

Modeling Atmospheres of Neutron Stars

Isolated NSs: **solitary** NSs or those in binaries **without accretion**

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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, Geminga 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

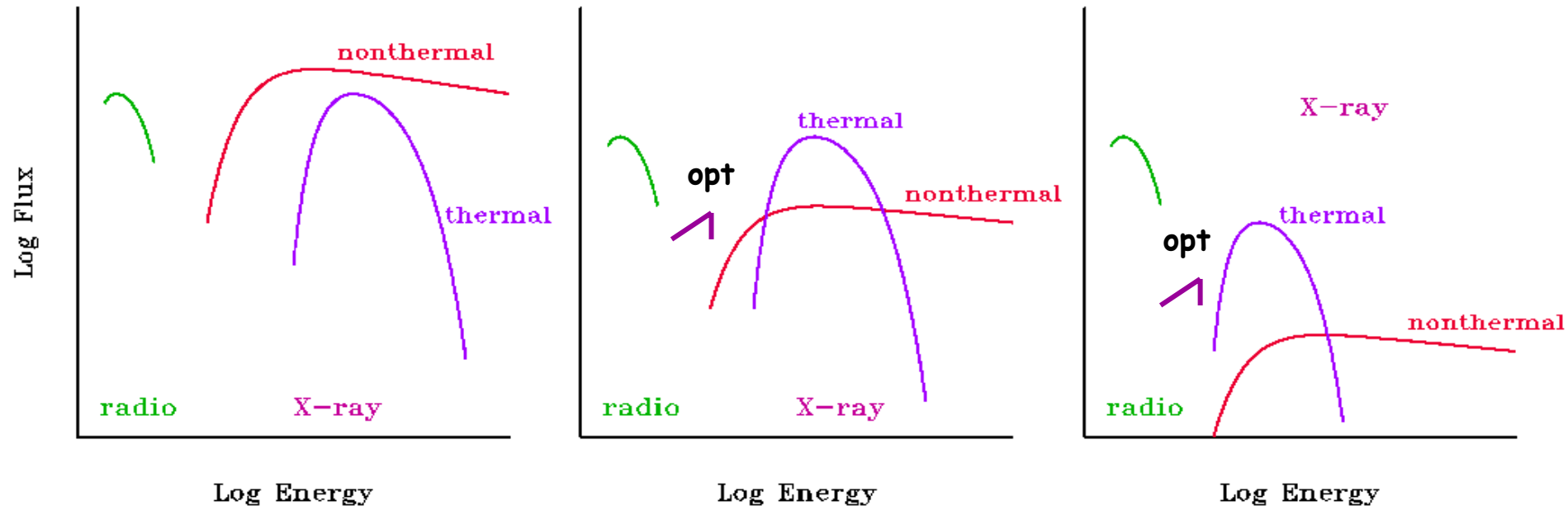
In total, thermal emission detected from about ~30 NSs:

- 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, $\sim \dot{E} \sim t^{-\beta}$, $\beta \sim 2-4$

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;

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

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

Crab, B1509-58,
 B0540-69

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

6-ms J0437-4715,
 B0950+08

Main questions

- Why is studying thermal emission needed?
- What is the state of the NS surface?
Gaseous 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

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

$T_{\text{surf}}(t) \Rightarrow$ 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:

$$T_{\text{surf}} < 1 \times 10^5 \text{ K} \quad @ \quad B = 1 \times 10^{13} \text{ G}$$

$$T_{\text{surf}} < 5 \times 10^5 \text{ K} \quad @ \quad B = 1 \times 10^{14} \text{ G}$$

$$T_{\text{surf}} < 1 \times 10^6 \text{ K} \quad @ \quad B = 5 \times 10^{14} \text{ G}$$

(Lai & Salpeter 1997)

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

A small amount of H,

surface density $\sim 10^{-3} - 10^{-1} \text{ g/cm}^2$

total amount $\sim 10^{10} - 10^{12} \text{ g}$,

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)

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

⇒ NS atmospheres are strongly **compressed**

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

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

⇒ **stratification** of chemical elements

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

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

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

\Rightarrow NS atmospheres are essentially **anisotropic**

\Rightarrow opacities depend on direction and polarization of radiation

\Rightarrow radiation is **polarized** and depends on B

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

\Rightarrow **atomic structure** is distorted by B

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

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

\Rightarrow altered **ionization equilibrium** and **equation of state**

NS atmosphere models with "low" magnetic fields, $B < 10^8 - 10^9 \text{ G}$
(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 $I_\nu(z, \mu)$

$$\mu \frac{d}{dy} I_\nu = k_\nu [I_\nu - S_\nu], \quad \mu = \cos \theta = \vec{\mathbf{n}} \cdot \vec{\mathbf{r}}, \quad dy = -\rho dz$$

$$k_\nu = \sigma_\nu + \alpha_\nu \quad \text{— total radiative opacity, scattering+absorption}$$

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

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

Comptonization is not important at $T < 5 \times 10^6 \text{ K}$

Most common (diffusion) approach:

$$\frac{d}{dy} k_\nu^{-1} \frac{d}{dy} f_\nu J_\nu = \alpha_\nu [J_\nu - B_\nu]$$

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

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

the Eddington factors (accounting for anisotropy of radiation):

$$f_\nu = [2 J_\nu]^{-1} \int_0^1 \mu^2 I_\nu d\mu \quad (\approx 1/3, \quad y \rightarrow \infty)$$

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

$$F_\nu = \frac{4\pi}{k_\nu} \frac{d}{dy} f_\nu J_\nu \quad \text{— spectral (monochromatic) flux}$$

- radiative equilibrium (electron conductivity is not important)

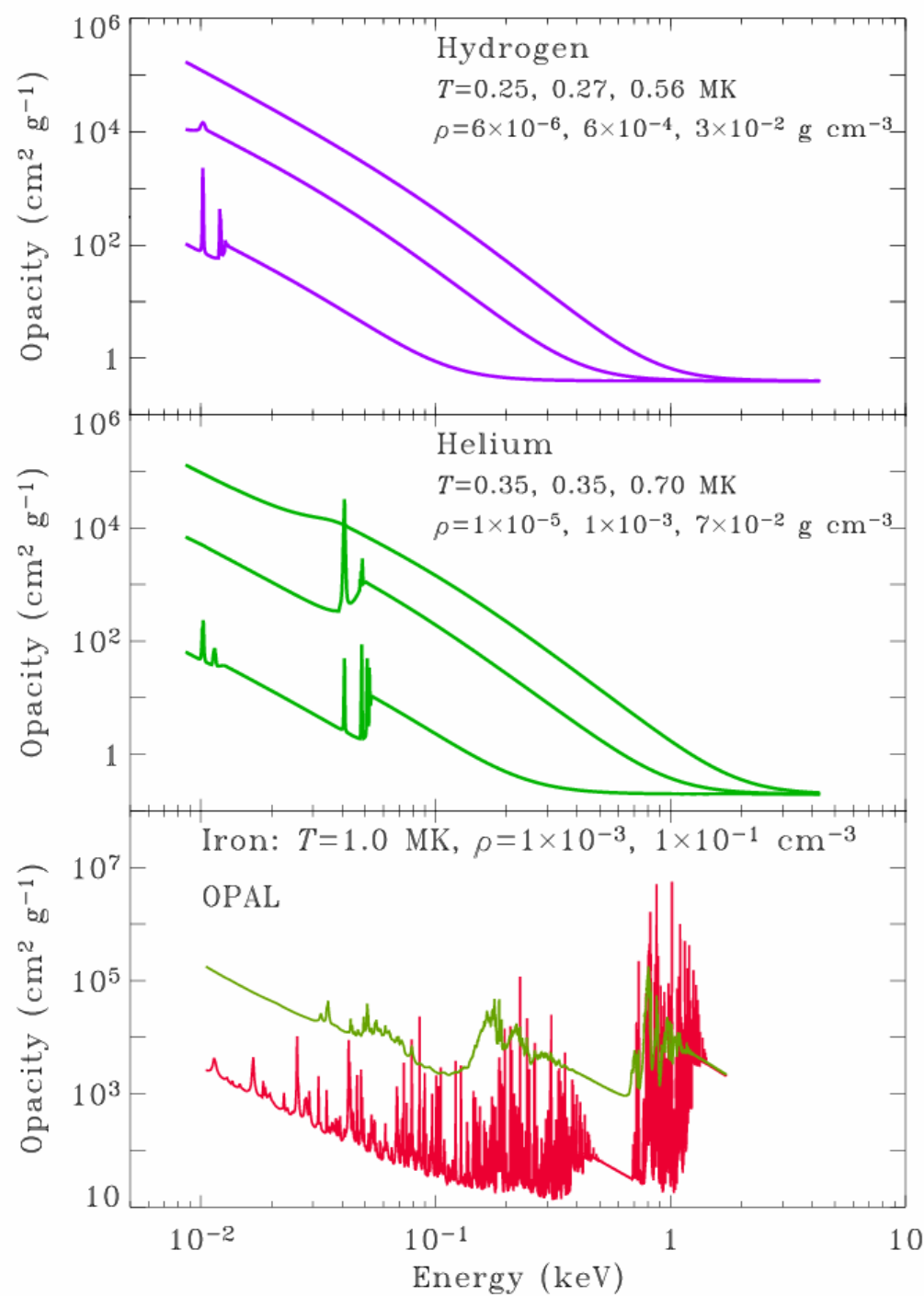
$$\int_0^{\infty} d\nu \int_{-1}^1 \mu I_{\nu} d\mu = \sigma_{\text{SB}} T_{\text{eff}}^4 \quad \rightarrow \quad \int_0^{\infty} \alpha_{\nu} [J_{\nu} - B_{\nu}] d\nu = 0$$

- hydrostatic equilibrium (radiative force is not important)

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

- 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

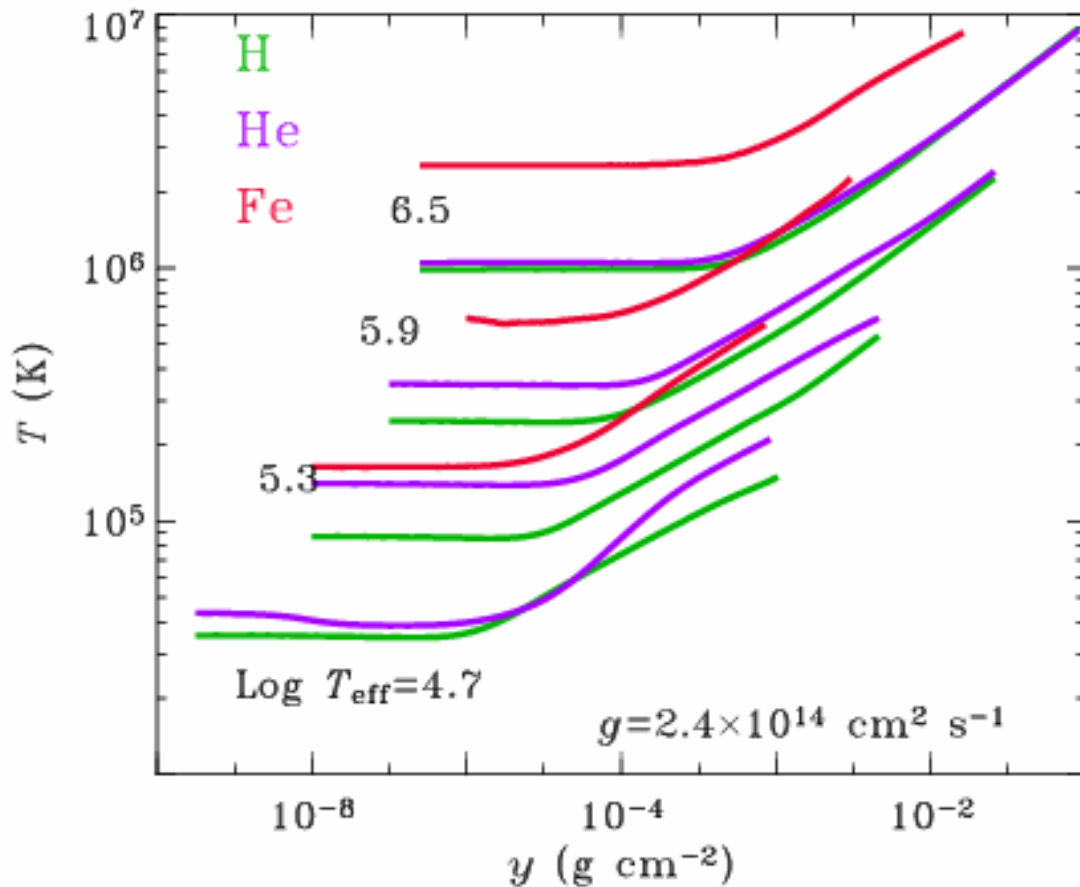
$$k_{\nu} \sim E^{-3}$$

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

Model output:

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

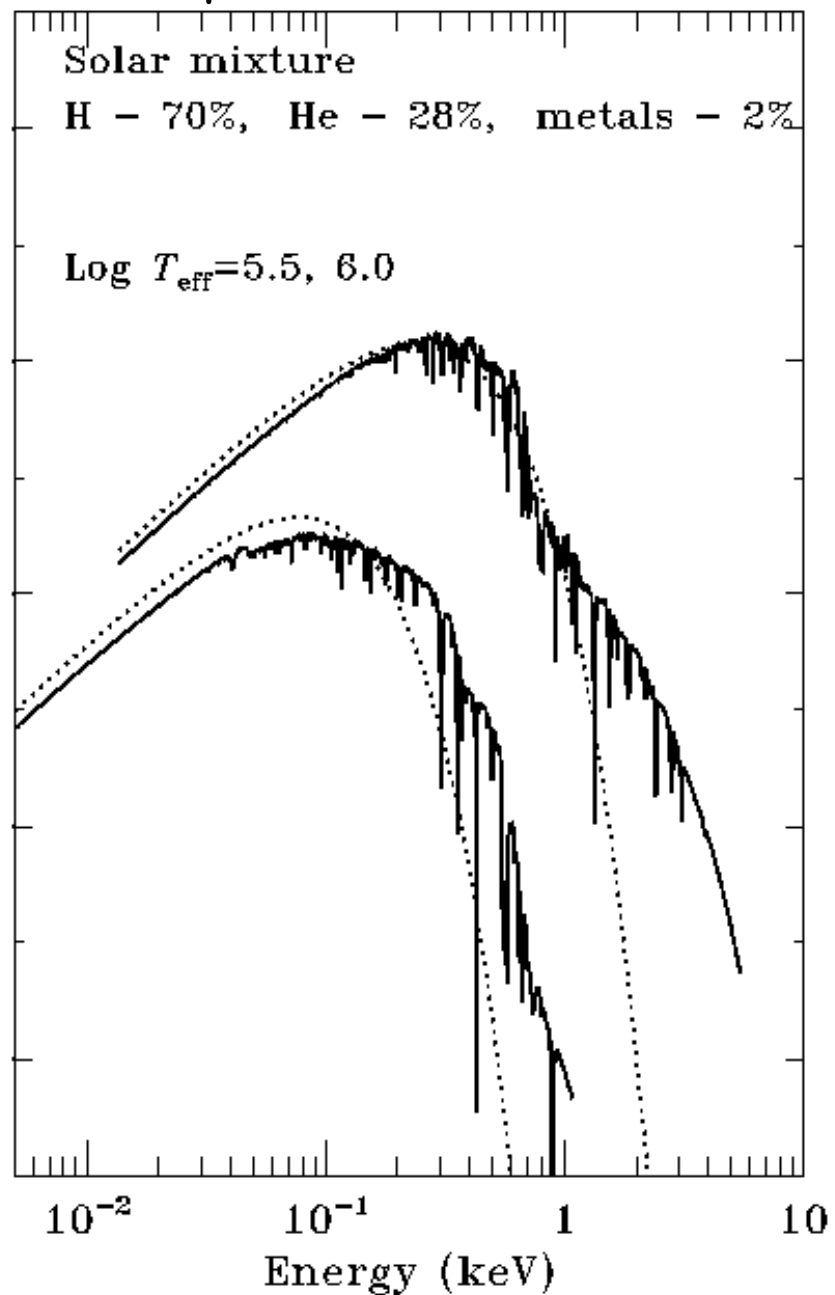
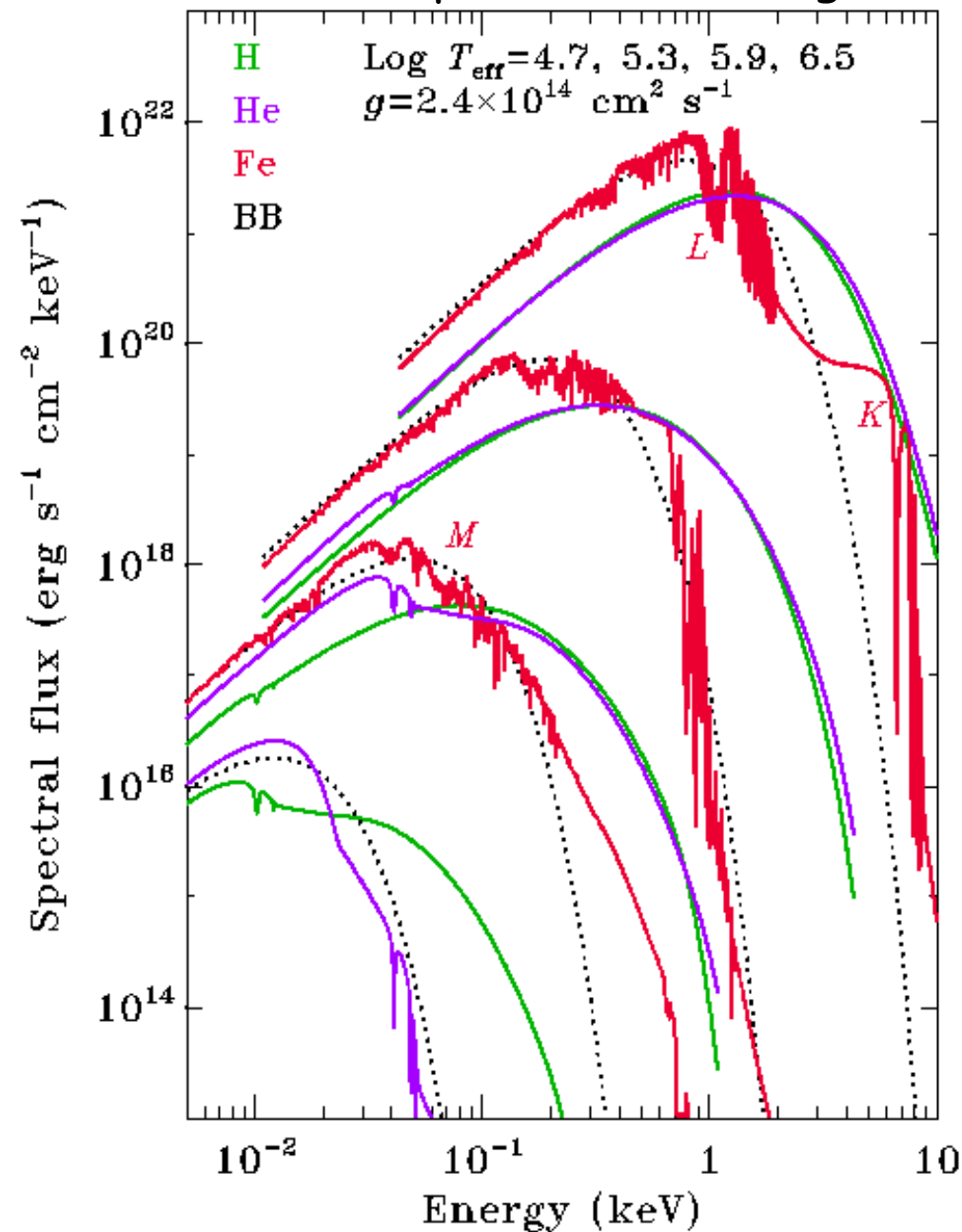
$I_\nu = \mu^{-1} \int_0^\infty S_\nu k_\nu \exp\left[-\mu^{-1} \int_0^y k_\nu dx\right] dy$ — specific intensity



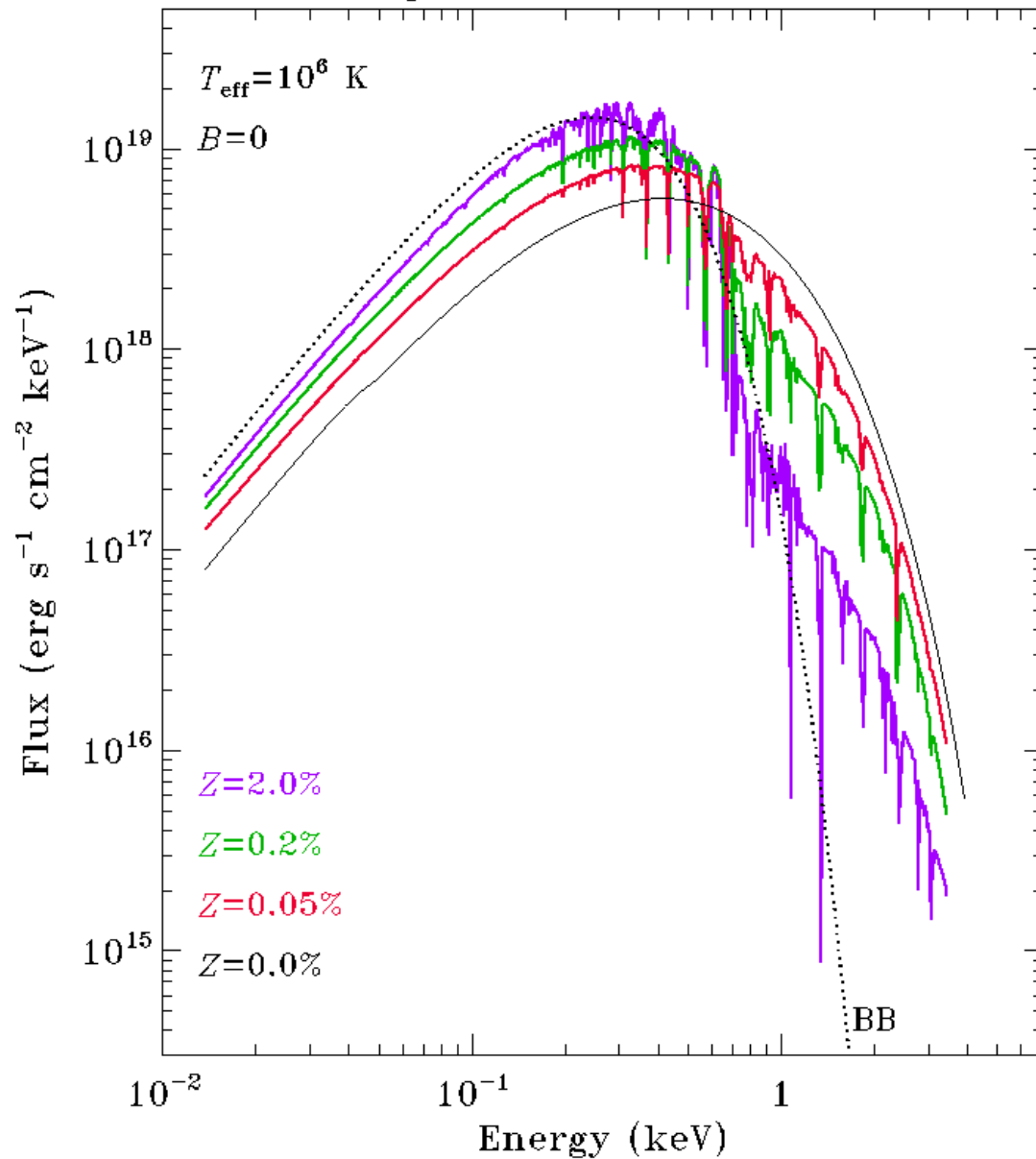
atmospheric structure:

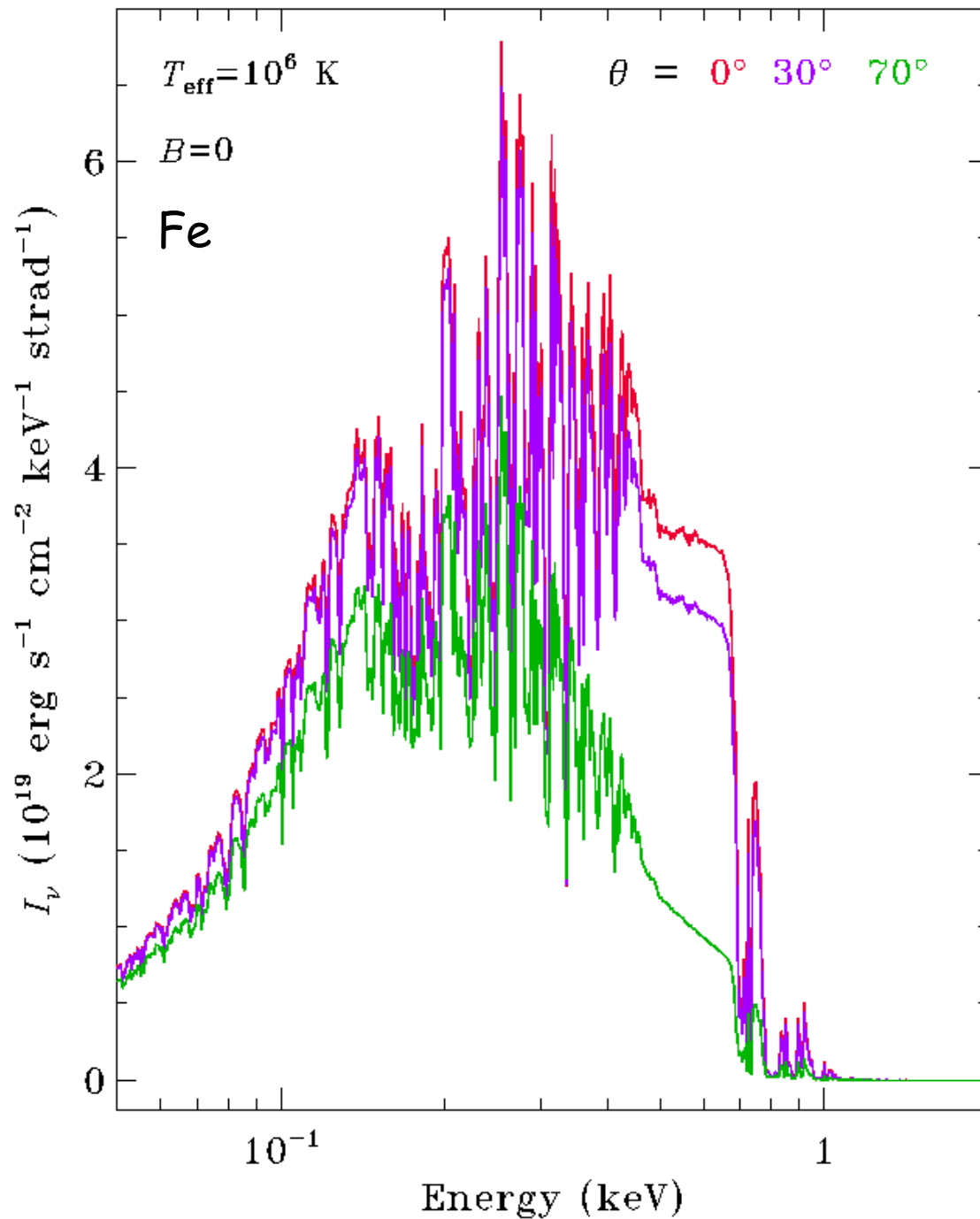
$T(y)$, $\rho(y)$

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, $B = 10^{10} - 10^{14} \text{ G}$

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

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

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

$$k_\nu^j(\vec{\mathbf{n}}) = \alpha_\nu^j + \sigma_\nu^j, \quad \sigma_\nu^j = \sum_{i=1}^2 \oint d\vec{\mathbf{n}}' \sigma_\nu^{ij}(\vec{\mathbf{n}}, \vec{\mathbf{n}}') \quad \text{— total radiative opacity, scattering+absorption}$$

- radiative and hydrostatic equilibrium

Diffusion approximation:

$$\frac{d}{dy} D_v^j \frac{d}{dy} J_v^j - \sigma_v [J_v^j - J_v^{3-j}] = \alpha_v^j \left[J_v^j - \frac{B_v}{2} \right]$$

$$\alpha_v^j = \frac{1}{4\pi} \oint d\vec{n} \alpha_v^j(\vec{n})$$

$$\sigma_v = \frac{1}{4\pi} \iint d\vec{n} d\vec{n}' \sigma_v^{12}(\vec{n}, \vec{n}')$$

$$D_v^j = D_j^{\parallel} \cos^2 \Theta_B + D_j^{\perp} \sin^2 \Theta_B, \quad D_j^{\parallel} = \int_0^1 \frac{\mu^2}{k_v^j} d\mu, \quad D_j^{\perp} = \frac{1}{2} \int_0^1 \frac{(1-\mu^2)}{k_v^j} d\mu$$

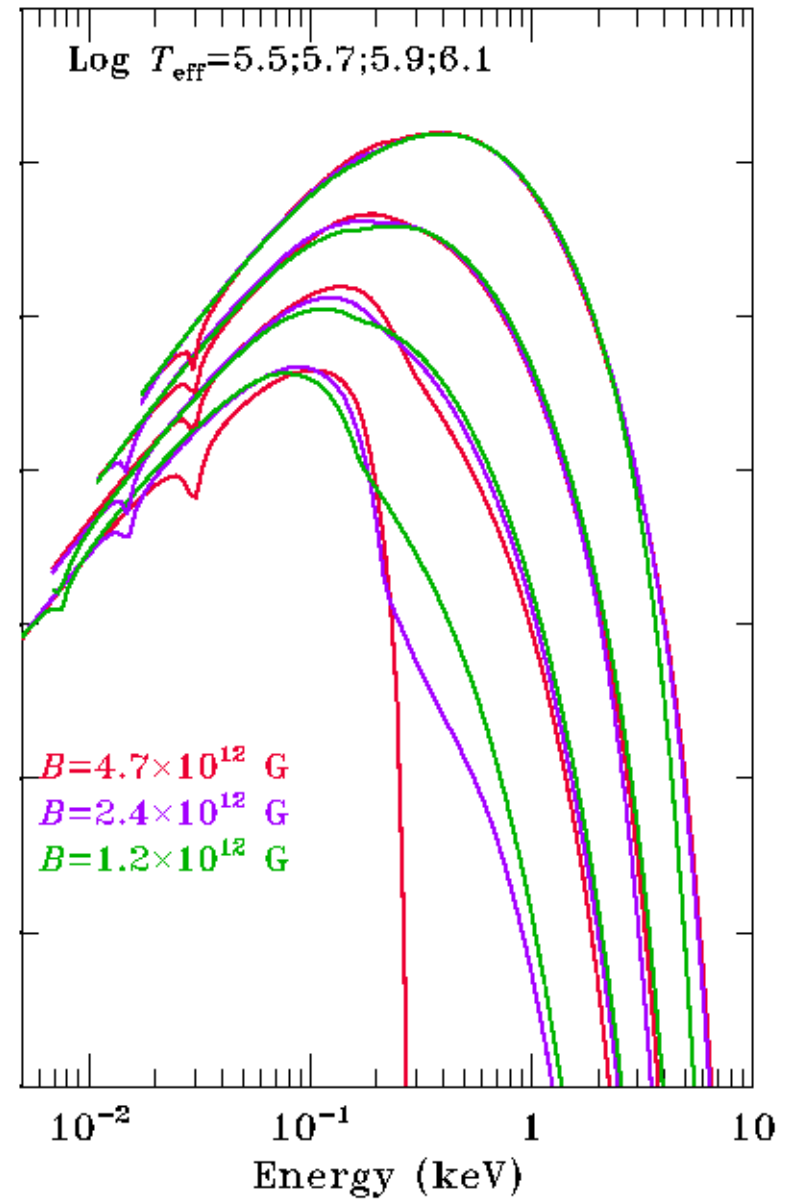
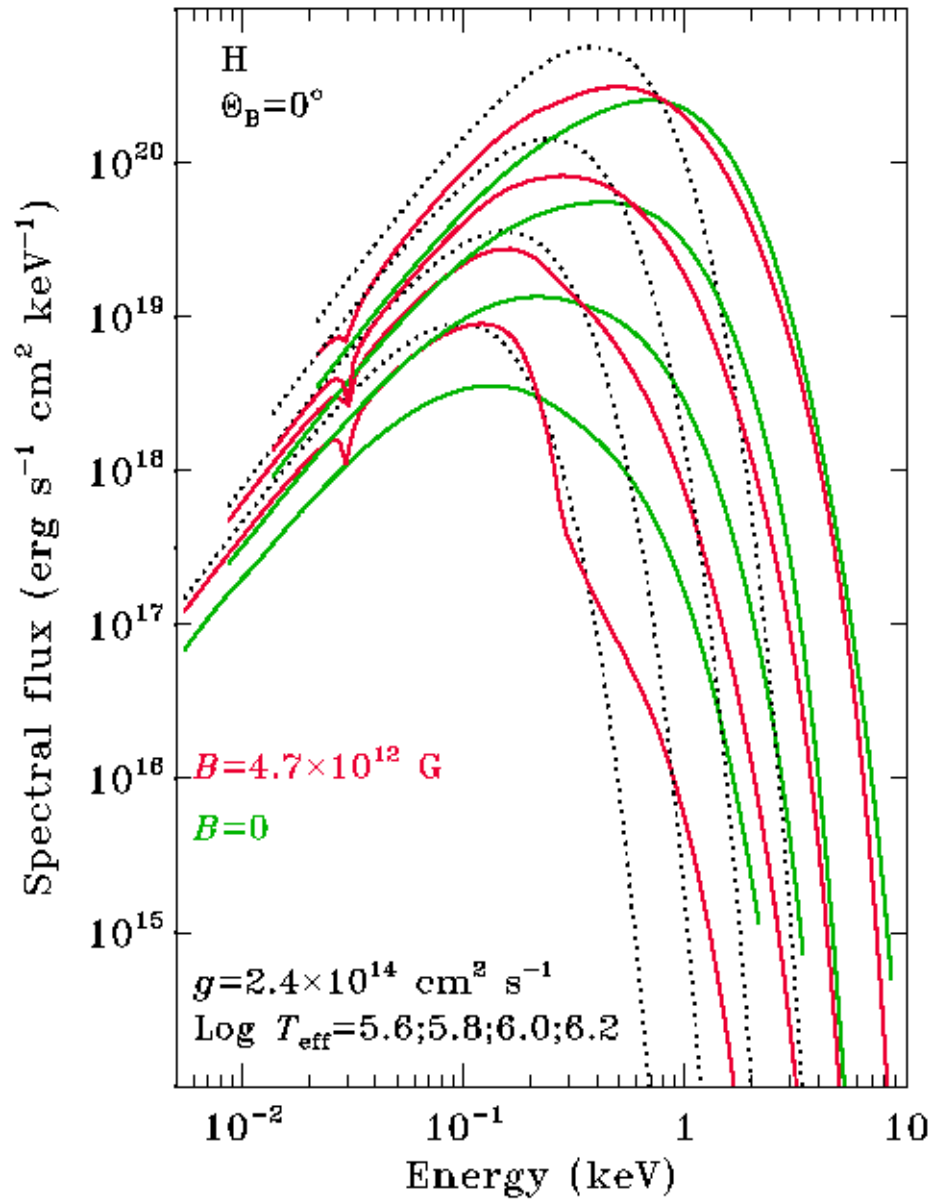
$$\cos \Theta_B = \vec{\mathbf{B}} \cdot \vec{\mathbf{r}}$$

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

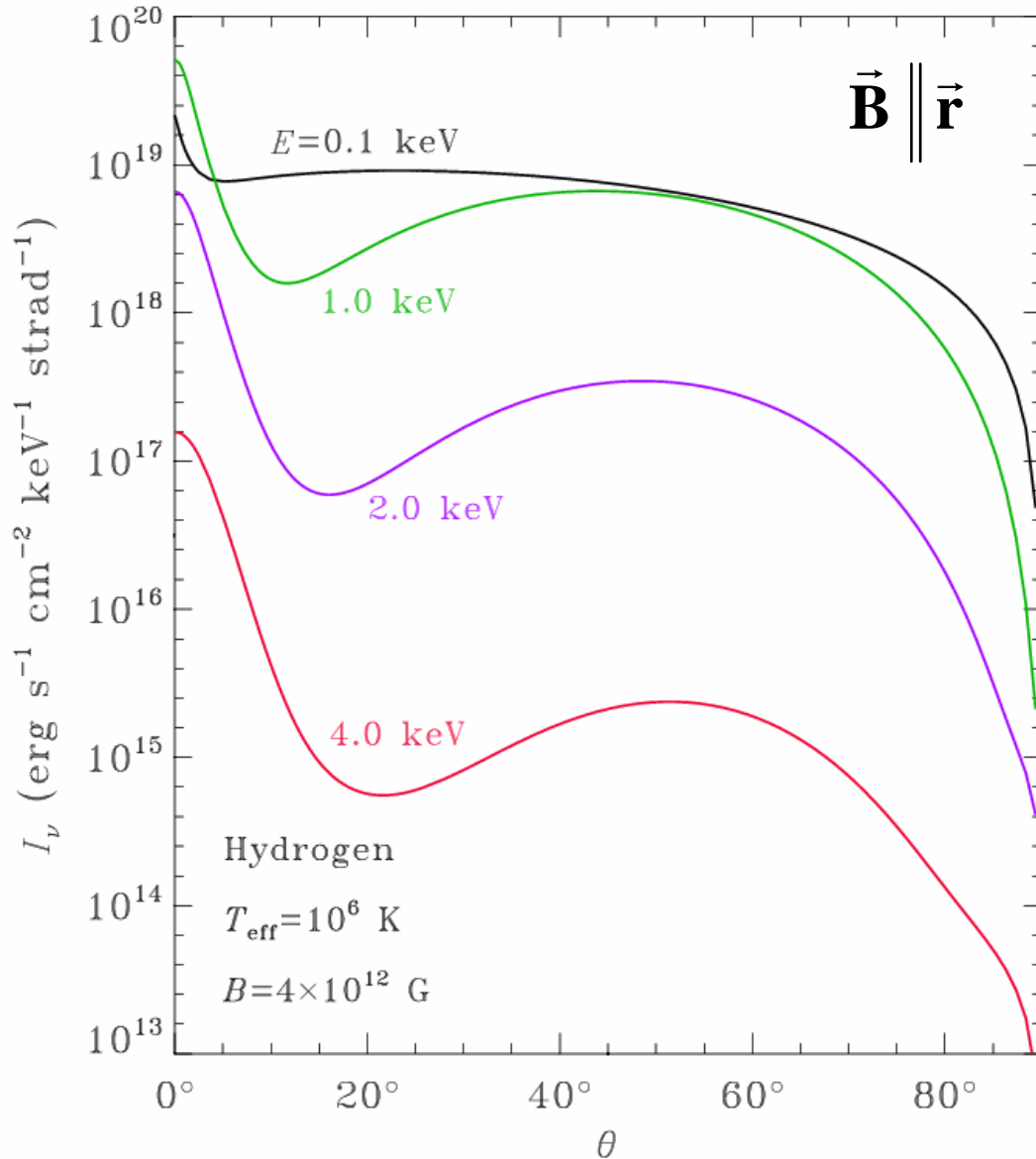
$$I_v^j = \mu^{-1} \int_0^{\infty} \left[\alpha_v^j \frac{B_v}{2} + \sum_{i=1}^2 \sigma_v^{ji} J_v^i \right] \exp \left[-\mu^{-1} \int_0^y k_v^j dx \right] dy$$

$$F_v^j = \int_0^1 \mu I_v^j d\mu$$

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

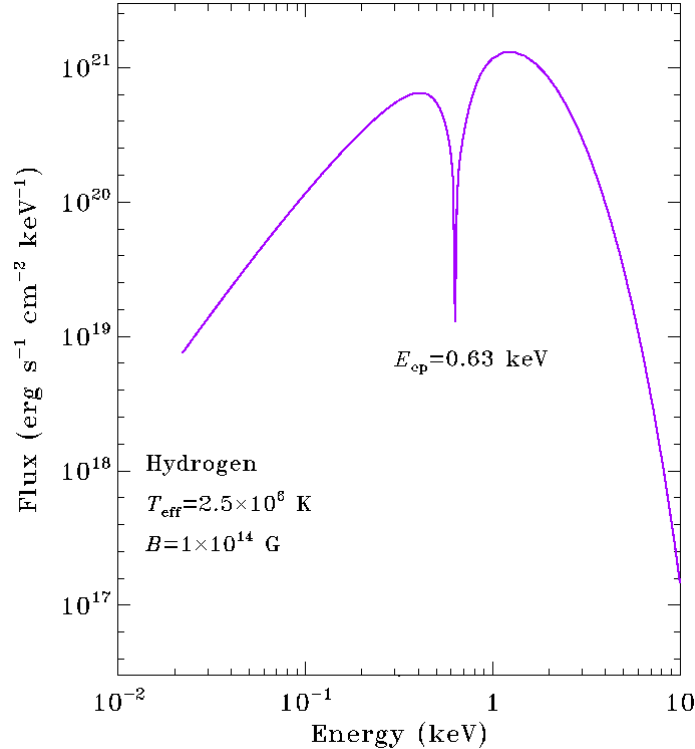


Angular dependence of radiation from a magnetized NS atmosphere:

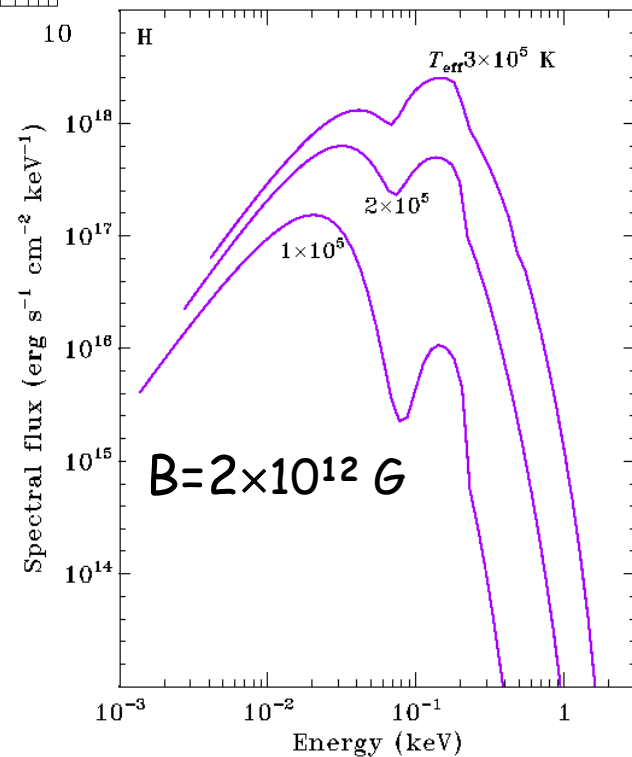


"pencil"-like structure along $\vec{\mathbf{B}}$
"fan"-like structure at larger angles

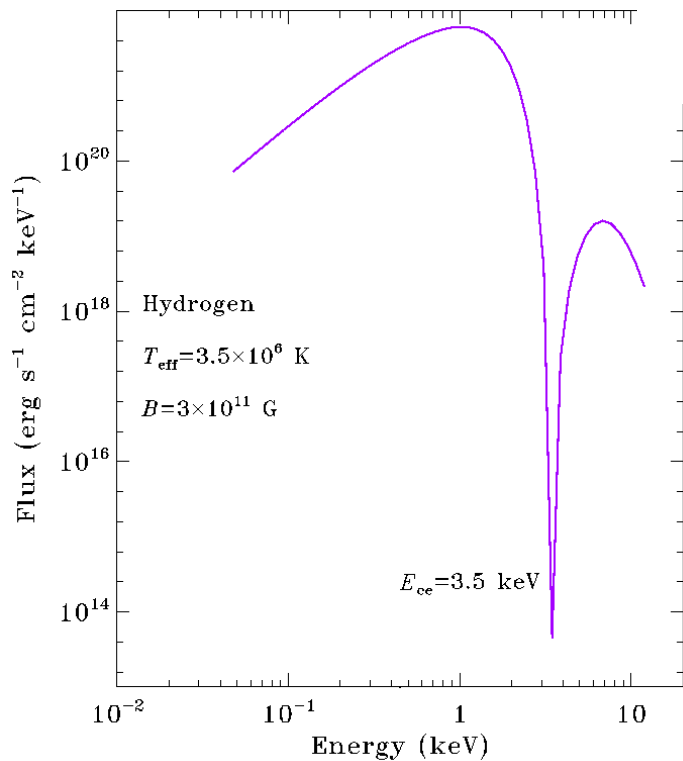
proton cyclotron line
 $B = 1 \times 10^{14} \text{ G}$



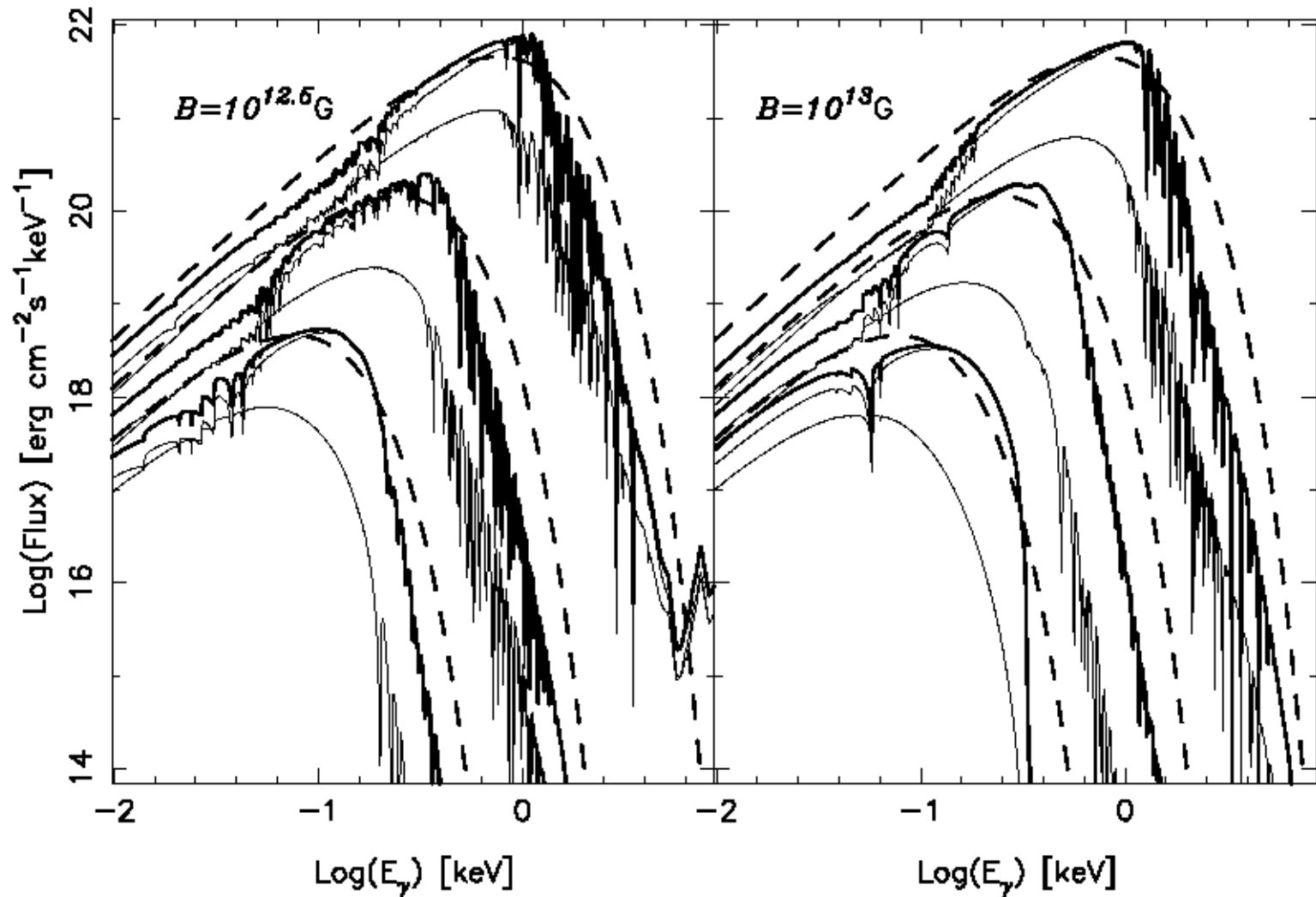
atomic transitions
 $T_{\text{eff}} < 5 \times 10^5 \text{ K}$



electron cyclotron line
 $B = 3 \times 10^{11} \text{ G}$



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



More on **hydrogen** NS models for $B > 10^{14} - 10^{15} \text{ G}$, 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: $F(E) = g_r \frac{1}{d^2} \int_S \mu I(g_r^{-1} E) dS \quad [\times \exp(-n_H \sigma)]$

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

E — observed (redshifted) energy

S — visible emitting area

d — distance to the object

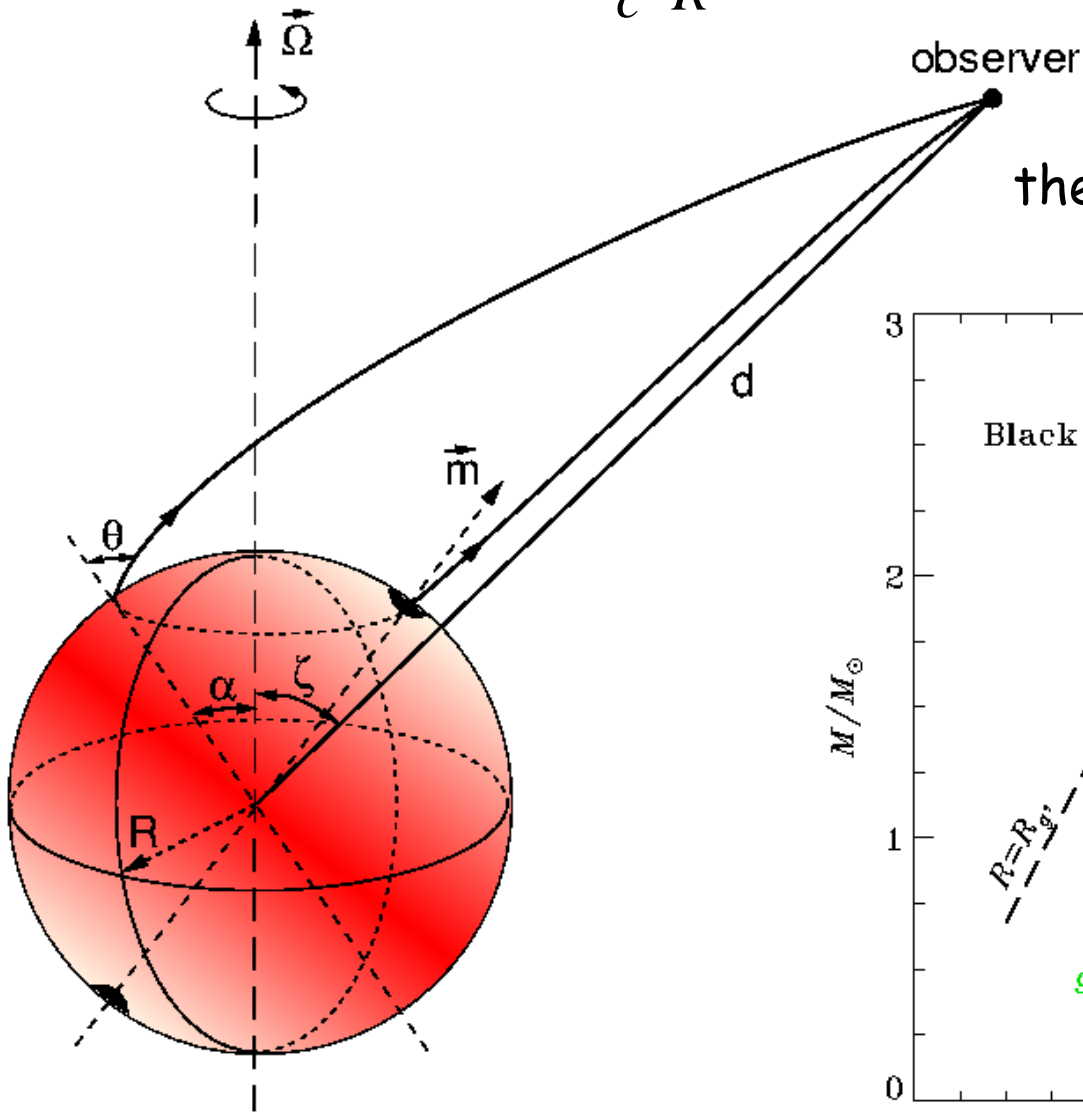
- nonuniform surface temperature and magnetic field
- gravitational bending of photon trajectories
- Doppler shifts of photon energies (for fast rotators)

Small heated spots (polar caps):

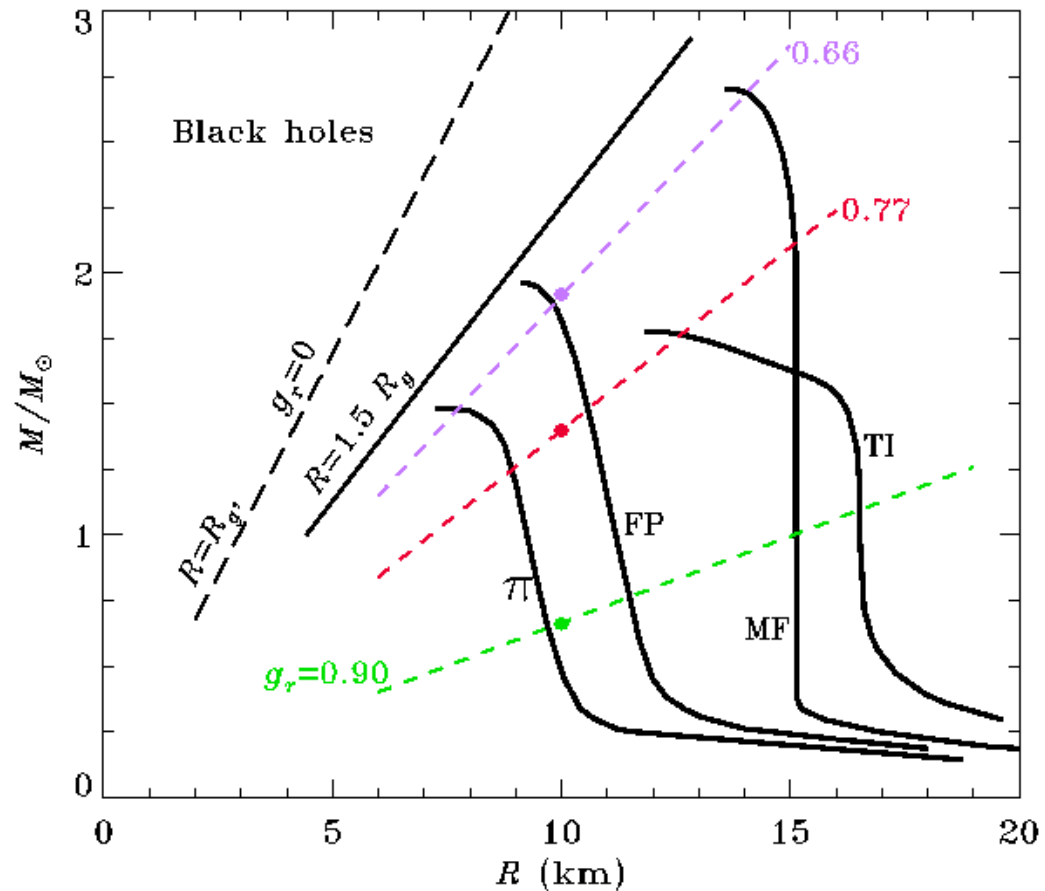
$$F(E) = g_r \frac{S_a}{d^2} I(g_r^{-1} E, \mu^*)$$

Gravitational bending of photon trajectories

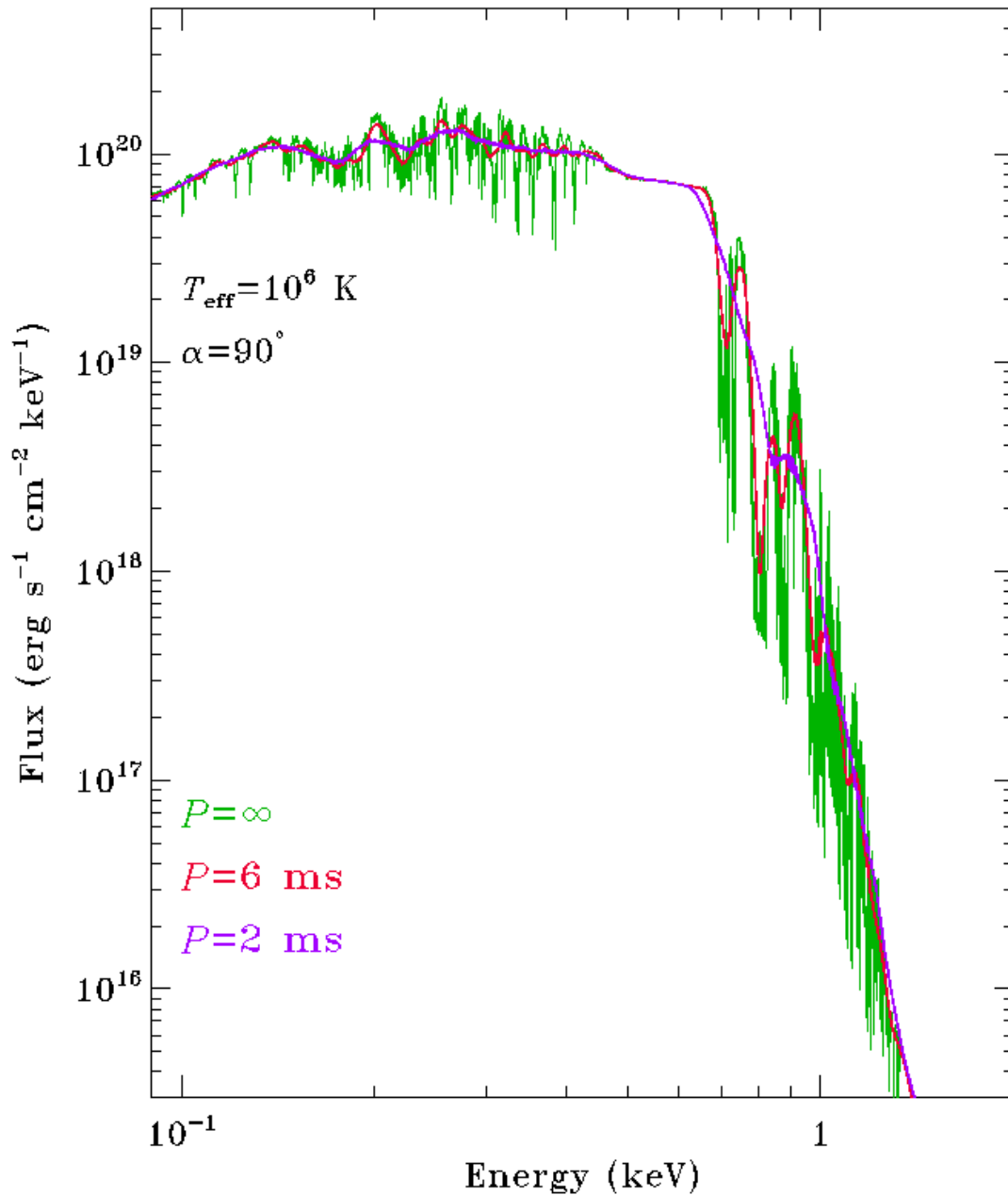
$$g_r = \left[1 - \frac{2GM}{c^2 R} \right]^{1/2}$$



the **whole** surface is visible if $g_r < 0.66$

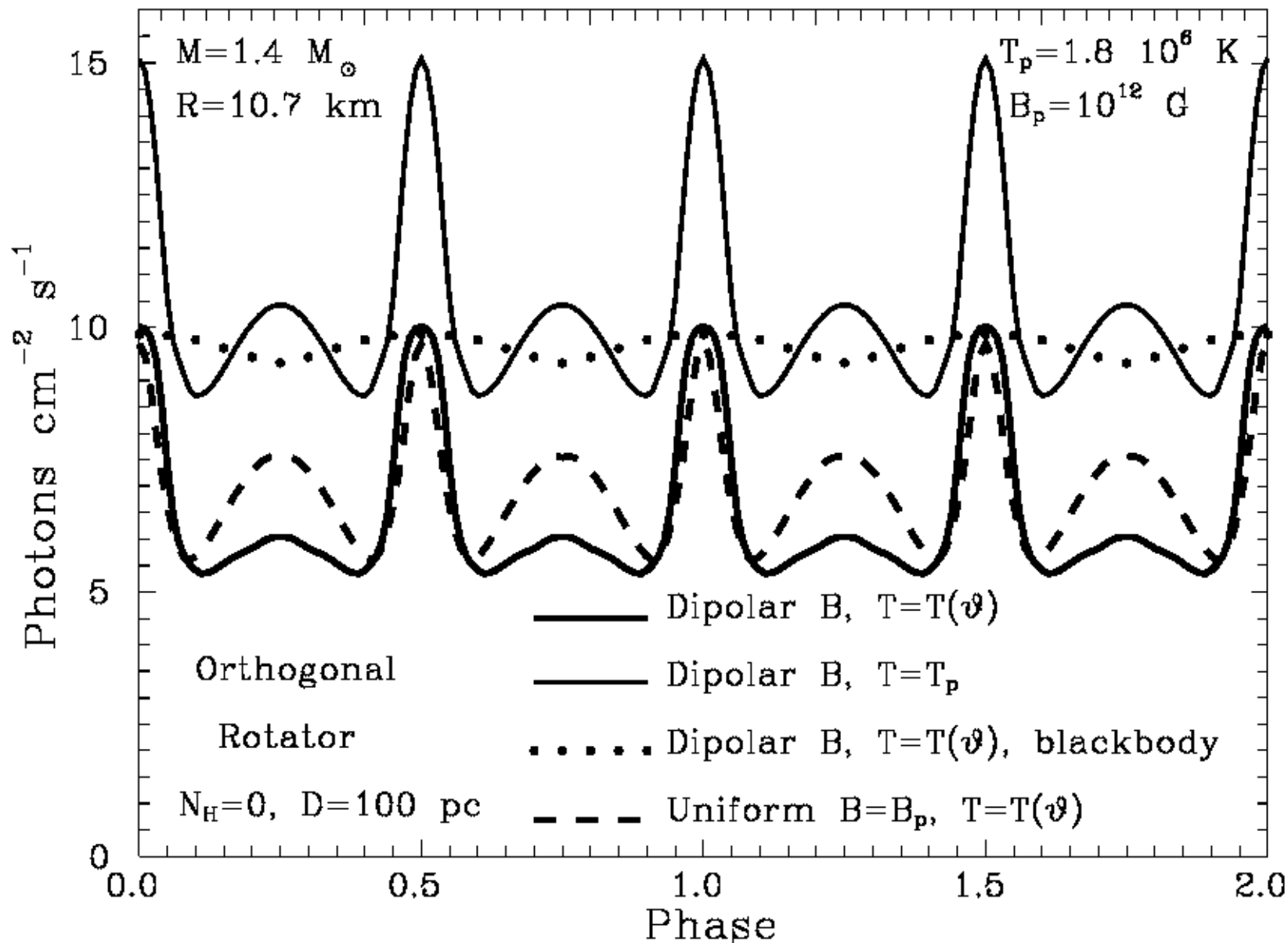


Effect of the Doppler shift

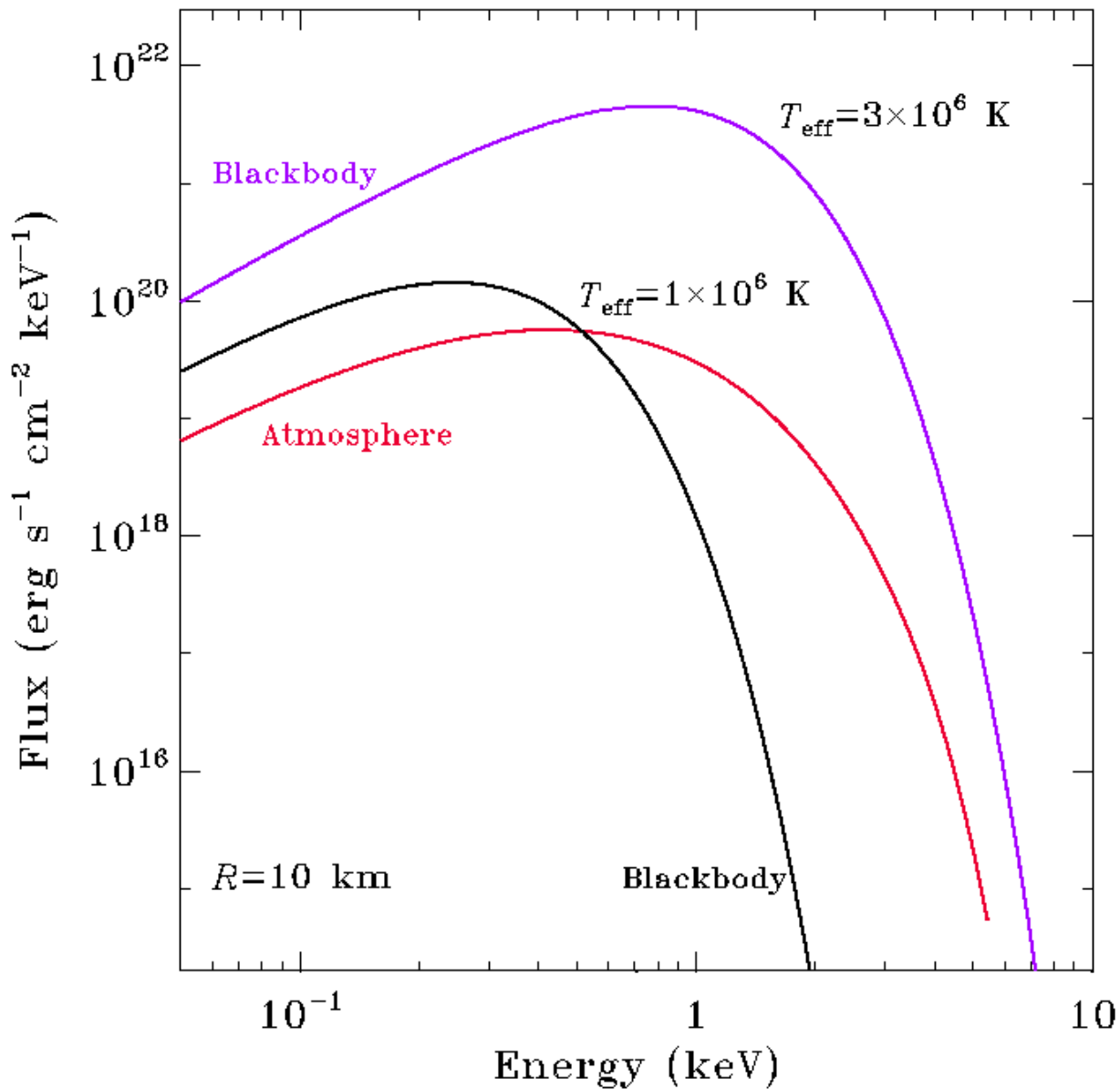


Spectra from the **whole** surface of a nonmagnetized NS (**iron** atmosphere)

Light curves of radiation from a magnetized NS



Practical aspect: NS atmosphere vs. blackbody model



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

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

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

XSPEC codes:

NSA, NSAGRAV — spectral fluxes for a wide range of
surface temperature,
magnetic field,
surface gravitational acceleration

NS atmospheres do not work:

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

PSR J1119-6127 (today's talk)

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 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 constructed 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

Everyone is welcome to contribute...