Thermal X-ray Emission from Isolated Neutron Stars

Isolated NSs: solitary NSs or those in binaries without accretion

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Neutron Star Crust and Surface: Observations and Models
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Short history

- Chiu & Salpeter (1964) and Tsuruta (1964):
  thermal radiation from the surface of a hot NS
  may be a source of cosmic X-rays

- First detections with Einstein (1978-81) and EXOSAT (1983-86):
  middle-aged PSRs B0656+14 and B1055-52
  central compact sources in the SNRs RCW 103, Puppis A, PKS 1209-52
  a few AXPs

- since 1991, X-ray studies with
  ROSAT, ASCA, EUVE, BeppoSax, Chandra and XMM-Newton

In total, thermal emission detected from about 50-60 NSs:

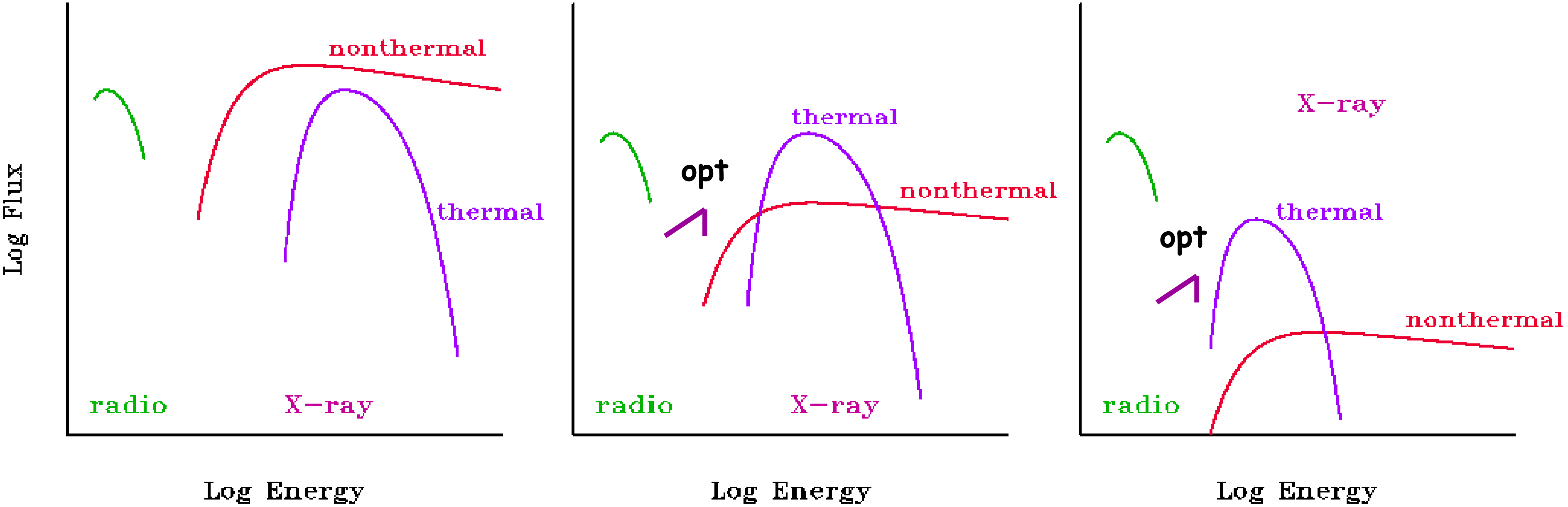
- from the whole surface (atmospheres?) of cooling NSs

- from polar caps heated by relativistic particles streaming down onto the surface from pulsar's magnetosphere

Thermal vs. Nonthermal emission in pulsars of different ages

Nonthermal (magnetospheric) emission, ~ $\dot{E} \sim t^{-\beta}$, $\beta \sim 2$—4

NSs cool down from $T \approx 10^{11}$ K (at birth) to 0.2-2 MK in 0.1-1 Myr



Young active (<1 kyr): nonthermal radiation dominates;

Crab, B1509-58, B0540-69

Middle-aged (10-100 kyr): thermal component from the whole surface;

Vela, B0656+14, B1055-15, Geminga, J0538+2817

Old (>1 Myr): thermal emission from hot polar caps;

6-ms J0437-4715, B0950+08

Main questions

- Why is studying thermal emission needed?
- What is the state of the NS surface?
  Gaseuos or liquid, or solid?
- What is the chemical composition of the NS surface?
  Hydrogen or heavier elements (e.g., iron)?
- What is the proper model for the thermal radiation?

- Why is studying thermal emission needed?

Comparing observed emission with theoretical models $\Rightarrow$

$\Rightarrow$ T_{surf}, B, R, M

$T_{surf}(t) \Rightarrow$ thermal evolution

R, M $\Rightarrow$ constraints on **EOS** and internal structure

surface chemical composition $\Rightarrow$

formation of NSs and their interaction with environment

- What is the state of the NS surface?

It depends on T_{surf}, B and chemical composition.
For hydrogen, the surface is in a condensed state if:

$T_{surf} < 1 \times 10^5$ K @ $B = 1 \times 10^{13}$ G
$T_{surf} < 5 \times 10^5$ K @ $B = 1 \times 10^{14}$ G (Lai & Salpeter 1997)
$T_{surf} < 1 \times 10^6$ K @ $B = 5 \times 10^{14}$ G

- What is the chemical composition of the NS surface?
  Heavy elements or hydrogen?

  A small amount of H,

  surface density $\sim 10^{-3} - 10^{-1}$ g/cm^2
  total amount $\sim 10^{10} - 10^{12}$ g,

  due to accretion from ISM or fallback of material ejected during the SNR explosion.

  Otherwise, heavier elements may be present.

- What is the proper model for the thermal radiation?

  Whatever is the physical state of the surface,
  its radiation should not be that of a black body.

Main aspects of the NS atmosphere modeling

- What's special about NS atmospheres?
  Why not to use standard stellar atmosphere models?

1. Enormous gravity at the surface ($M \approx 1.4\ M_\odot$, $R \approx 10$ km)

$$g \approx 10^{14} \quad \text{vs.} \quad 10^{4} \ \text{cm}^2/\text{s} \quad \text{for usual stars}$$

⇒ NS atmospheres are strongly compressed

$$\rho \approx 10^{-2} - 10^{1} \quad \text{vs.} \quad 10^{-7} \ \text{g/cm}^3$$

$$\text{height} \approx kT_{sur}/m_p g \approx 10^{-1} - 10^{1} \quad \text{vs.} \quad 10^{8} \ \text{cm}$$

⇒ stratification of chemical elements

⇒ non-ideality effects (pressure ionization, smoothed spectral features)

2. Huge magnetic fields, $B = 10^{10} - 10^{14}$ G

$\Rightarrow E_{ce} = 11.6\ (B/10^{12}\ \mathrm{G})$ keV $\gg kT_{sur} \sim 0.1$ keV, E $\sim$0.1—1 keV

$\Rightarrow$ NS atmospheres are essentially anisotropic

$\Rightarrow$ opacities depend on direction and polarization of radiation

$\Rightarrow$ radiation is polarized and depends on B

$\Rightarrow \gamma = E_{ce} / (Z^2\ \mathrm{Ry}) = 850\ Z^{-2}\ (B/10^{12}\ \mathrm{G}) \gg 1$

$\Rightarrow$ atomic structure is distorted by B

$\Rightarrow$ increase of binding (ionization) energies of bound states

$I/(Z^2\mathrm{Ry}) \approx \ln^2(\gamma/Z^2) \gg 1$, $I_H \approx 0.2$ keV at $B = 10^{13}$ G

$\Rightarrow$ altered ionization equilibrium and equation of state

NS atmosphere models with "low" magnetic fields, $B < 10^8 - 10^9$ G (millisecond pulsars, NS transients in quiescence)

General scheme (Mihalas 1978):

(Romani 1987, Zavlin et al. 1996, Gänsike et al. 2001, Zavlin & Pavlov 2002)

- radiative transfer in isotropic 1-D medium for specific radiative intensity $I_\nu(z,\mu)$

$$\mu \frac{\mathrm{d}}{\mathrm{d}y} I_\nu = k_\nu \left[I_\nu - S_\nu \right], \quad \mu = \cos\theta = \vec{\mathbf{n}} \cdot \vec{\mathbf{r}}, \quad \mathrm{d}y = -\rho\, \mathrm{d}z$$

$k_\nu = \sigma_\nu + \alpha_\nu$ — total radiative opacity, scattering+absorption

$S_\nu = \left[\sigma_\nu J_\nu + \alpha_\nu B_\nu\right] k_\nu^{-1}$ — source function

$J_\nu = \frac{1}{2}\int_{-1}^{1} I_\nu \,\mathrm{d}\mu$ — mean intensity

Comptonization is not important at $T < 5\times10^6$ K

Most common (diffusion) approach:

$$\frac{\mathrm{d}}{\mathrm{d}y}\, k_\nu^{-1} \frac{\mathrm{d}}{\mathrm{d}y}\, f_\nu J_\nu = \alpha_\nu \left[J_\nu - B_\nu \right]$$

$$k_\nu^{-1} \frac{\mathrm{d}}{\mathrm{d}y}\, f_\nu J_\nu = h_\nu J_\nu \Big|_{y=0}$$ — no incident emission

$$J_\nu = B_\nu \Big|_{y\to\infty}$$ — equilibrium solution

the Eddington factors (accounting for anisotropy of radiation):

$$f_\nu = \left[2 J_\nu \right]^{-1} \int_0^1 \mu^2 I_\nu \,\mathrm{d}\mu \quad \left(\approx \tfrac{1}{3}, \quad y \to \infty \right)$$

$$h_\nu = \left[2 J_\nu \right]^{-1} \int_0^1 \mu \left[I_\nu(\mu) + I_\nu(-\mu) \right] \mathrm{d}\mu \quad \left(\approx \tfrac{1}{2} \right)$$

$$F_\nu = \frac{4\pi}{k_\nu} \frac{\mathrm{d}}{\mathrm{d}y}\, f_\nu J_\nu$$ — spectral (monochromatic) flux

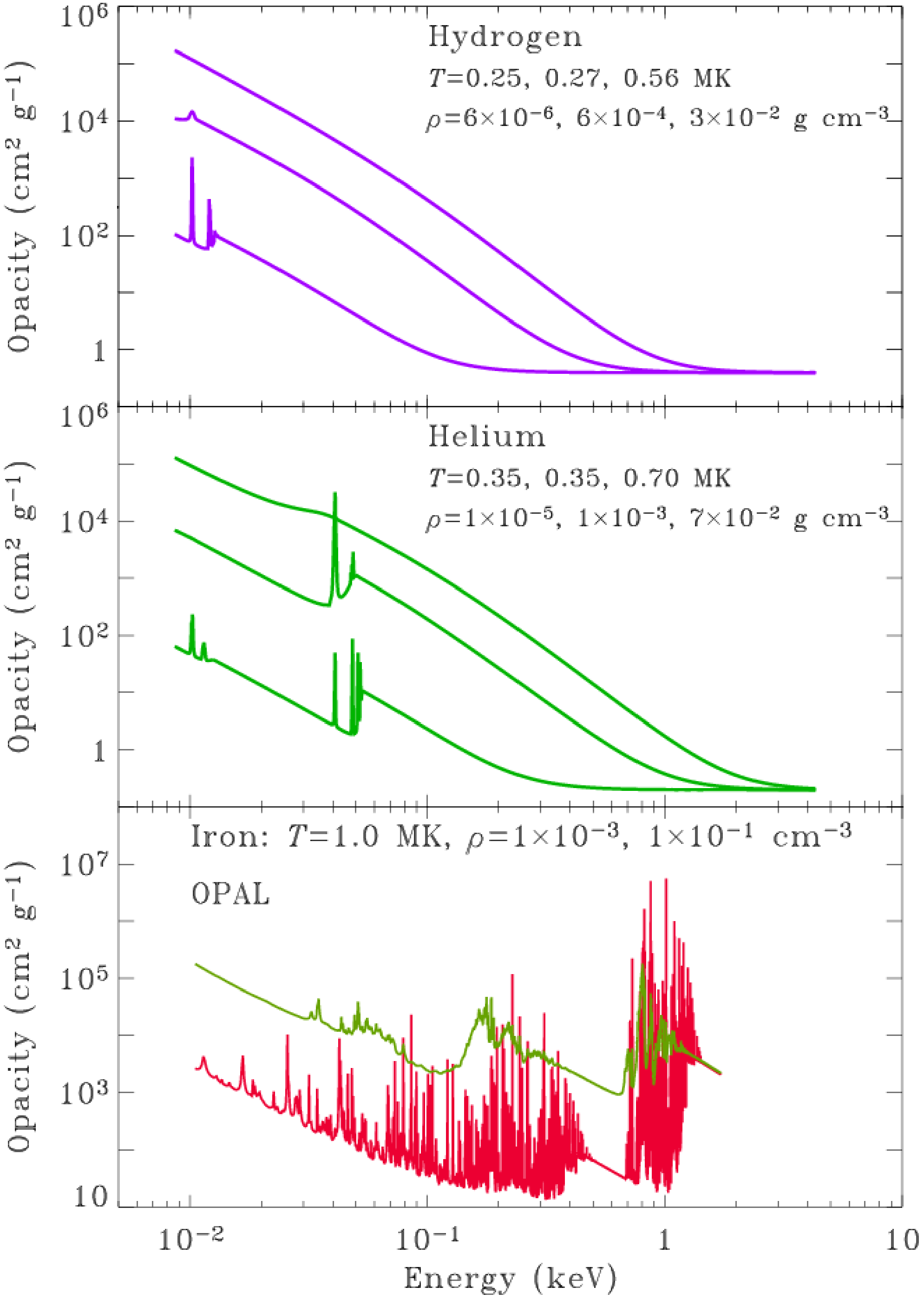
- radiative equilibrium (electron conductivity is not important)

$$\int_0^\infty \mathrm{d}\nu \int_{-1}^{1} \mu\, I_\nu\, \mathrm{d}\mu = \sigma_{\mathrm{SB}}\, T_{\mathrm{eff}}^4 \quad \rightarrow \quad \int_0^\infty \alpha_\nu \left[J_\nu - B_\nu \right] \mathrm{d}\nu = 0$$

- hydrostatic equilibrium (radiative force is not important)

$$P = k_{\mathrm{B}}\, N\, T = g\, y$$

- ionization equilibrium
  based on the occupation-probability formalism for non-ideal plasmas
  (e.g., Hummer & Mihalas 1988)



- radiative opacities:

  absorption due to free-free, bound-free and bound-bound transitions

  the Thomson scattering on electrons

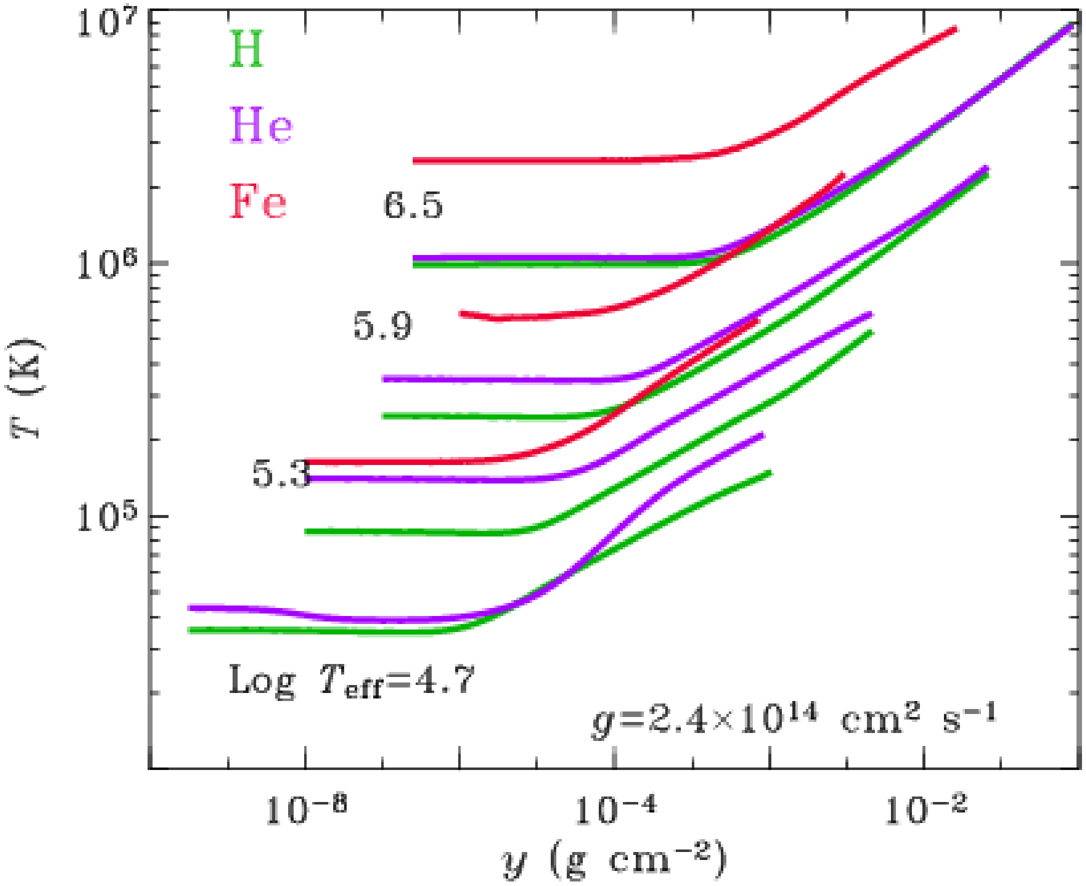
$$k_\nu \sim E^{-3}$$

Model input: T_{eff}, M, R (or g), chemical composition

Model output:

$F_\nu = 4\pi h_\nu J_\nu$ — spectral (monochromatic) flux at $y = 0$

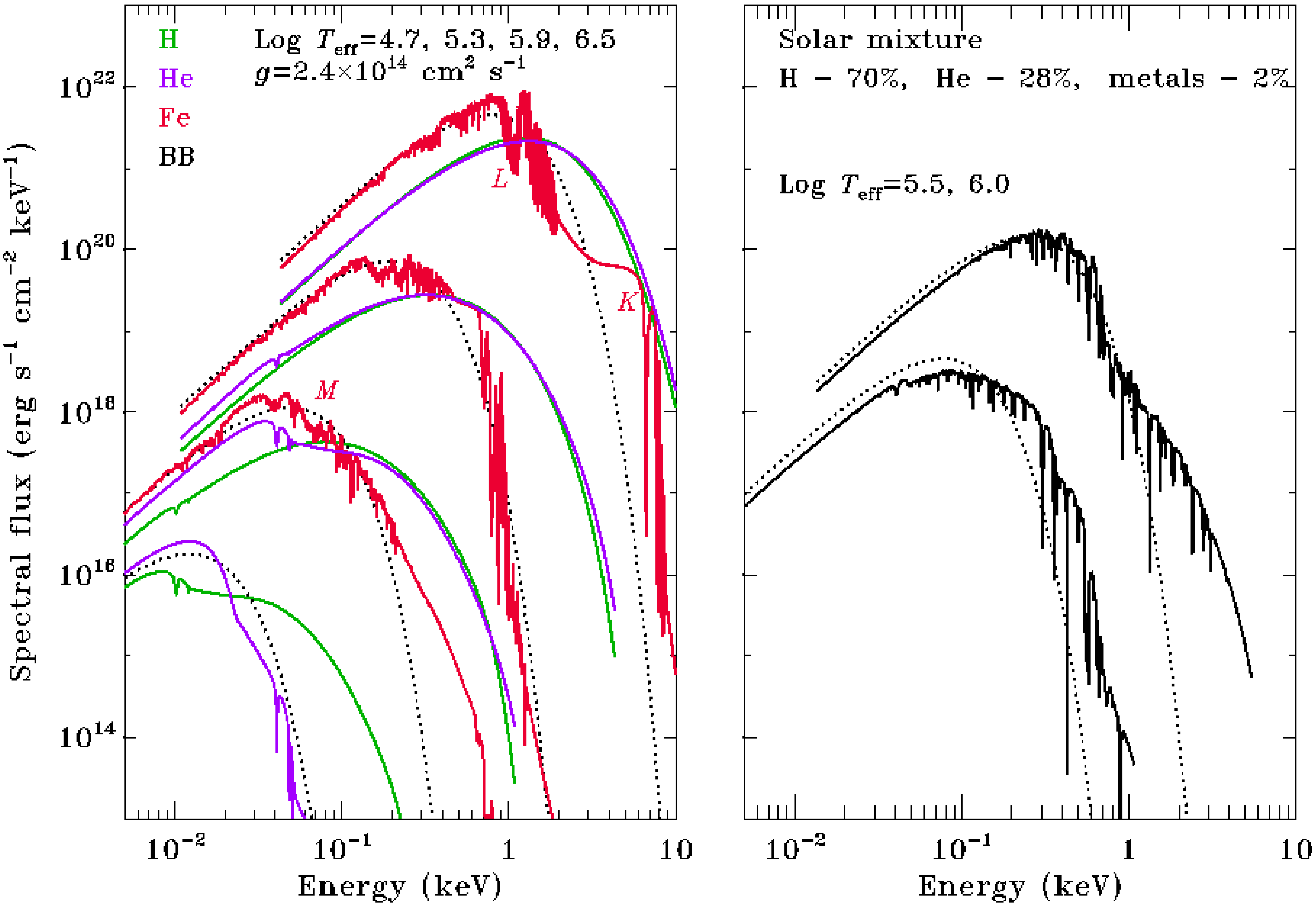
$I_\nu = \mu^{-1} \int^{\infty} S_\nu k_\nu \exp\left[-\mu^{-1} \int^{y} k_\nu \,\mathrm{d}x\right] \mathrm{d}y$ — specific intensity



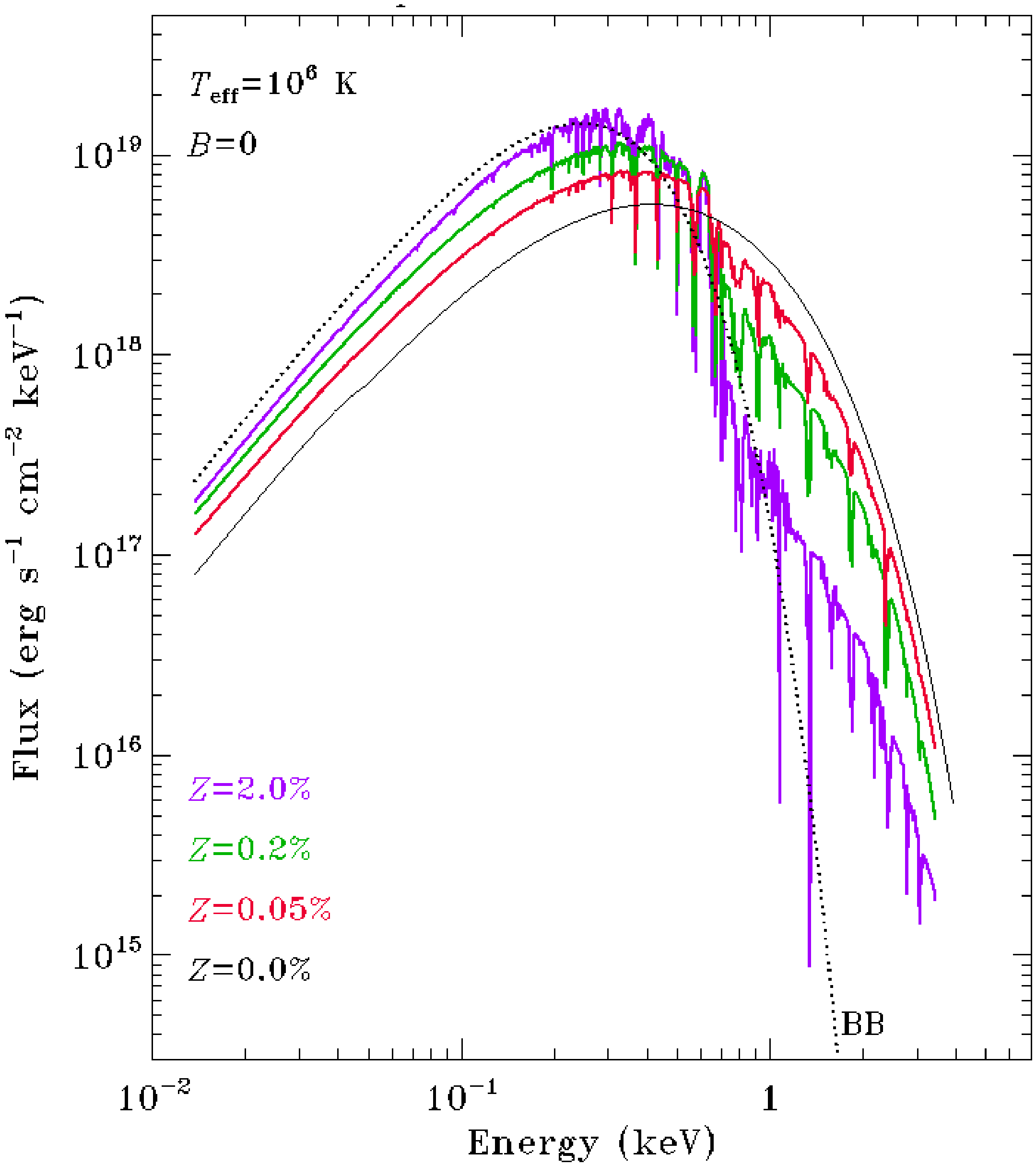
atmospheric structure:

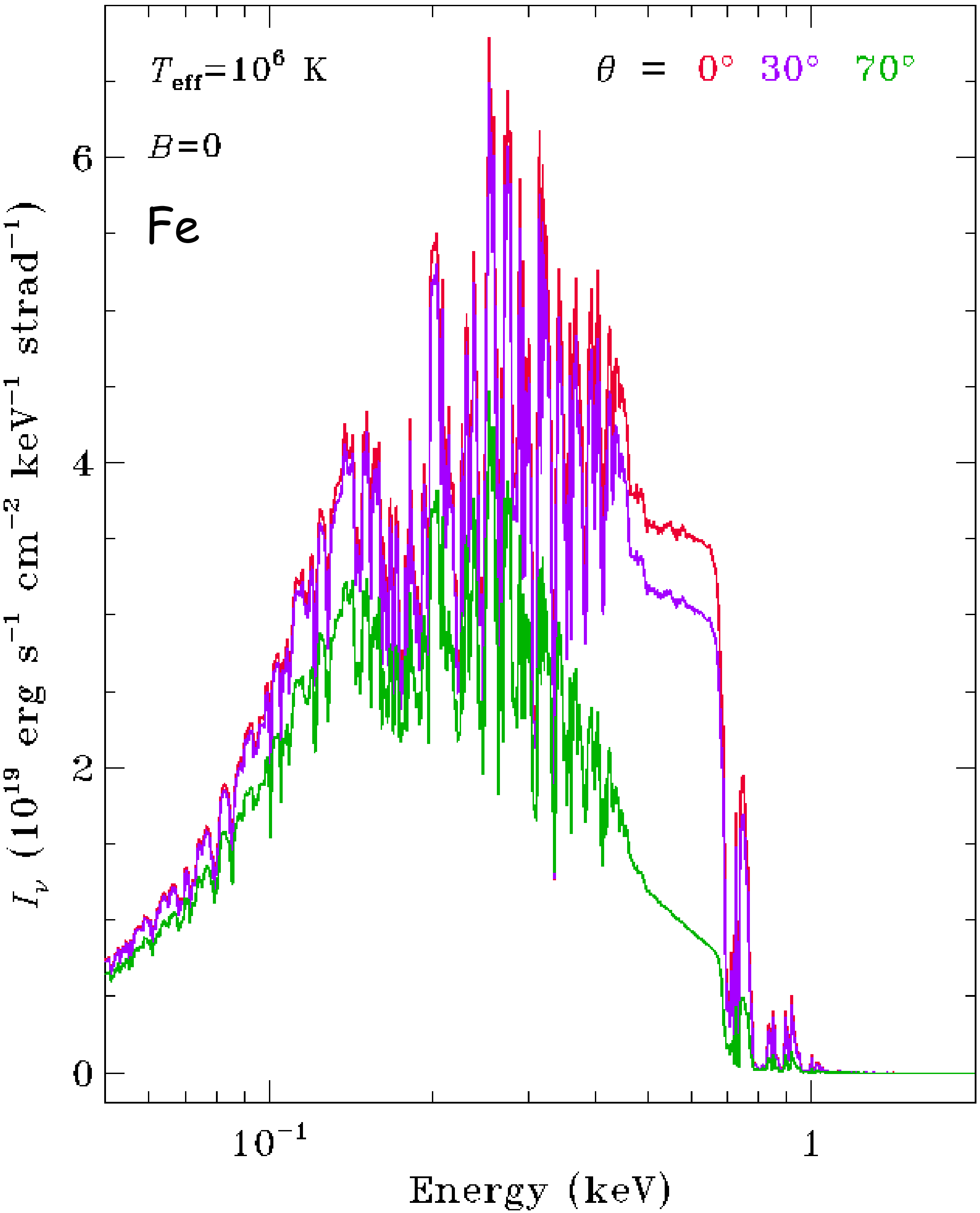
$T(y), \rho(y)$

Spectra of nonmagnetic NS atmospheres



Spectra of nonmagnetic NS atmospheres with various abundances of heavy elements





Angular dependences of specific intensities —

radiation is anisotropic even in nonmagnetic case

limb-darkening effect

NS atmosphere models with strong magnetic fields, $B = 10^{10} - 10^{14}$ G

(all ordinary pulsars, magnetars, radio-quiet INSs [?])

- radiative transfer for two polarization modes, extra- and ordinary ones, with orthogonal polarizations (Gnedin & Pavlov 1974)

$$\mu \frac{\mathrm{d}}{\mathrm{d}y} I_\nu^{\mathrm{j}}(\vec{\mathbf{n}}) = k_\nu^{\mathrm{j}}(\vec{\mathbf{n}})\; I_\nu^{\mathrm{j}}(\vec{\mathbf{n}}) -$$

$$- \left[\sum_{\mathrm{i}=1}^{2} \oint \mathrm{d}\vec{\mathbf{n}}'\, I_\nu^{\mathrm{i}}(\vec{\mathbf{n}}')\, \sigma_\nu^{\mathrm{i\,j}}(\vec{\mathbf{n}},\vec{\mathbf{n}}') + \alpha_\nu^{\mathrm{j}}(\vec{\mathbf{n}}) \frac{B_\nu}{2} \right]$$

$$k_\nu^{\mathrm{j}}(\vec{\mathbf{n}}) = \alpha_\nu^{\mathrm{j}} + \sigma_\nu^{\mathrm{j}}\,, \quad \sigma_\nu^{\mathrm{j}} = \sum_{i=1}^{2} \oint \mathrm{d}\vec{\mathbf{n}}'\, \sigma_\nu^{\mathrm{i\,j}}(\vec{\mathbf{n}},\vec{\mathbf{n}}')$$

— total radiative opacity, scattering+absorption

- radiative and hydrostatic equilibrium

Diffusion approximation:

$$\frac{\mathrm{d}}{\mathrm{d}y} D^{\mathrm{j}}_{\nu} \frac{\mathrm{d}}{\mathrm{d}y} J^{\mathrm{j}}_{\nu} - \sigma_{\nu} \left[J^{\mathrm{j}}_{\nu} - J^{3-\mathrm{j}}_{\nu} \right] = \alpha^{\mathrm{j}}_{\nu} \left[J^{\mathrm{j}} - \frac{B_{\nu}}{2} \right]$$

$$\alpha^{\mathrm{j}}_{\nu} = \frac{1}{4\pi} \oint \mathrm{d}\vec{\mathbf{n}}\, \alpha^{\mathrm{j}}_{\nu}(\vec{\mathbf{n}})$$

$$\sigma_{\nu} = \frac{1}{4\pi} \oint\!\!\oint \mathrm{d}\vec{\mathbf{n}}\, \mathrm{d}\vec{\mathbf{n}}'\, \sigma^{12}_{\nu}(\vec{\mathbf{n}}, \vec{\mathbf{n}}')$$

$$D^{\mathrm{j}}_{\nu} = D^{\|}_{\mathrm{j}} \cos^{2}\Theta_{B} + D^{\perp}_{\mathrm{j}} \sin^{2}\Theta_{B}\,, \quad D^{\|}_{\mathrm{j}} = \int_{0}^{1} \frac{\mu^{2}}{k^{\mathrm{j}}_{\nu}}\, \mathrm{d}\mu\,, \quad D^{\perp}_{\mathrm{j}} = \frac{1}{2} \int_{0}^{1} \frac{(1-\mu^{2})}{k^{\mathrm{j}}_{\nu}}\, \mathrm{d}\mu$$

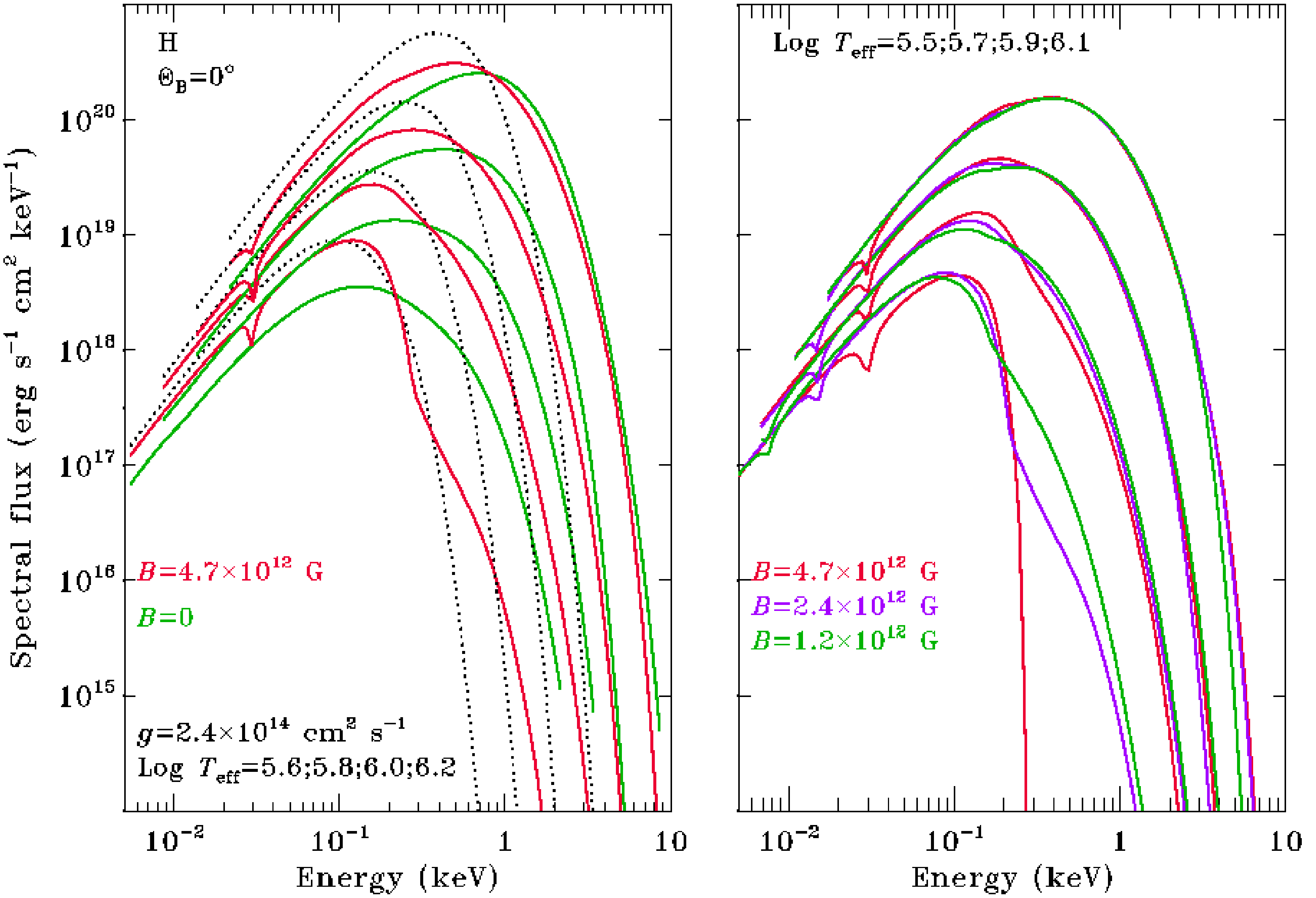
$$\cos\Theta_{B} = \vec{\mathbf{B}} \cdot \vec{\mathbf{r}}$$

Model output: specific intensity and spectral flux at $y = 0$

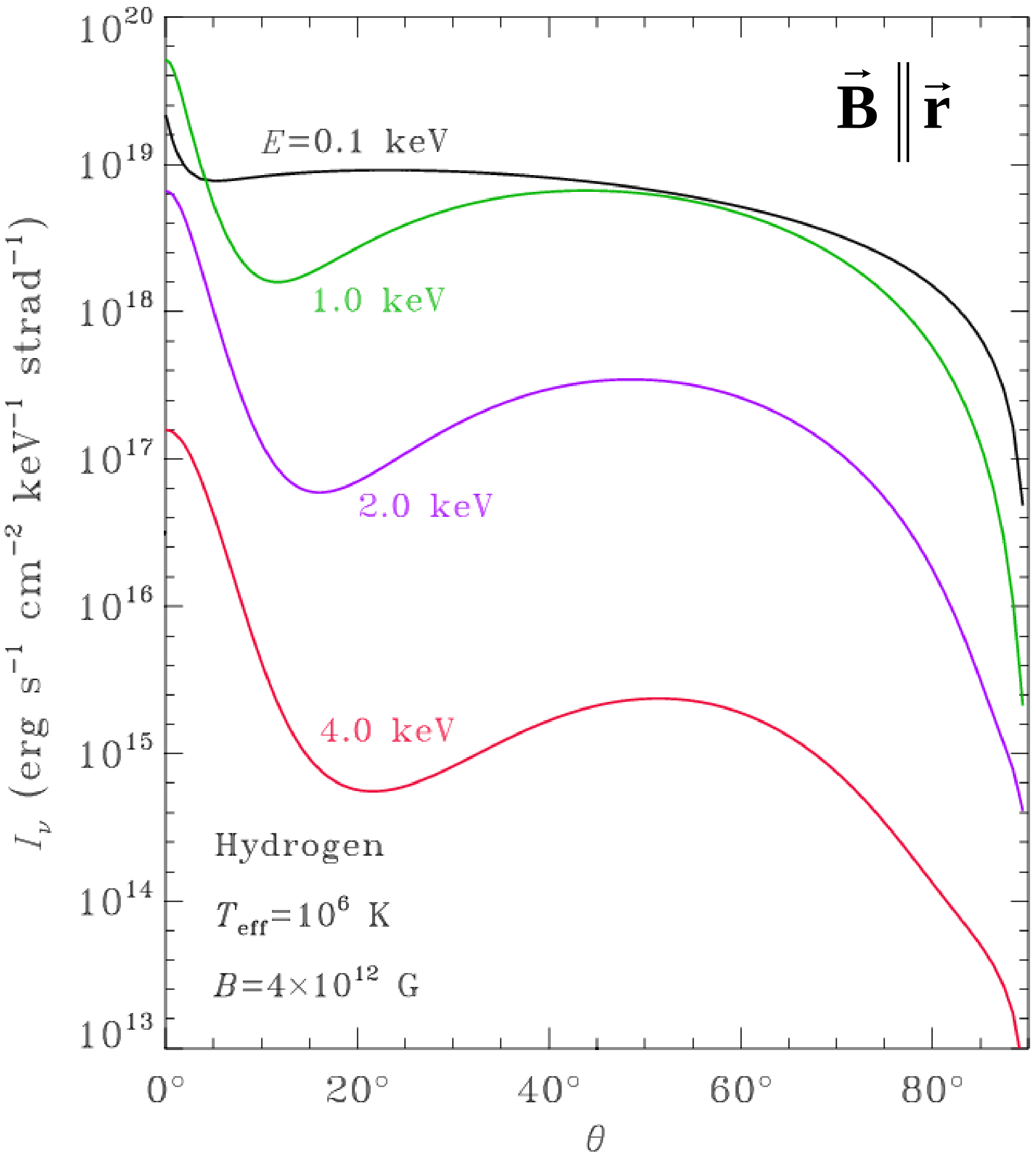
$$I^{\mathrm{j}}_{\nu} = \mu^{-1} \int_{0}^{\infty} \left[\alpha^{\mathrm{j}}_{\nu} \frac{B_{\nu}}{2} + \sum_{\mathrm{i}=1}^{2} \sigma^{\mathrm{ji}}_{\nu} J^{\mathrm{j}}_{\nu} \right] \exp\left[-\mu^{-1} \int_{0}^{y} k^{\mathrm{j}}_{\nu}\, \mathrm{d}x \right] \mathrm{d}y$$

$$F^{\mathrm{j}}_{\nu} = \int_{0}^{1} \mu I^{\mathrm{j}}_{\nu}\, \mathrm{d}\mu$$

NS atmosphere models with strong magnetic fields, $B = 10^{11} - 10^{14}$ G



Angular dependence of radiation from a magnetized NS atmosphere:

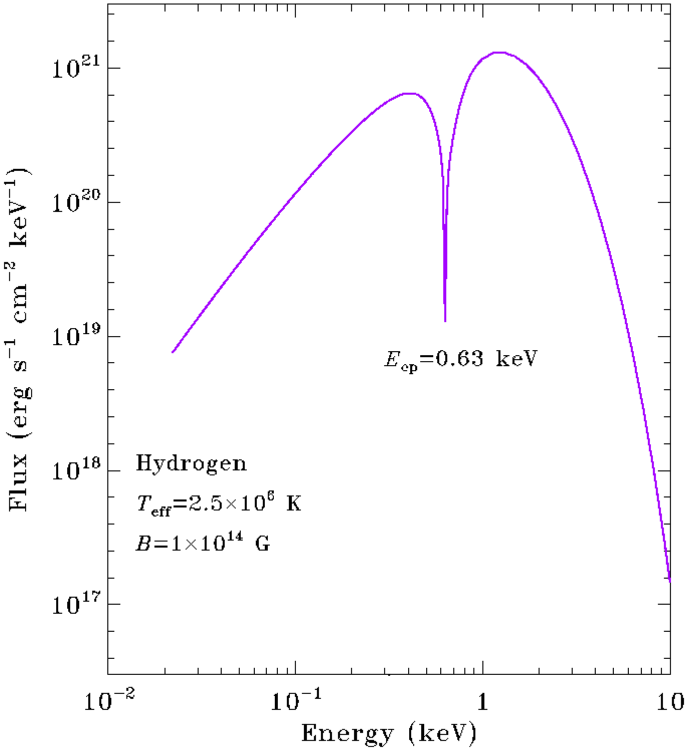


"pencil"-like structure along $\vec{\mathbf{B}}$

"fan"-like structure at larger angles

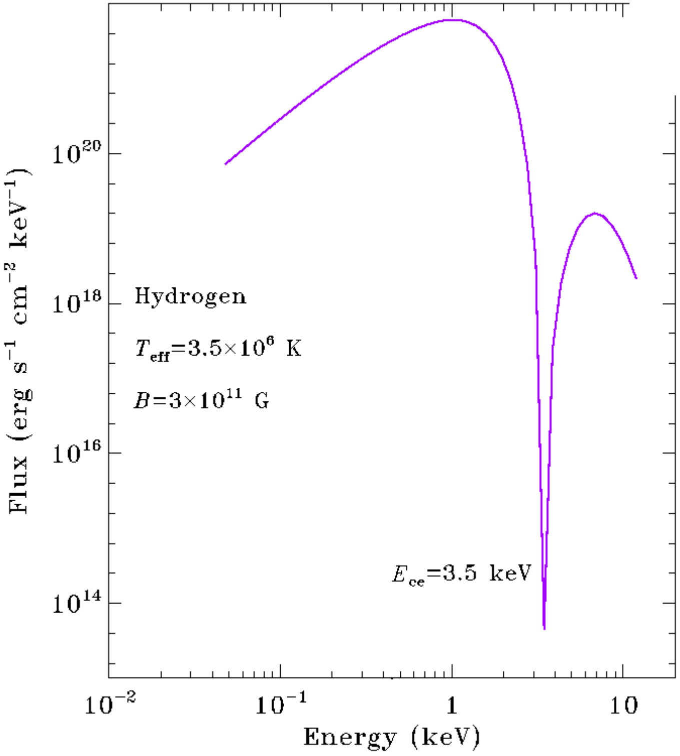
proton cyclotron line

$B = 1\times10^{14}$ G



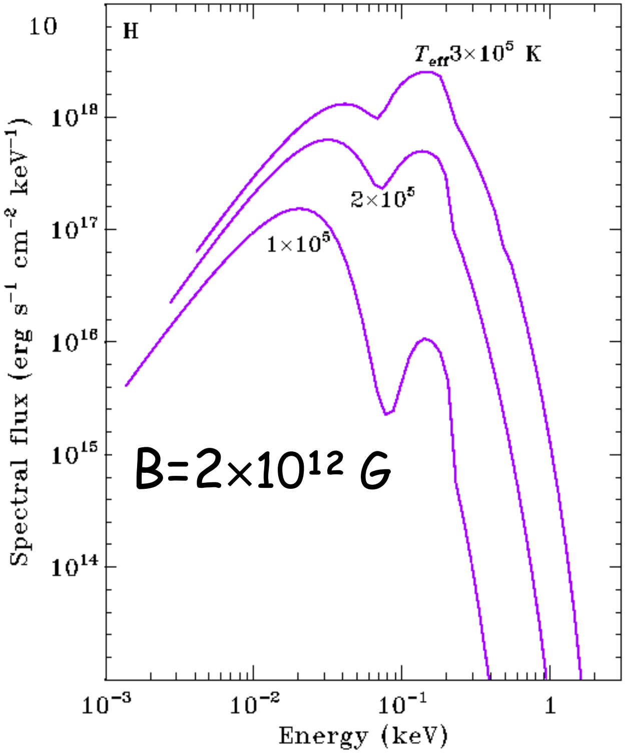
electron cyclotron line

$B = 3\times10^{11}$ G



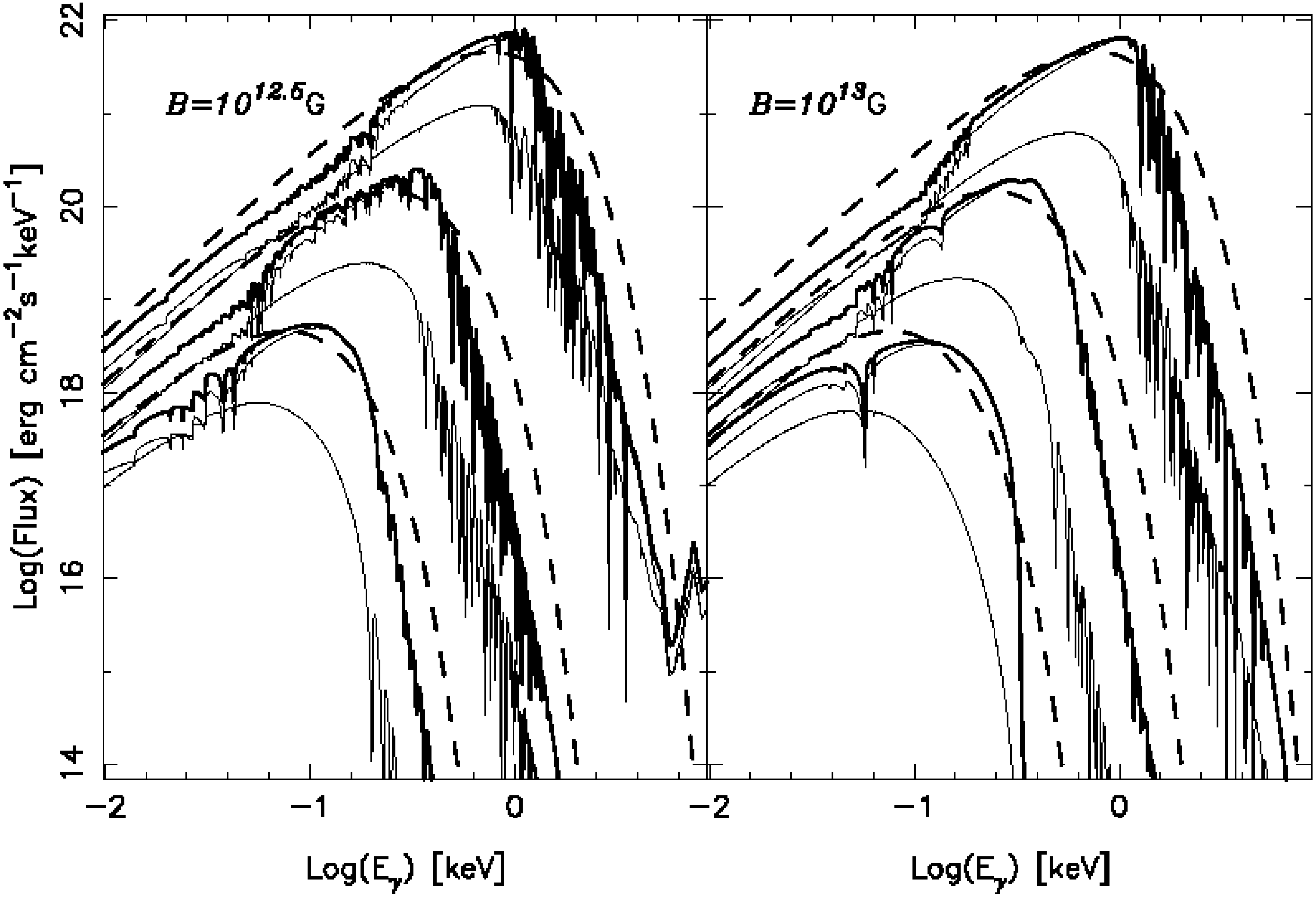
atomic transitions

$T_{eff} < 5\times10^5$ K



$B=2\times10^{12}$ G

Iron magnetized NS atmosphere models (Rajagopal et al. 1997)



More on hydrogen NS models for $B > 10^{14}$—10^{15} G, fully ionized case:

Özel 2001, Zane et al. 2001, Ho & Lai 2001 →

studying vacuum-polarization effects (Gnedin et al. 1977):
conversion of normal modes of radiation —
in particular, it affects cyclotron lines (makes them very narrow)

More on partially ionized hydrogen atmosphere models:

Ho et al. 2003, Ho & Lai 2004 →
spectral features due to bound-free and bound-bound transitions

First magnetized NS atmosphere models for C, O, Ne chemical compositions (Mori et al. 2006)

Thermal emission as seen by a distant observer

General case: $F(E) = g_r \frac{1}{d^2} \int_S \mu\, I(g_r^{-1}E)\, \mathrm{d}S \qquad [\times \exp(-n_{\mathrm{H}}\sigma)]$

$g_r = \left[1 - \frac{2GM}{c^2 R}\right]^{1/2}$ — redshift parameter

E — observed (redshifted) energy

S — visible emitting area

d — distance to the object

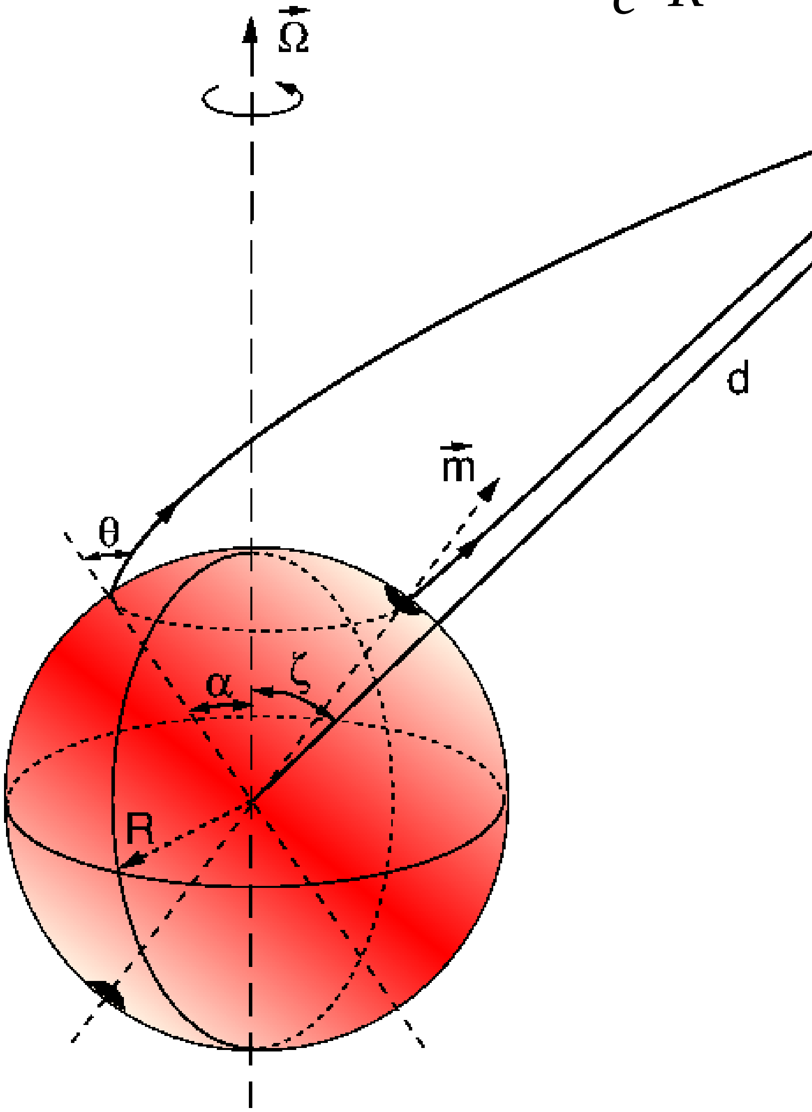
- nonuniform surface temerature and magnetic field
- gravitational bending of photon trajectories
- Doppler shifts of photon energies (for fast rotators)

Small heated spots (polar caps):

$$F(E) = g_r \frac{S_a}{d^2}\, I(g_r^{-1}E\,, \mu^*)$$

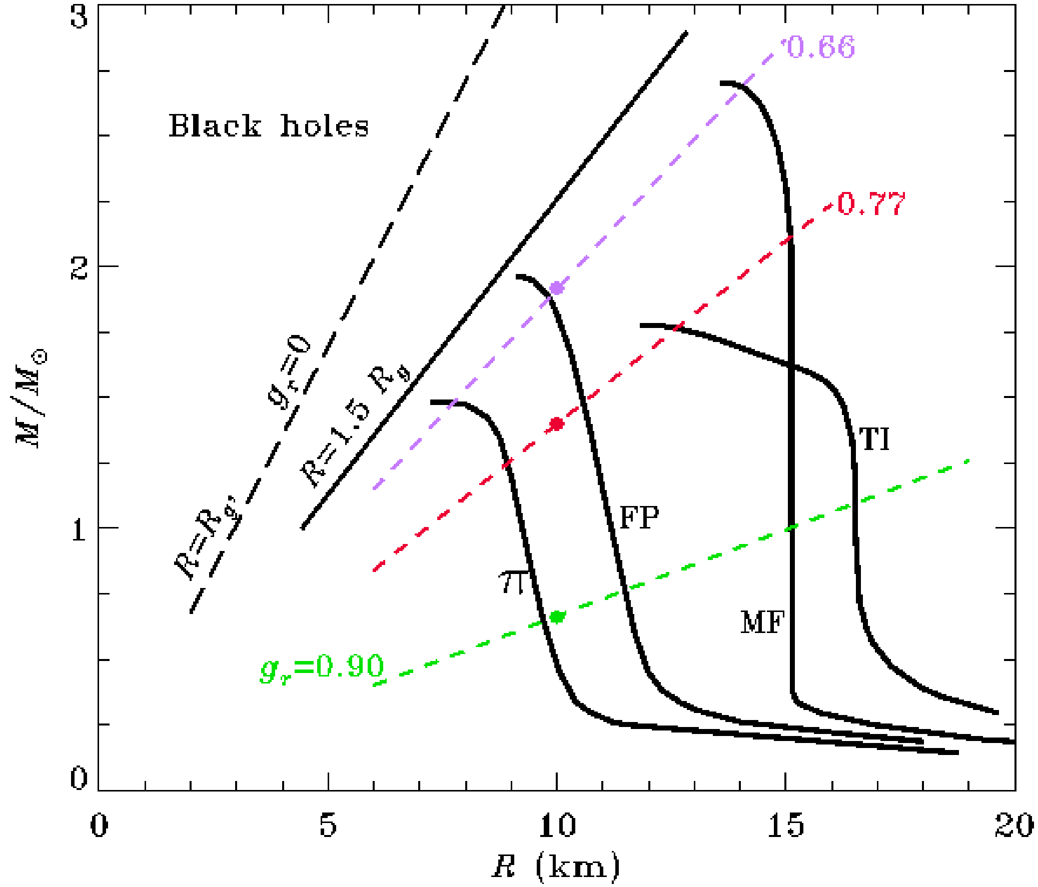
Gravitational bending of photon trajectories

$$g_r = \left[1 - \frac{2GM}{c^2 R}\right]^{1/2}$$

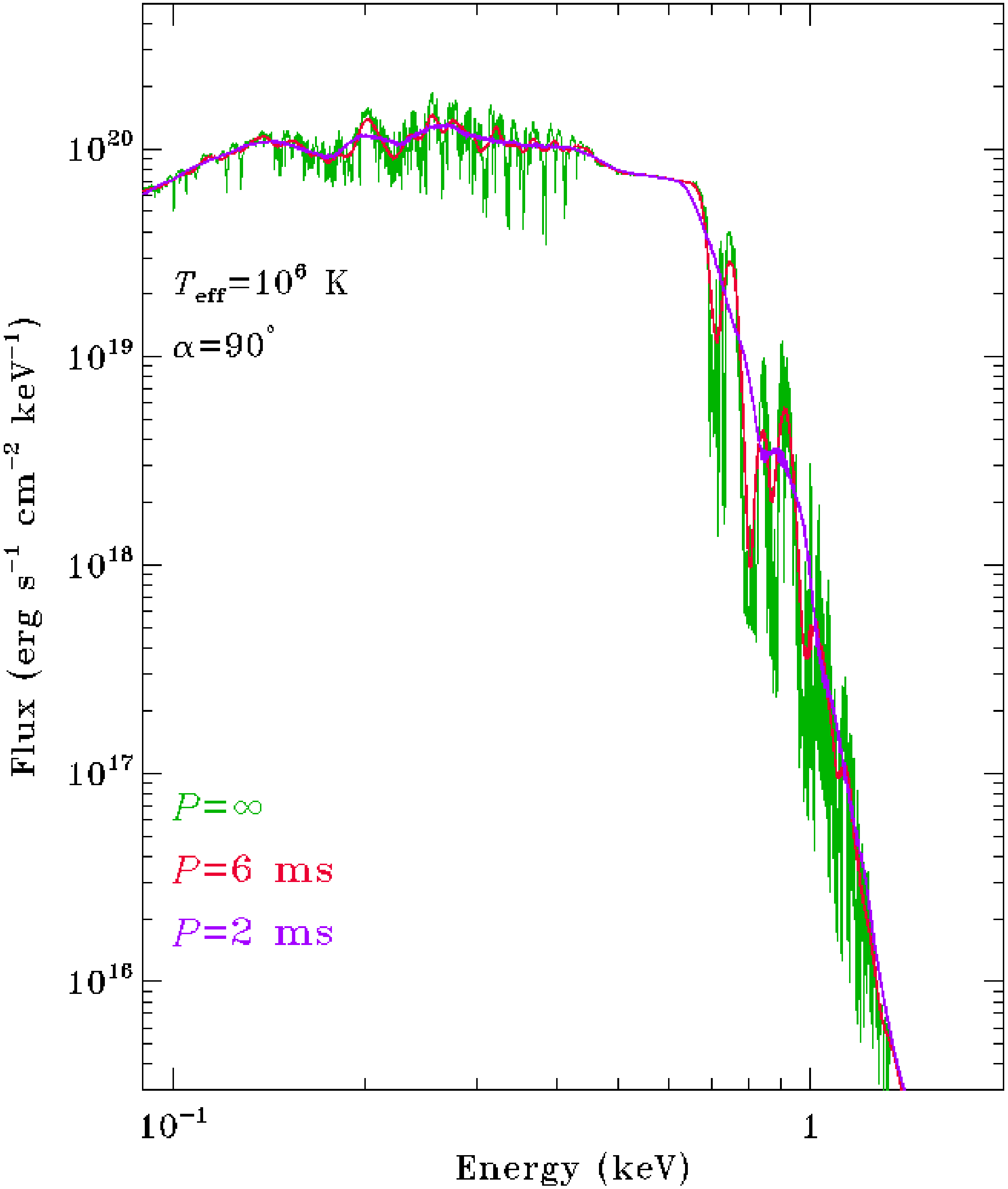


the **whole** surface is visible if

$$g_r < 0.66$$

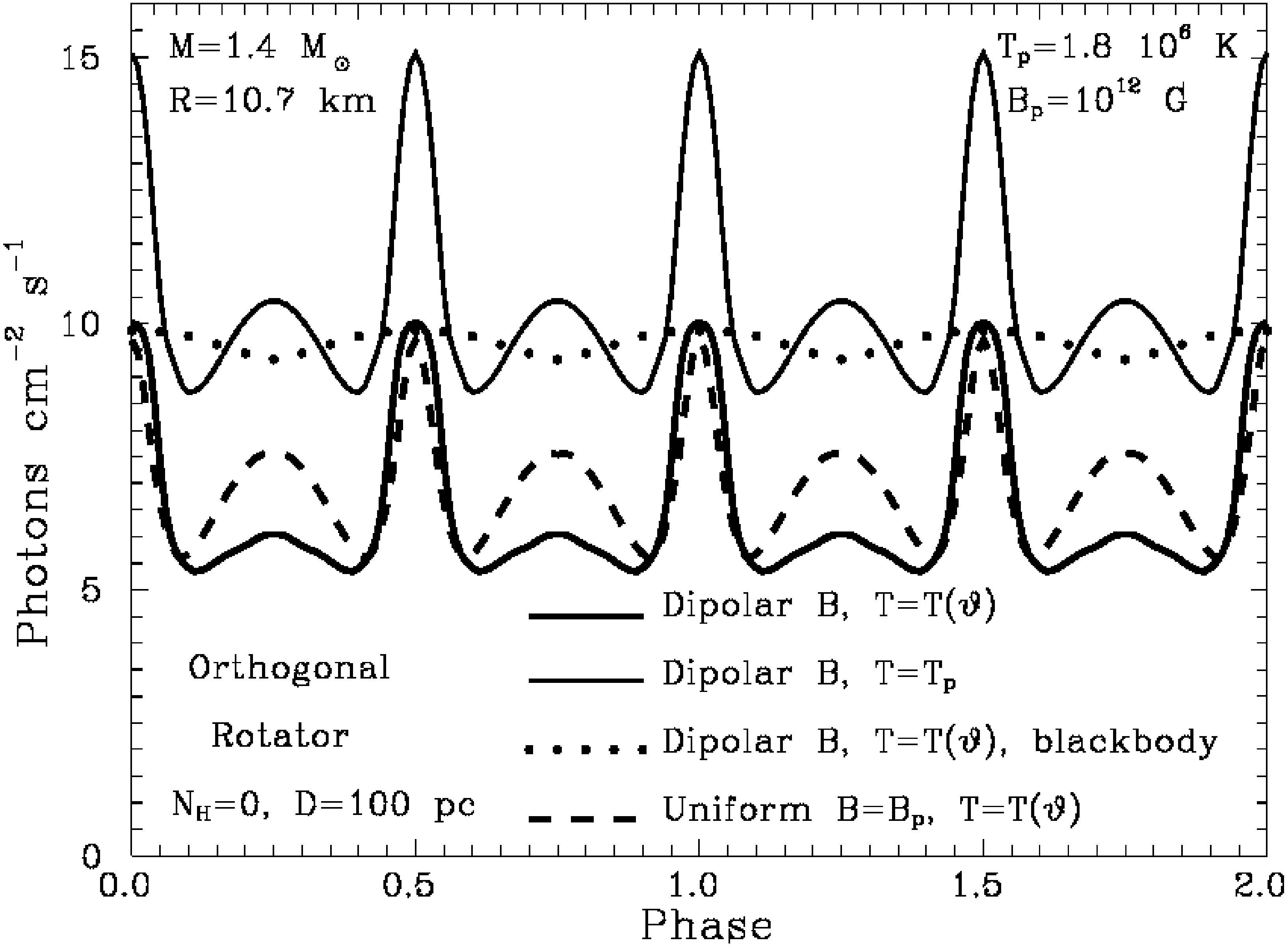


Effect of the Doppler shift

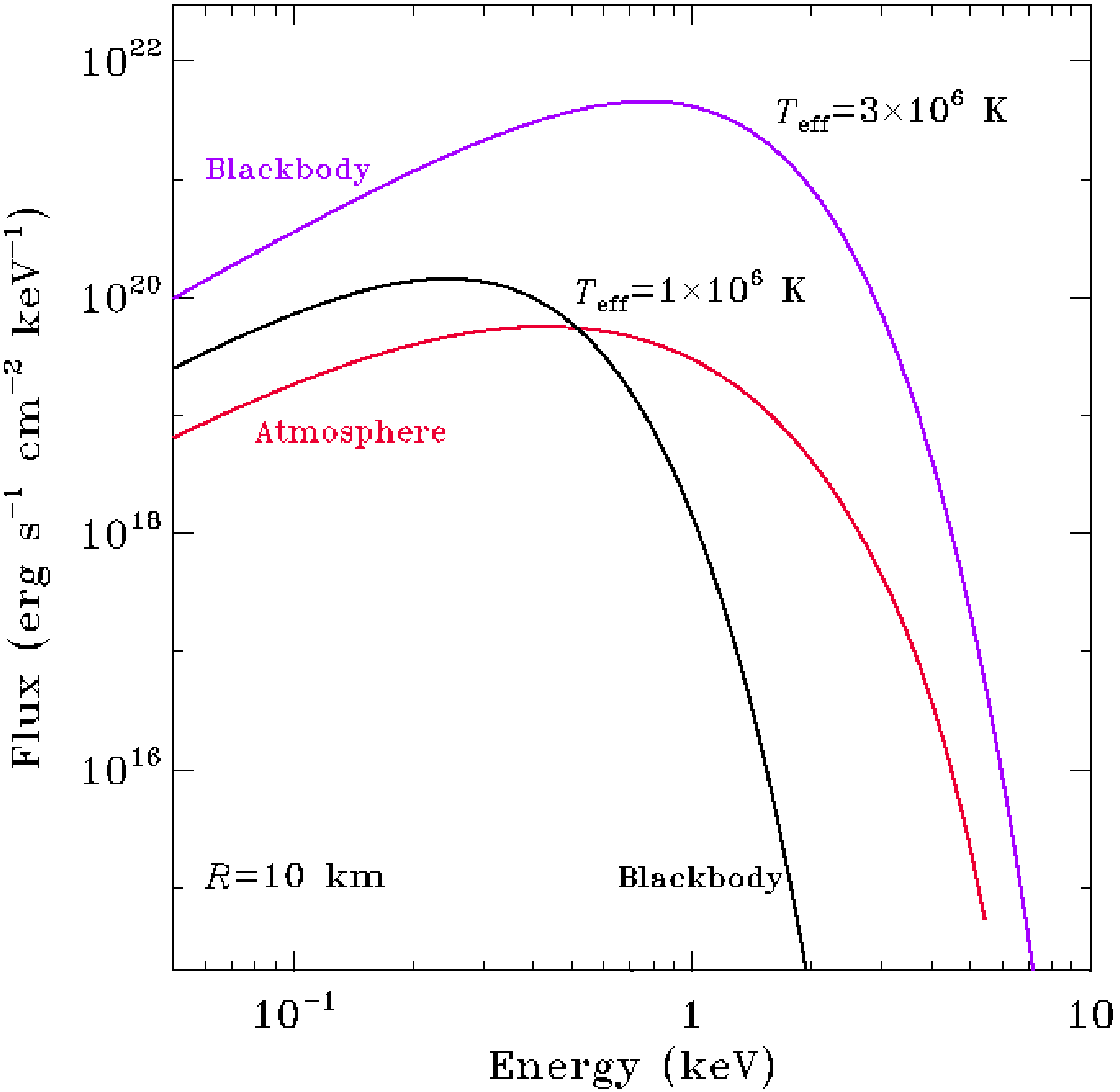


Spectra from the whole surface of a nonmagnetized NS (iron atmosphere)

Light curves of radiation from a magnetized NS



Practical aspect: NS atmosphere vs. blackbody model



$T_{bb} / T_{atm} \approx$ 2-3

$S_{atm} / S_{bb} \approx$ 50-200

Successful applications of hydrogen atmosphere models:

- young pulsars, Vela, J0538+2817, B1706-44 (10—30 kyr), whose thermal emission originates from the whole NS surface of T>1 MK
- millisecond and old pulsars with thermal X-ray component emitted from heated polar caps, J0437-4715, J2124-3358, J0030+0451, J1024-0719, B0950+08, J2043+2740
- compact central sources in the SNR Puppis A, RX J0822-4300, and in the SNR CTA 1, RX J0007+7302 — thermal emission from the whole NS surface
- transiently accreting NSs in X-ray binaries, Aql X-1, Cen X-4, KS 1713-260, 4U 2129+47, MXB 1659-29 — quiescent radiation is interpreted as emitted from the whole NS surface due to heat released in the compressed material
- hydrogen atmosphere models can be useful for distinguishing between transiently accreting NSs and black holes, in quiescence

NS atmospheres do not work:

middle-aged pulsars (100 — 300 kyr), Geminga, PSRs 0656+14, 1055-52...

old radio-quiet isolated NSs, RX J1856-3754, J0720-3125, J1308+2127...

These have lower surface temperatures, (0.5 —0.7) MK, and high magnetic fields → atmospheres may not exist

Problems, future work

- bound-bound transitions in superstrong field $B > 10^{14}$ G, when the lines get into observable X-ray range
- molecules and molecular chains in strong magnetic fields
- reliable models for partially ionized atmospheres for for various chemical compositions
- radiative transfer approach based on two polarization modes is inaccurate for partially ionized plasma
- solving the radiative transfer equations for the four Stokes parameters using the polarizability tensor constracted with aid of the Kramers-Kronig relation
- “thin“ atmosphere models — optically thick only at lower energies

From atmospheres to condensed surfaces

- solids and liquids in strong magnetic fields
- phase transition from atmospheres to condensed surface
- reliable models for emissivity of condensed surface