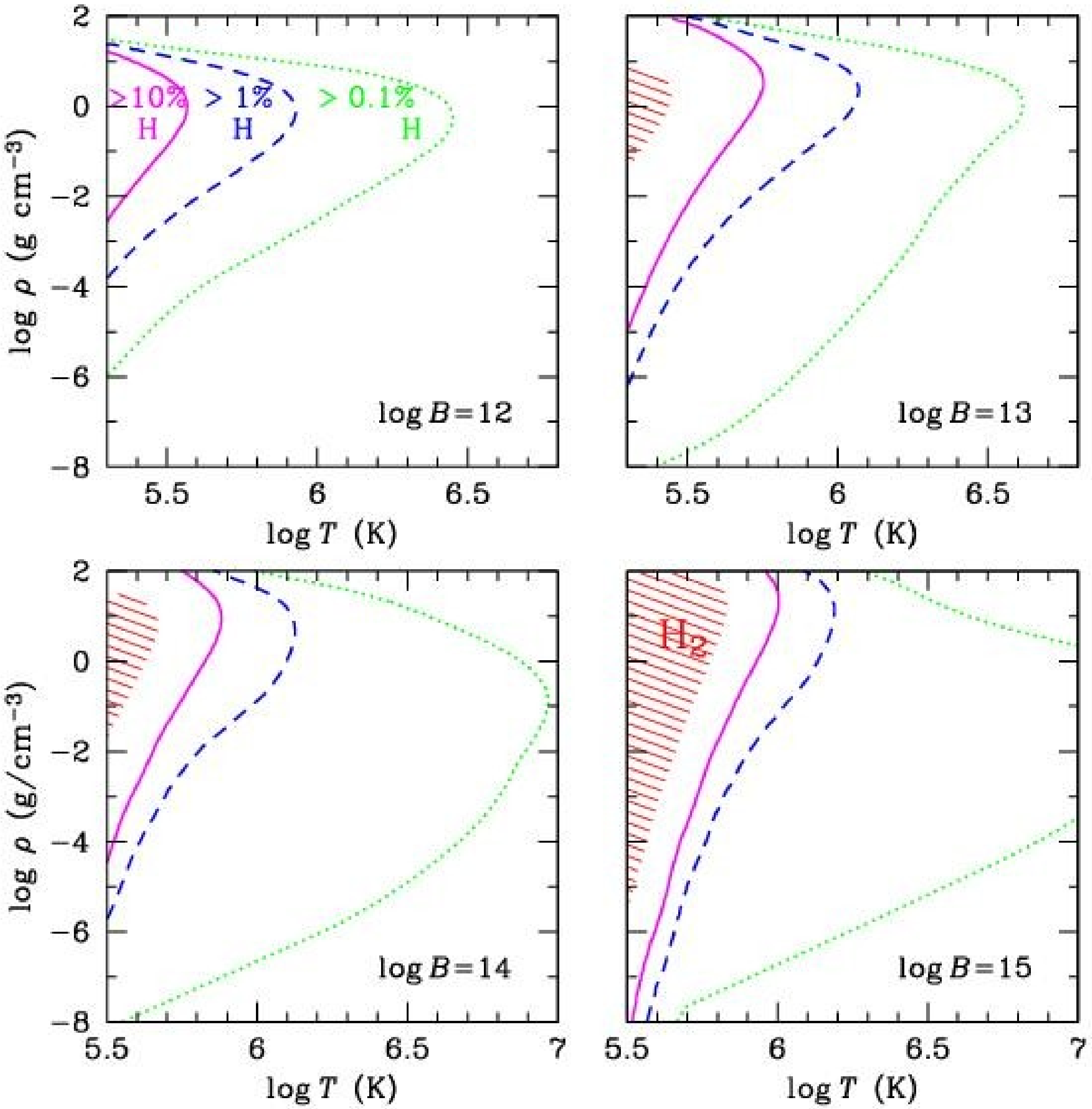
$$\beta_{\mathrm{p}} = E_{cp}/k_{\mathrm{B}}T \approx 0.0732\, B_{12}/T_6$$

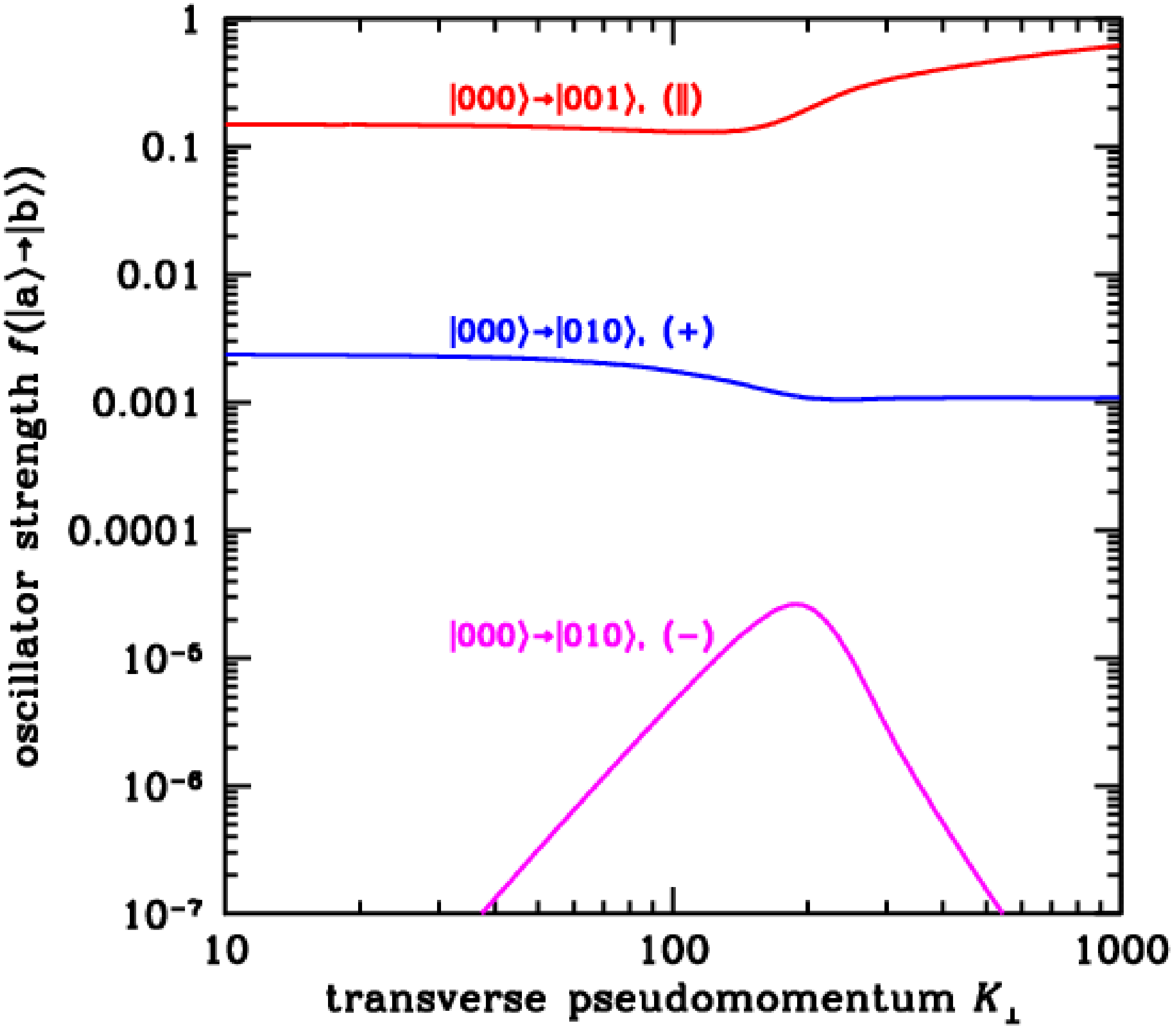
$$F_{\mathrm{id}}^{\mathrm{H}} = k_{\mathrm{B}} T \sum_{s\nu} N_{s\nu} \int \left\{ \ln\left[N_{s\nu} \lambda_{\mathrm{H}} \frac{(2\pi\hbar)^2}{V} p_{s\nu}(K_\perp) \right] - 1 - \epsilon_{s\nu}(K_\perp)/(k_{\mathrm{B}}T) \right\} p_{s\nu}(K_\perp)\, \mathrm{d}^2 K_\perp + N_{\mathrm{H}} k_{\mathrm{B}}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



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

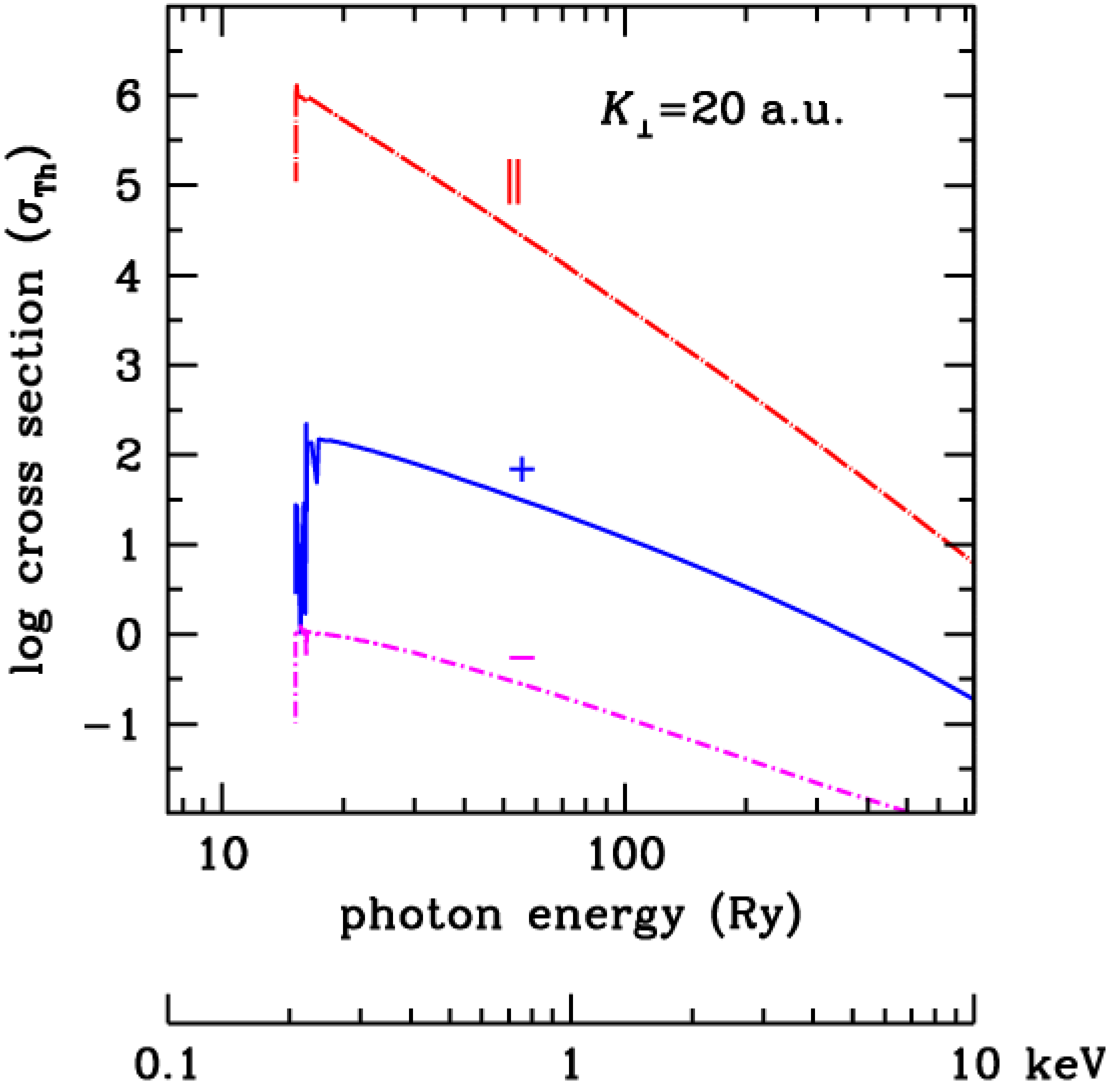
Ionization equilibrium of hydrogen in strong magnetic fields



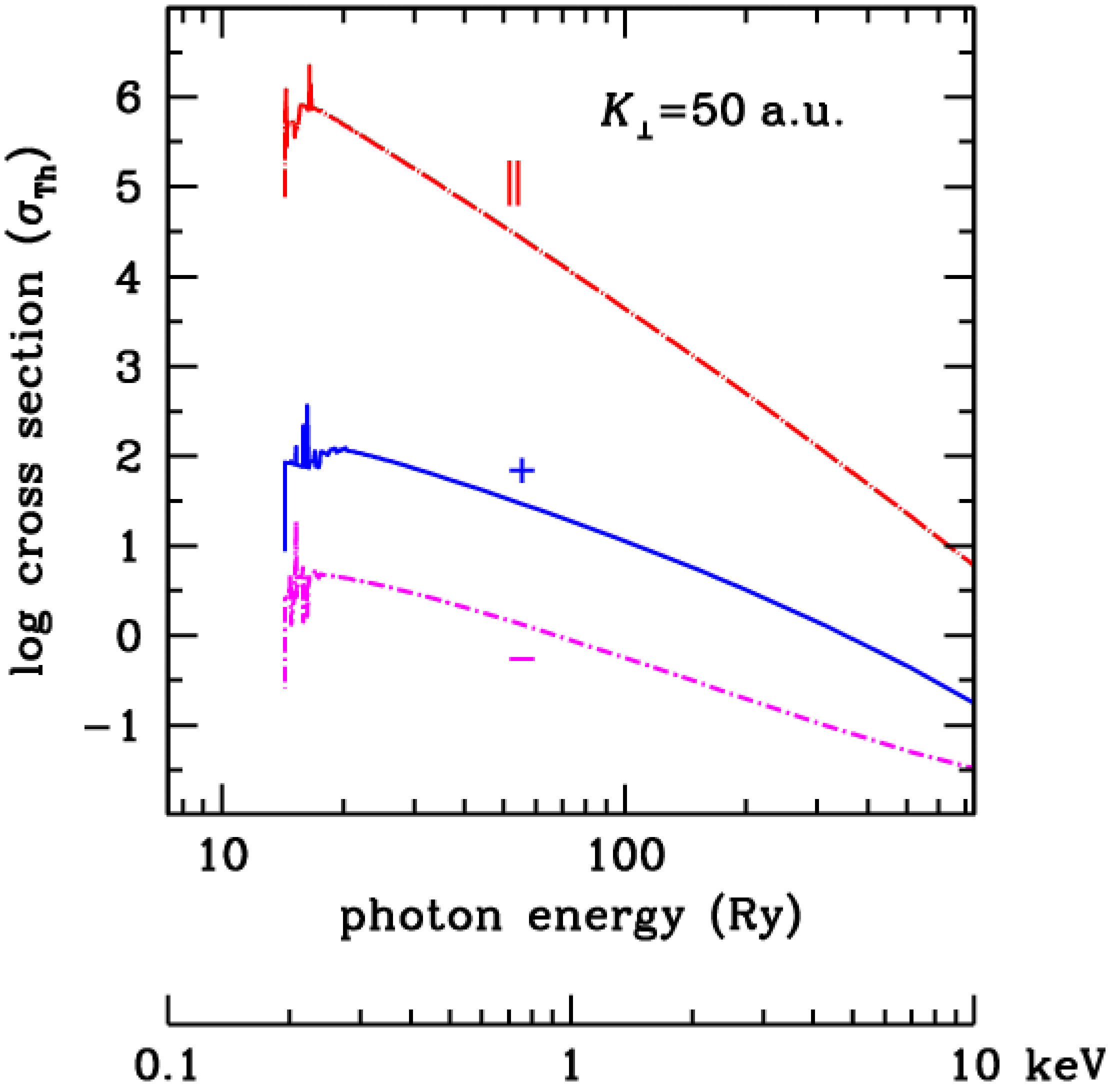


Oscillator strengths for transitions between 2 levels of the hydrogen atom at B=2.35×10^{12} G, as functions of pseudomomentum

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

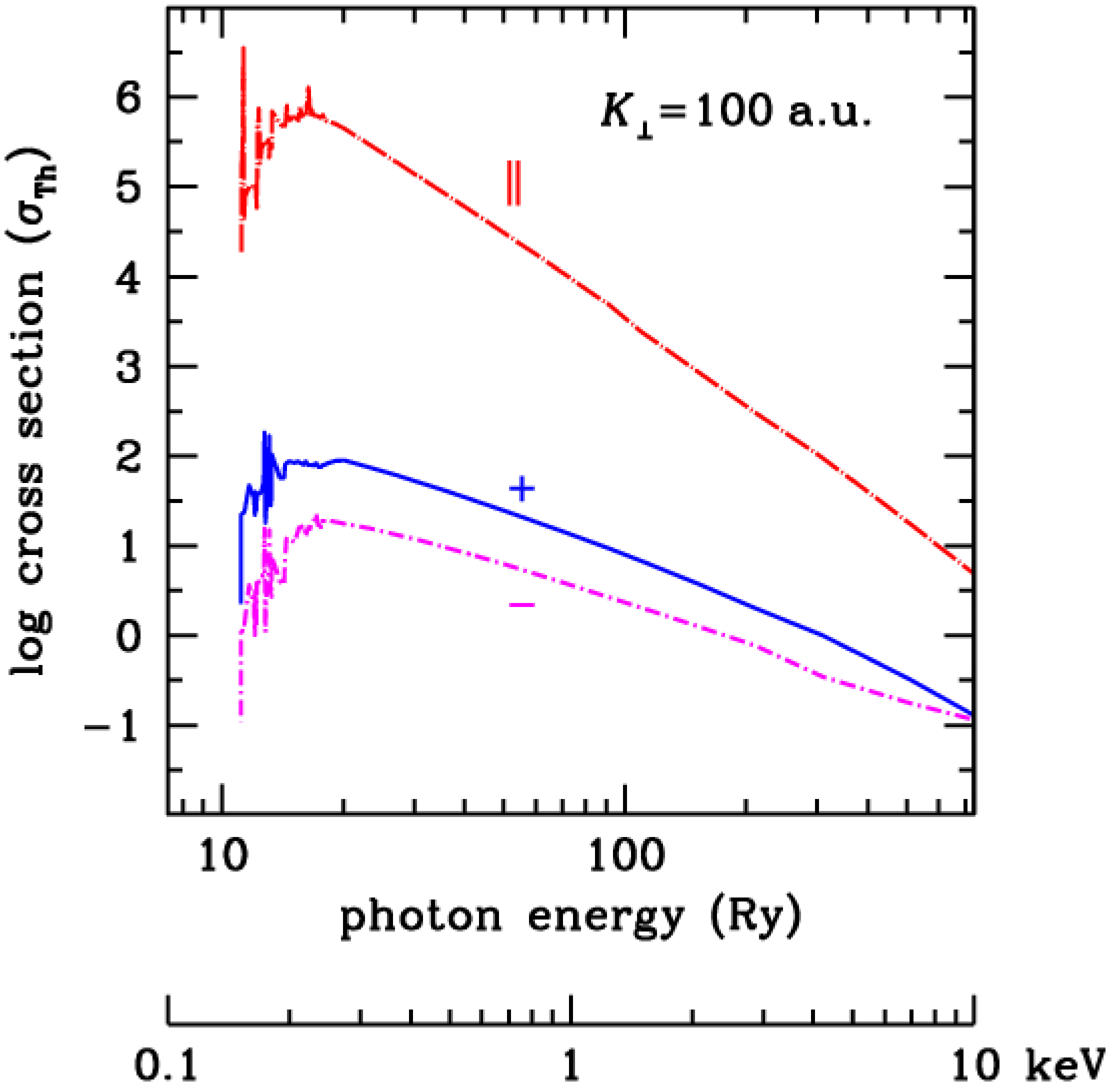


Photoionization cross sections for the ground-state H atom at $B=2.35\times10^{12}$ G
[Potekhin & Pavlov (1997) *Astrophys. J.* **483**, 414]

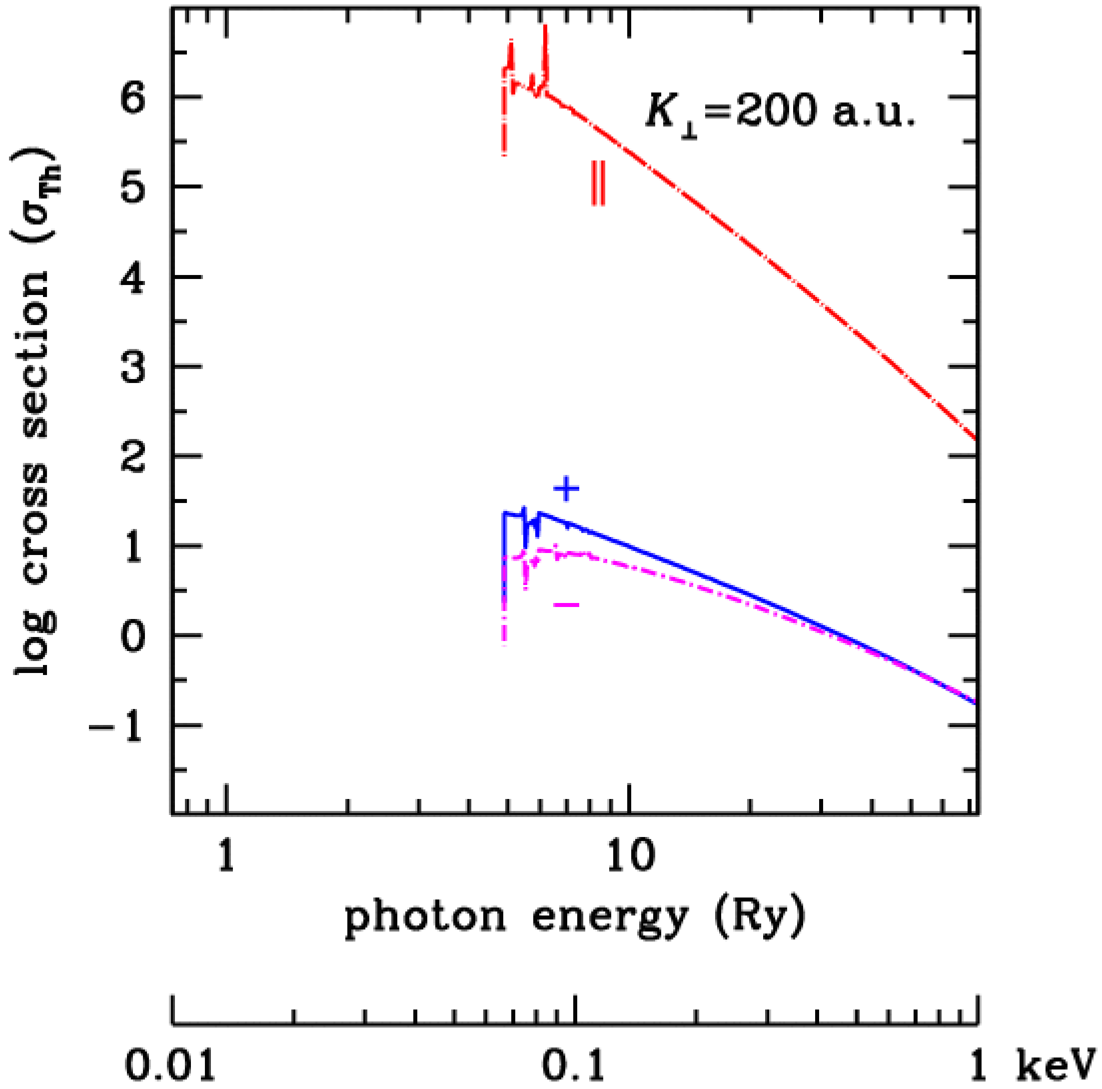


Photoionization cross sections for the ground-state H atom at $B=2.35\times10^{12}$ G

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

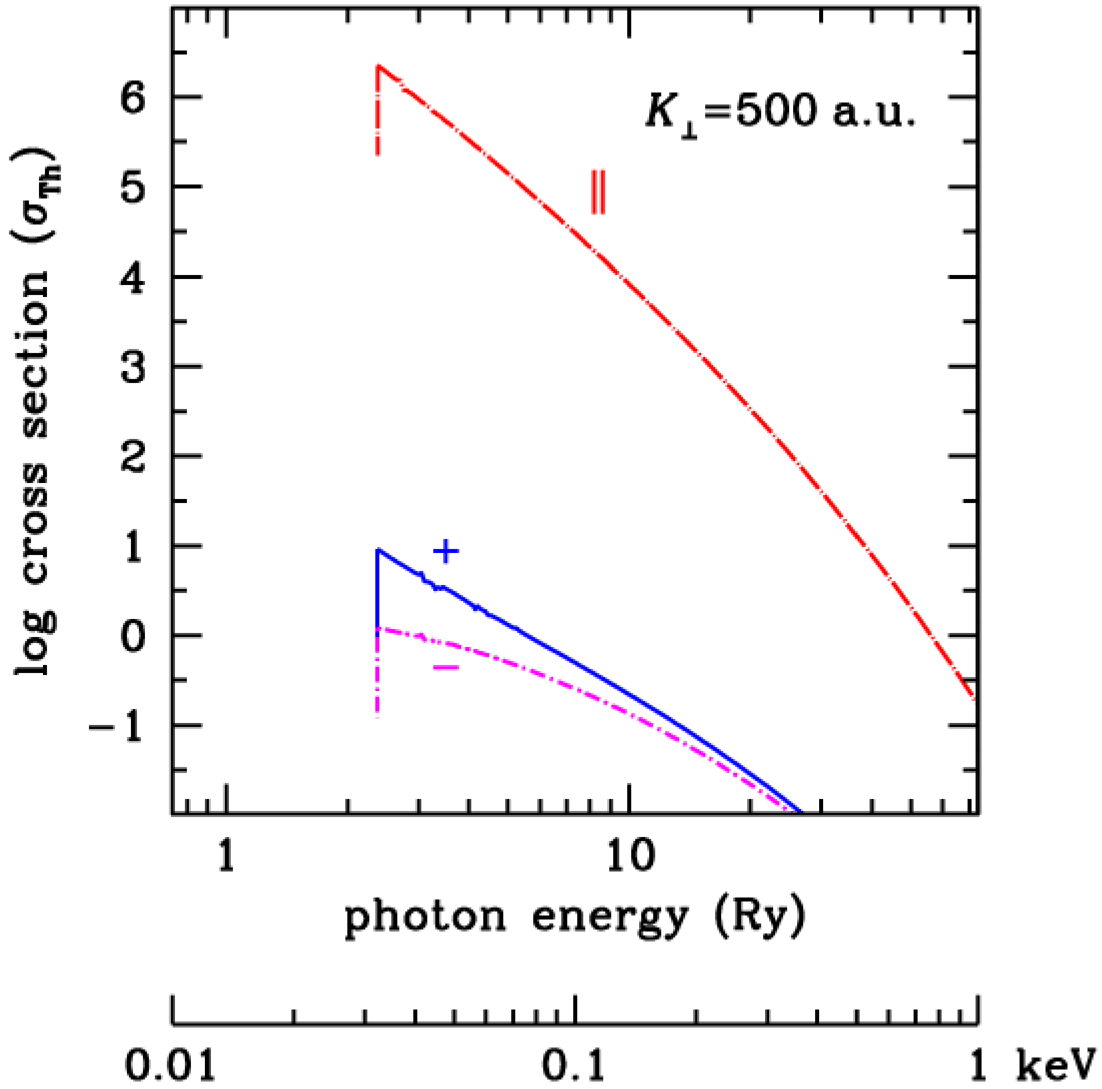


Photoionization cross sections for the ground-state H atom at *B*=2.35×10^{12} G
[Potekhin & Pavlov (1997) *Astrophys. J.* **483**, 414]



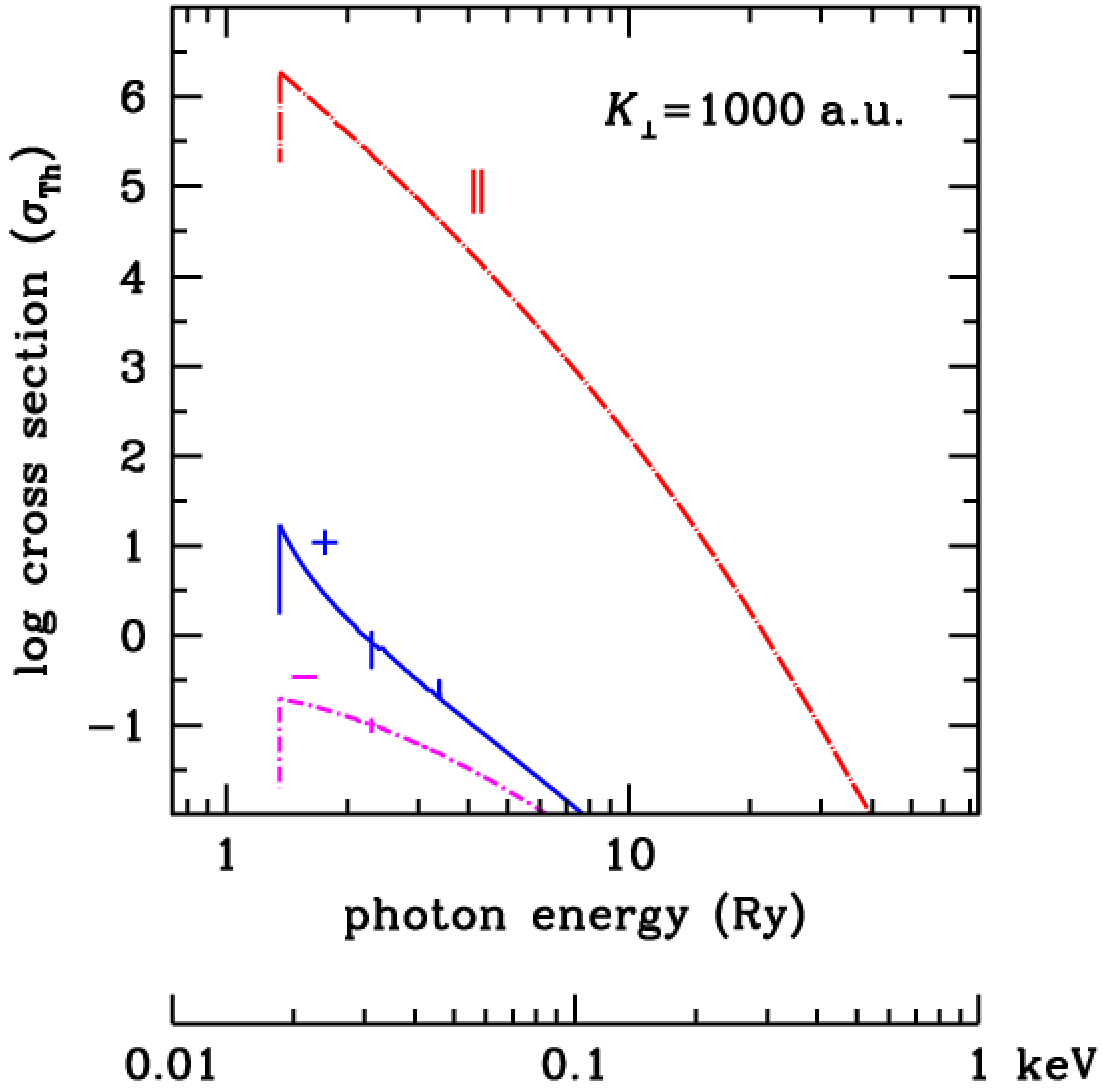
Photoionization cross sections for the ground-state H atom at B=2.35×10^{12} G

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



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

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

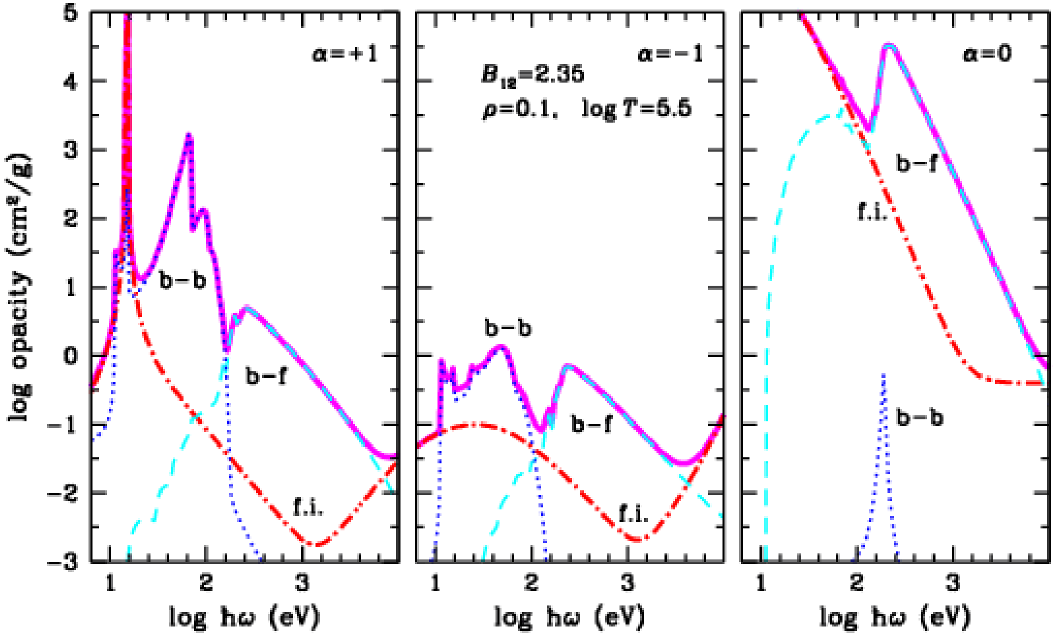


Photoionization cross sections for the ground-state H atom at B=2.35×10^{12} G

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

Plasma absorption and polarizabilities in strong magnetic fields:

The effects of nonideality and partial ionization

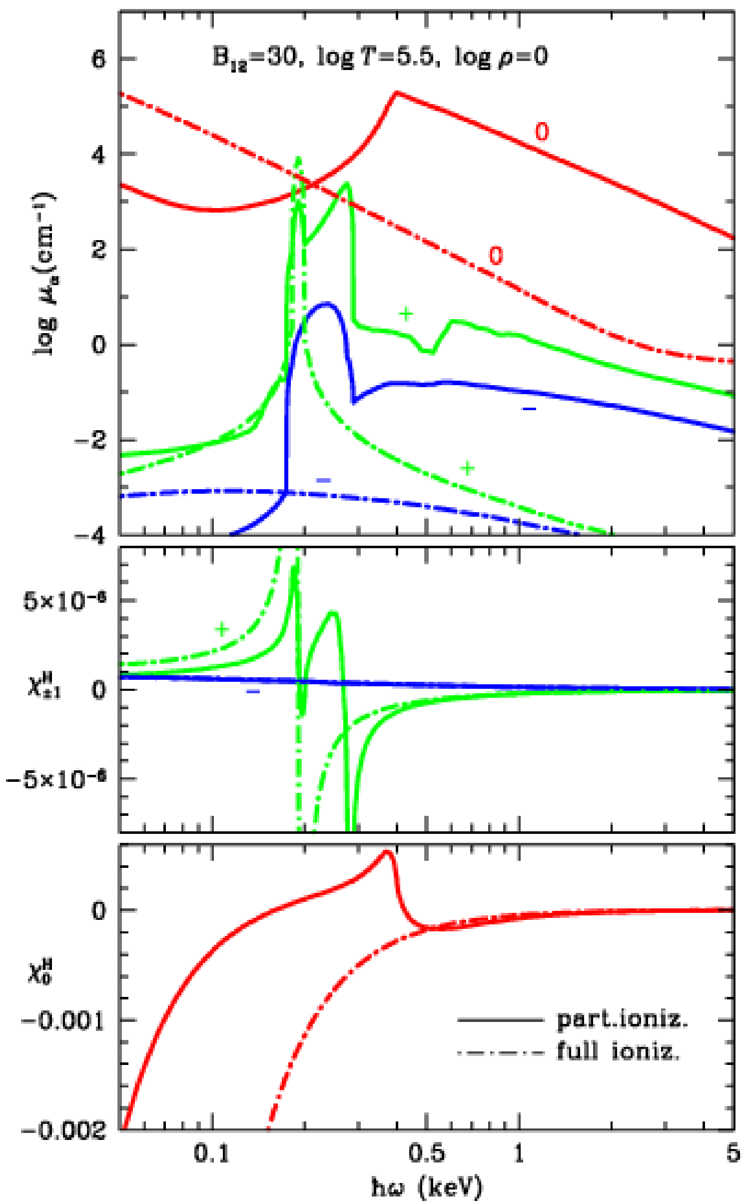


Spectral opacities for 3 basic polarizations.

Solid lines – taking into account bound states,

dot-dashes –full ionization

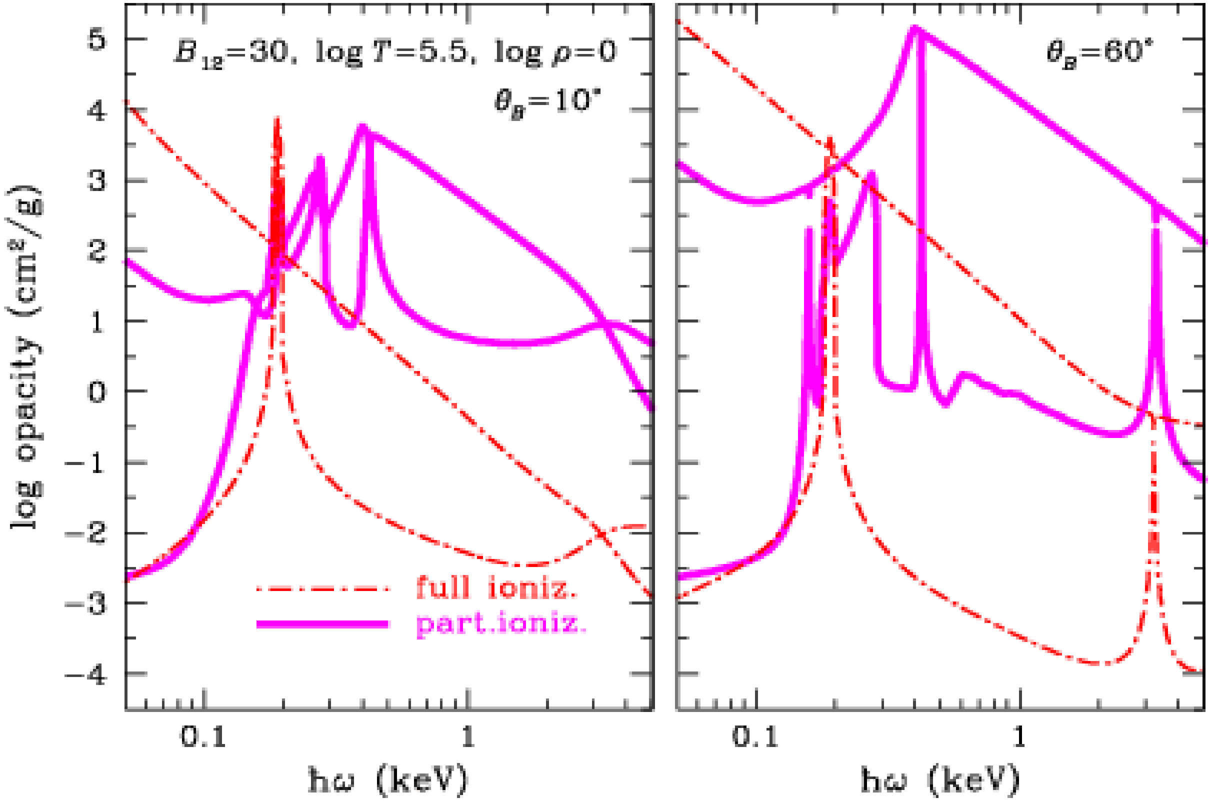
[Potekhin & Chabrier (2003) *ApJ* **585**, 955]



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



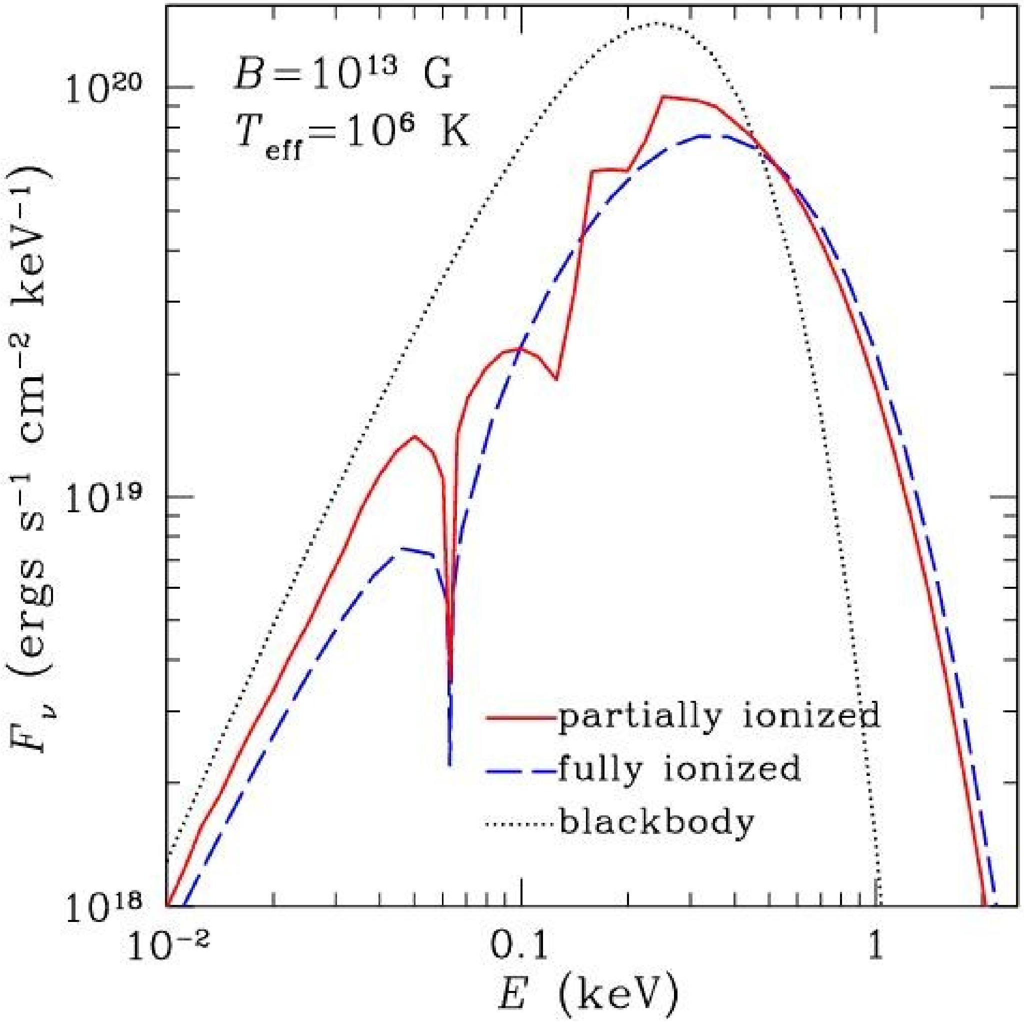
Opacities for two normal modes of electromagnetic radiation in models of an ideal fully ionized (dash-dot) and nonideal partially ionized (solid lines) plasma

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

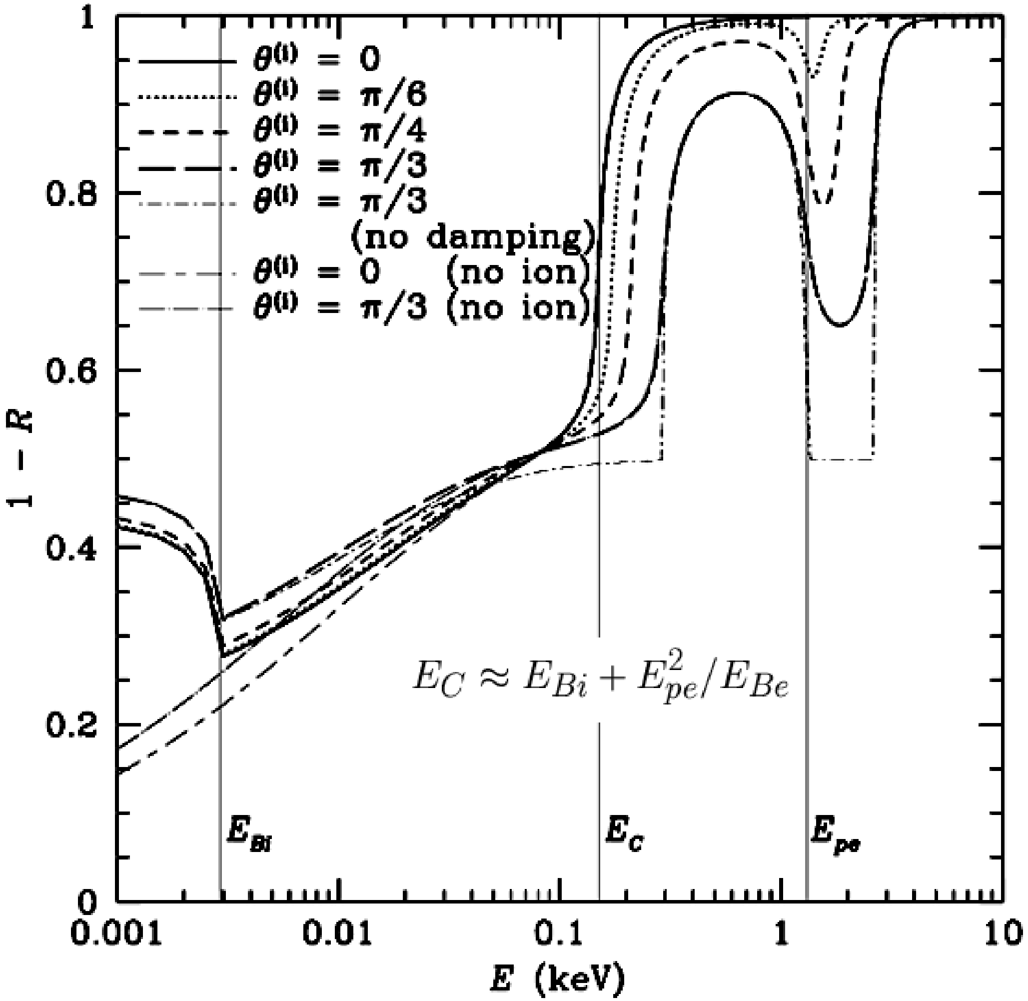
Potekhin et al. (2006)
J.Phys.A: Math. Gen **39**, 4453



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)

Radiation from condensed surface

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

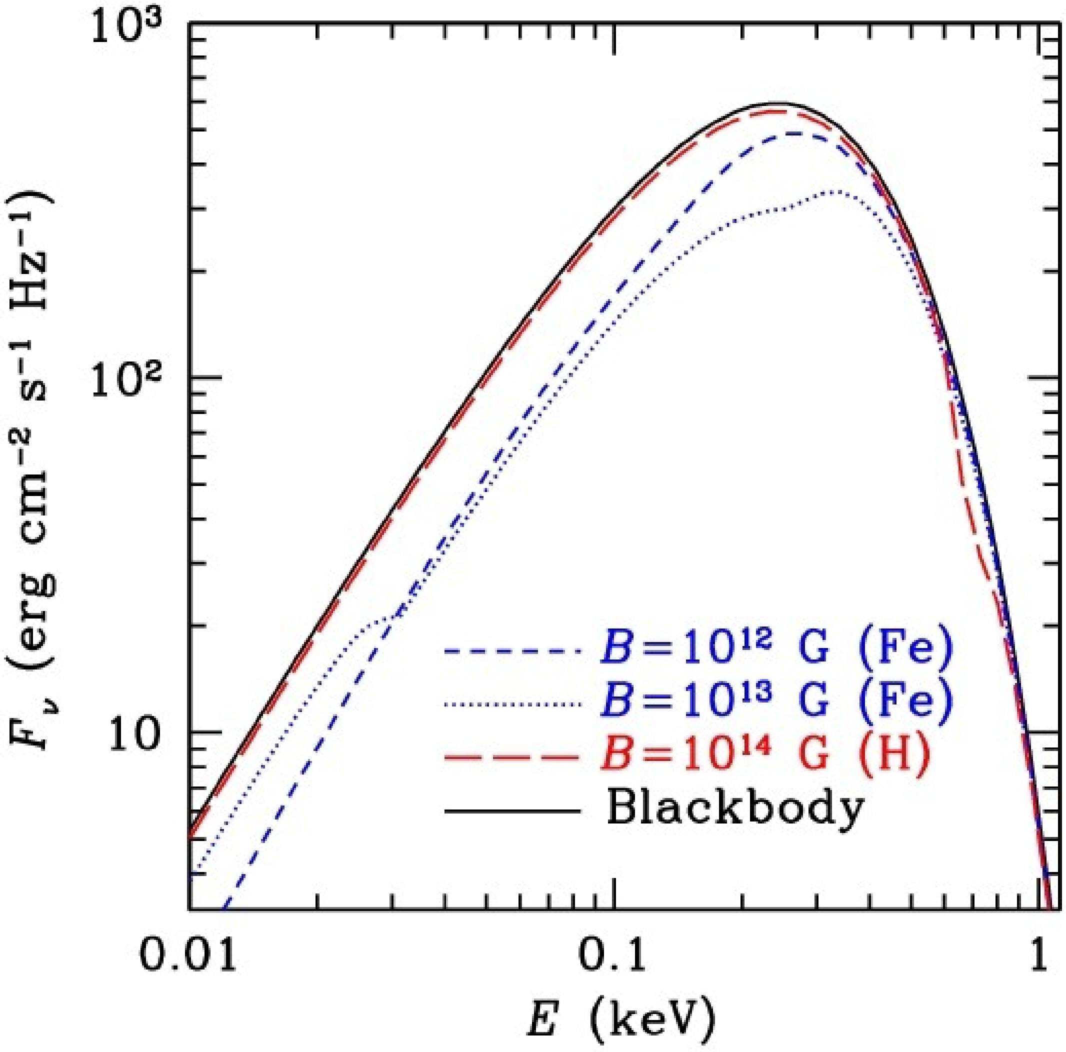


Dimensionless emissivity of the iron surface as function of photon energy

***B*=10^{12} G**, θ_B=90^o, different angles $\theta^{(i)}$ between incident photon direction and normal to the surface

Radiation from condensed surface

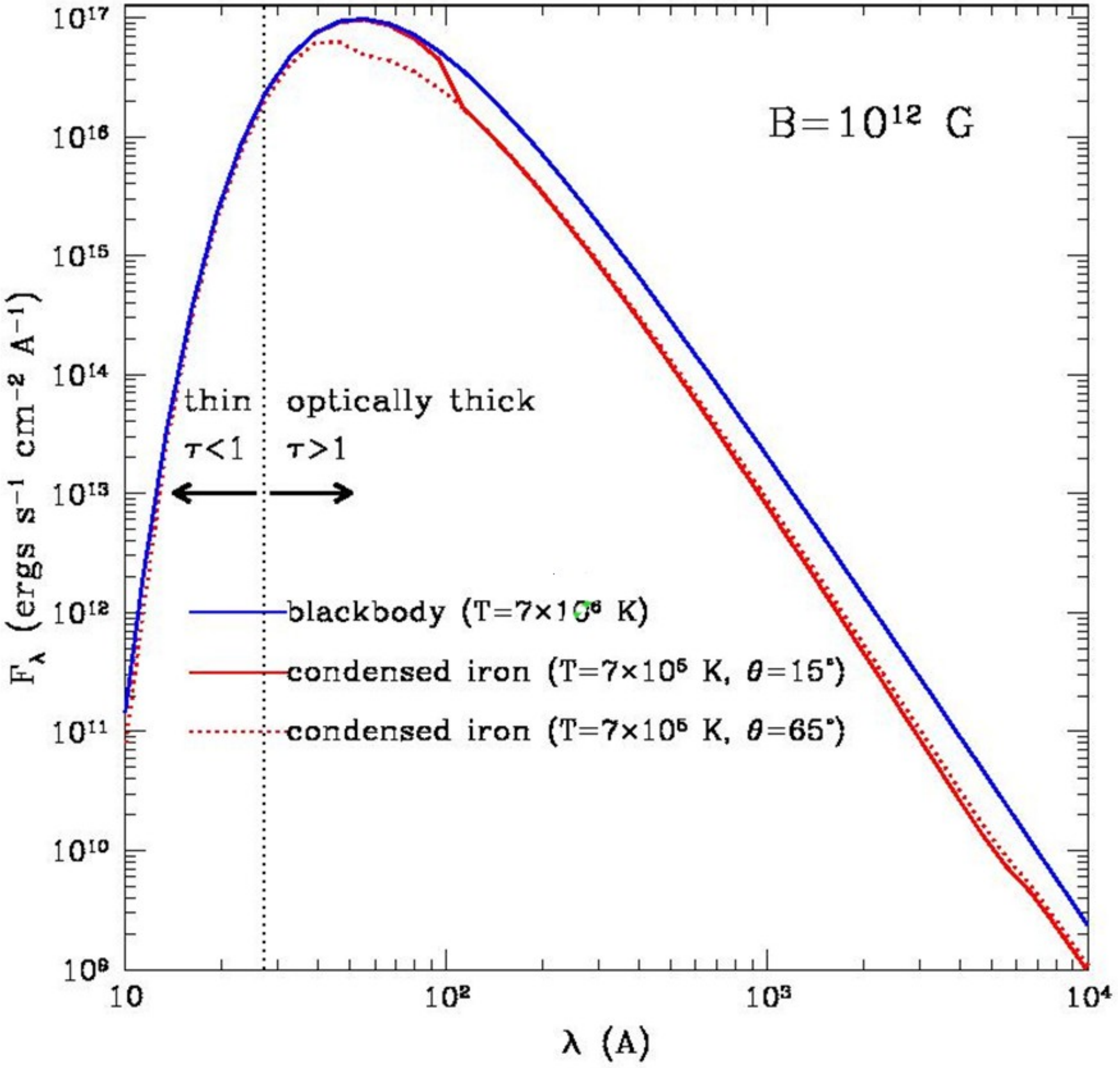
van Adelsberg, Lai, & Potekhin
(2005) *ApJ* **628**, 902

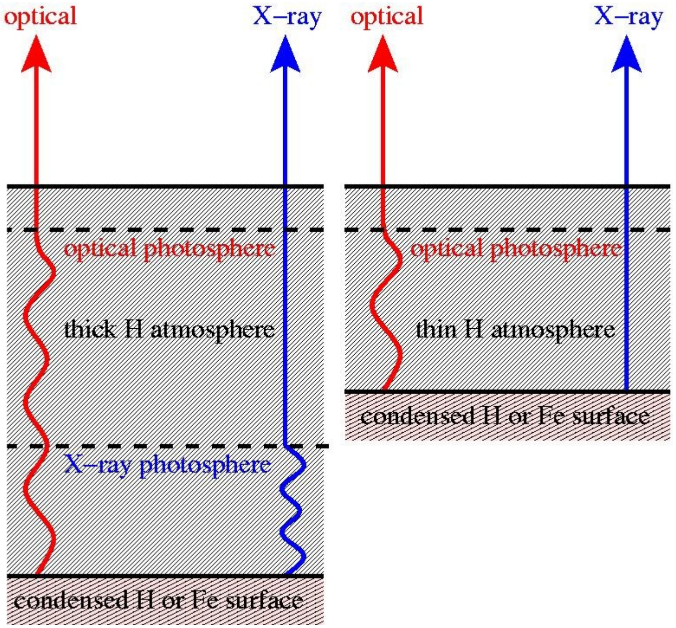


Monochromatic flux from the condensed surface in various cases
[Matthew van Adelsberg, for Potekhin *et al*. (2006) *J.Phys.A: Math. Gen.* **39**, 4453]

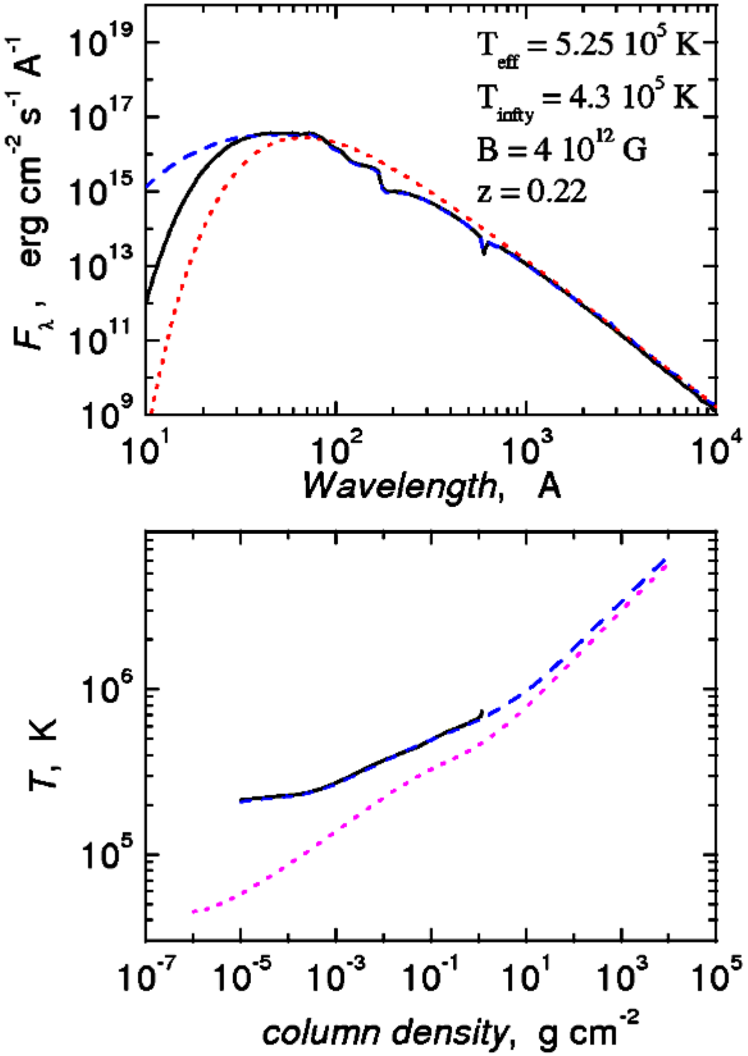
Condensed surface covered by atmosphere

(Wynn Ho)

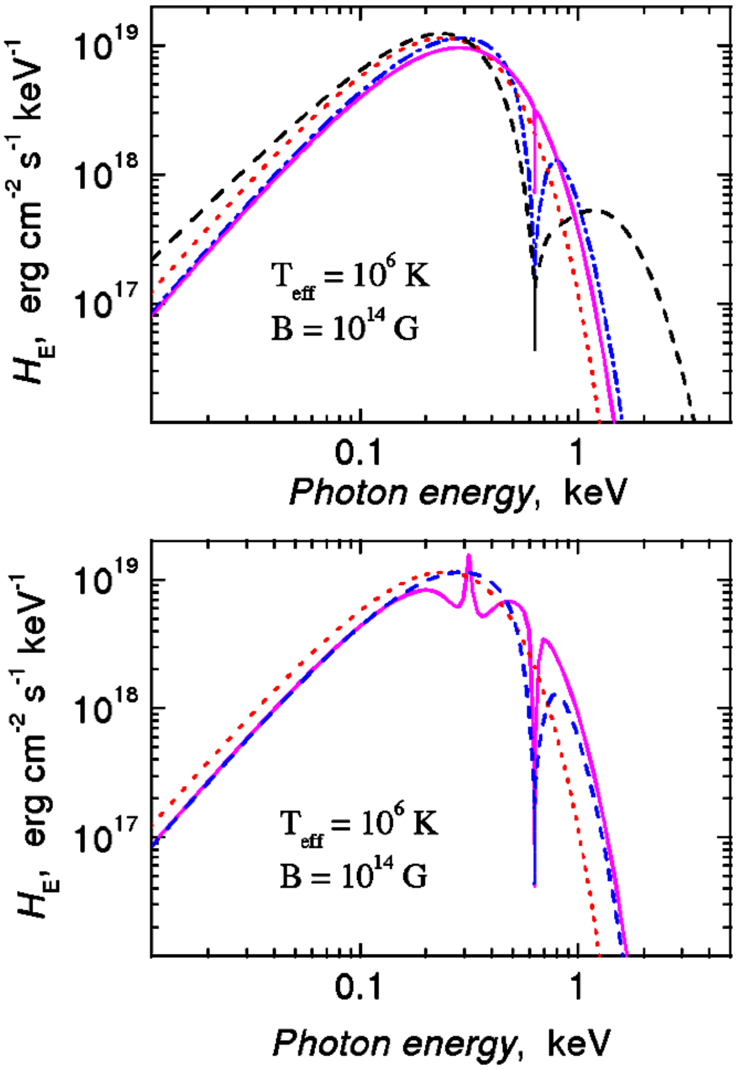




Thin and layered atmospheres



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)

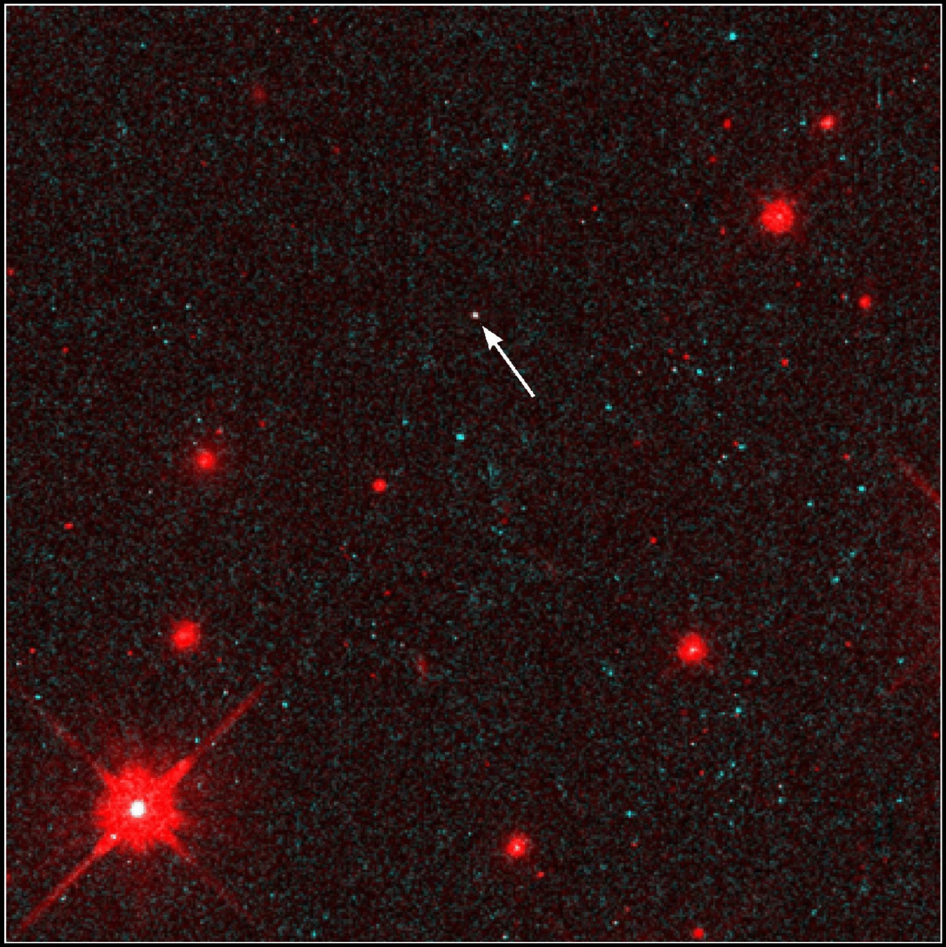


Emergent spectra of fully ionized atmospheres. Top – H (semi-infinite – dashes, 100 g cm^{-2} – dot-dash, 1 g cm^{-2} – solid); bottom – H/He (25/75 g cm–2). Dottel lines – blackbody.

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

Application of the theory to observations:

The case of RX J1856.35−3754 (“Walter’s star”)

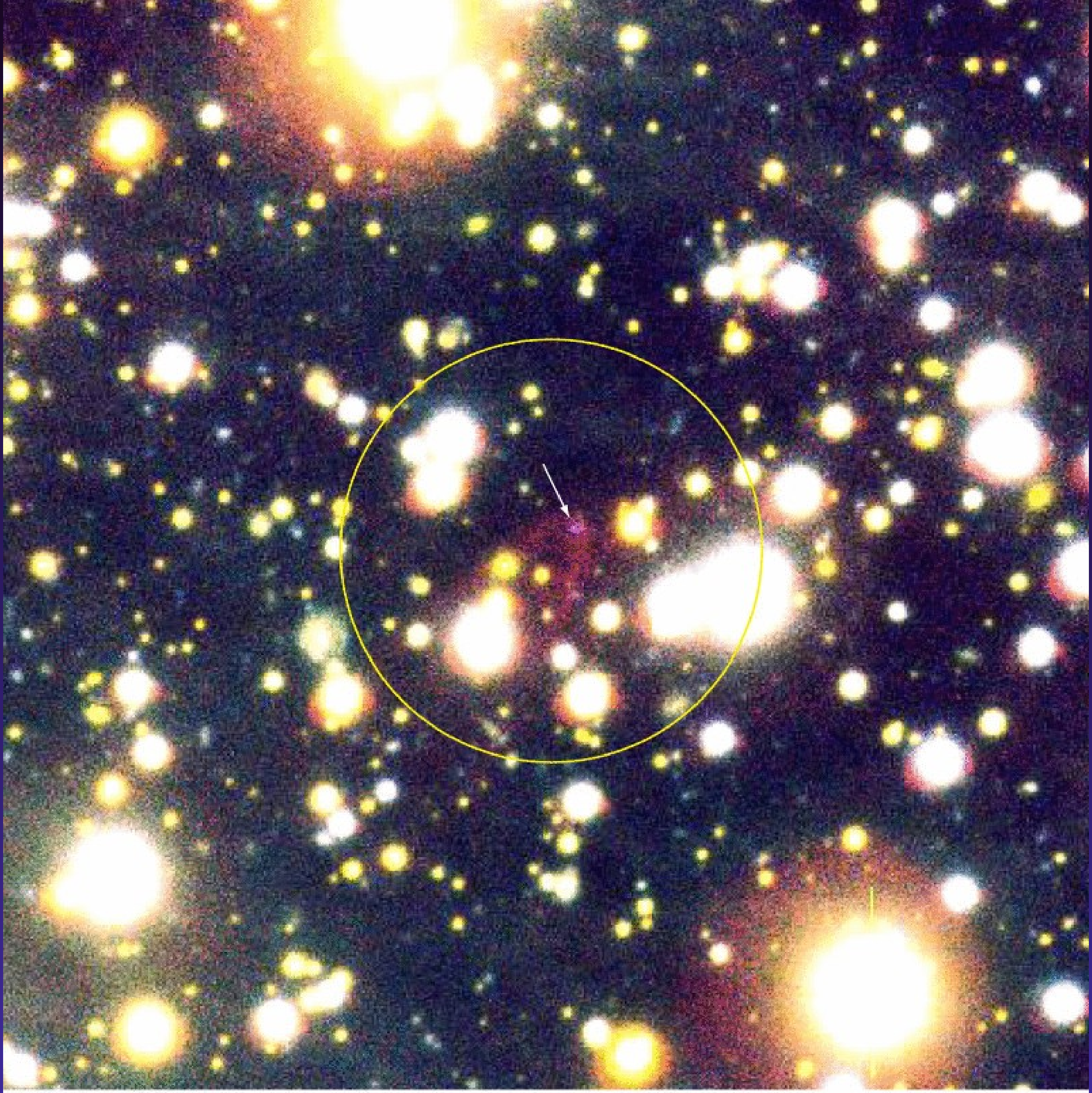


Isolated Neutron Star RX J185635-3754

Hubble Space Telescope • WFPC2

PRC97-32 • ST ScI OPO • September 24, 1997

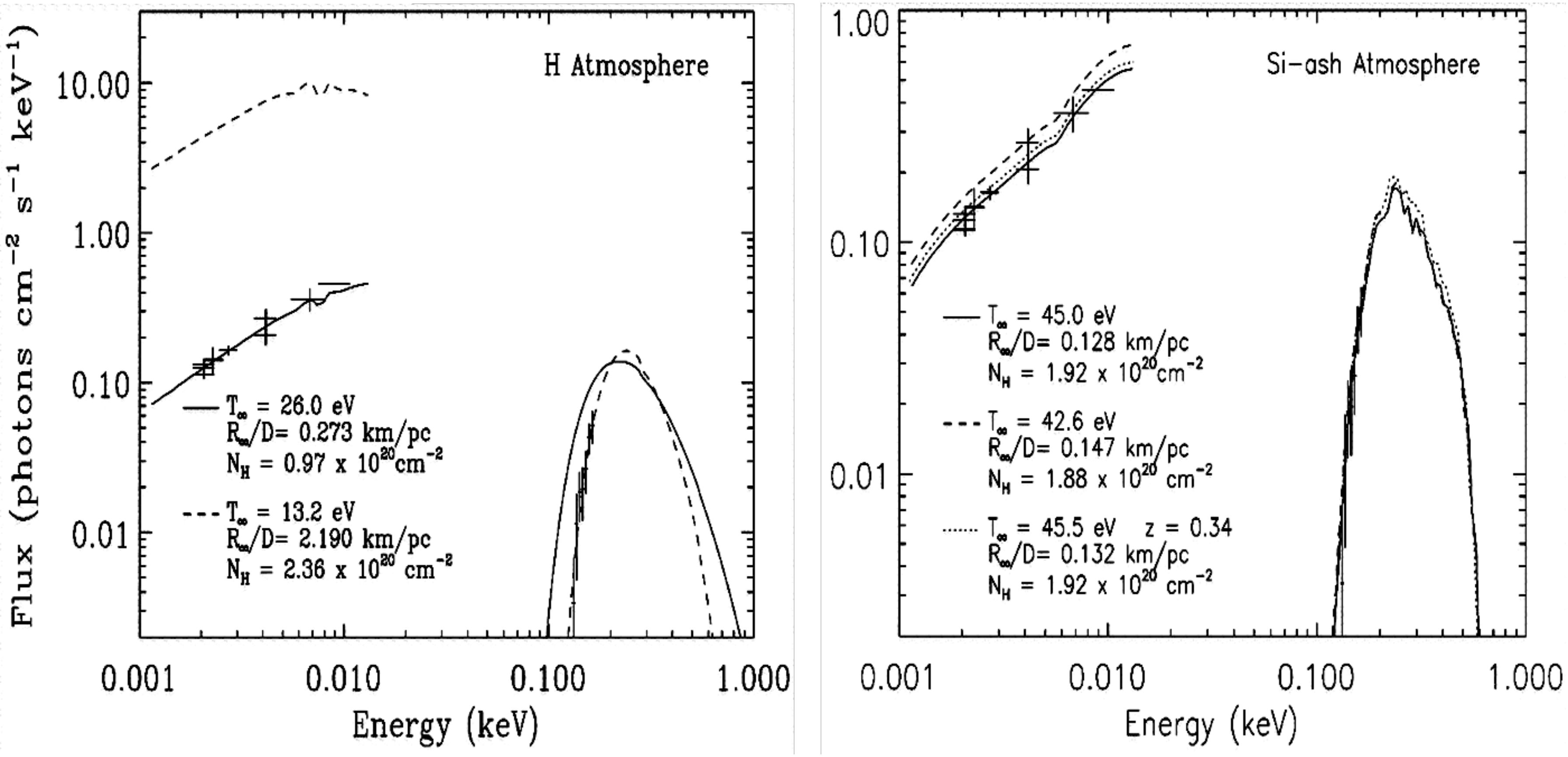
F. Walter (State University of New York at Stony Brook) and NASA



A Bowshock Nebula Near the Neutron Star RX J1856.5-3754 (Detail)
(VLT KUEYEN + FORS2)

ESO PR Photo 23b/00 (11 September 2000)

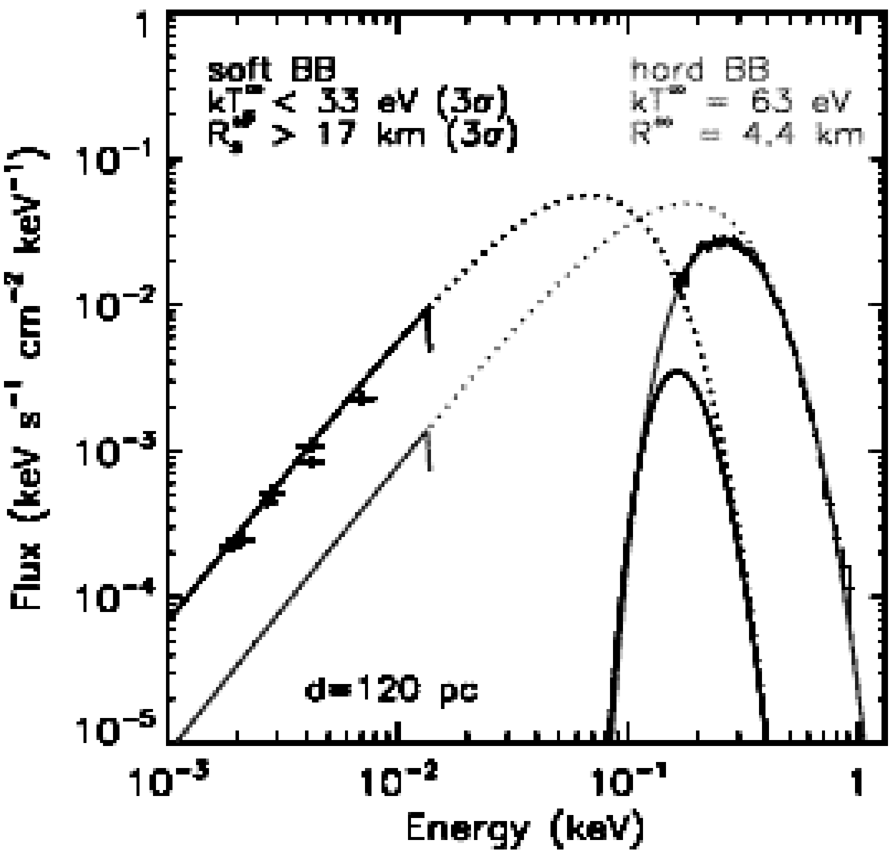
Previous attempts to model the spectrum *without allowance for a strong magnetic field*



Pons et al. (2002) *ApJ* **564**, 981: H and Si atmosphere models

Previous attempts to model the spectrum

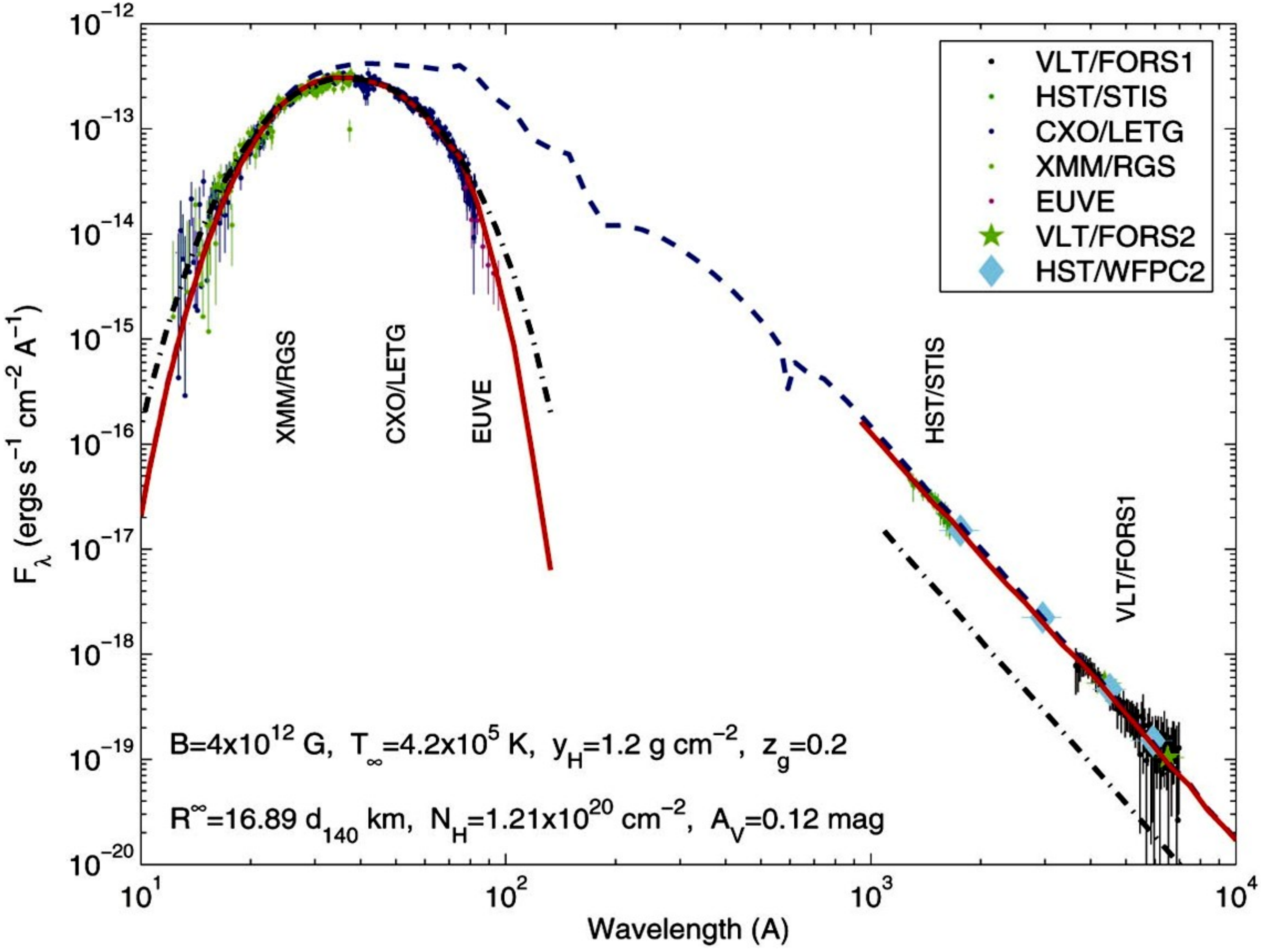
(another example)



Burwitz et al. (2003) *A&A* **399**, 1109: combination of two blackbody models

W.C.G.Ho, D.Kaplan, P.Chang, M.van Adelsberg, A.Y.Potekhin (2007) *MNRAS*, **375**, 821

Magnetic hydrogen atmosphere models and the neutron star RX J1856.5-3754



Conclusions

- **Cores** of the neutron stars consist of **ultradense plasmas** composed of nucleons, leptons, hyperons, and/or possibly quarks. **Theoretical models** of (poorly known) properties of such plasmas can be tested through observations of neutron-star **thermal radiation**.
- I order to link observations with theoretical models of the cores, one needs to model **heat diffusion** and formation of thermal **radiation spectrum**, which requires knowledge of thermodynamic and kinetic properties of the nonideal, strongly magnetized plasmas in the atmospheres and heat-insulating envelopes.
- **Practical models** of the EOS and the conductive and radiative opacities of strongly magnetized plasmas, applicable to the neutron stars, **are developed** in recent years. The results allow one to model neutron-star thermal spectra which can be used for interpretation of observations. Nevertheless, there remain **unsolved problems** that restrict the applicability of these models.