# Helium in Atmospheres of Neutron Stars

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Why Helium?
What are the NS surface layers made of?

Iron? (final product of thermonuclear burning)

Hydrogen? (lightest and most abundant element…)

Helium? (next lightest and most abundant after hydrogen)

Mid-Z elements?
(O, C, N, Si…) (abundant elements, created in thermonuclear burning)

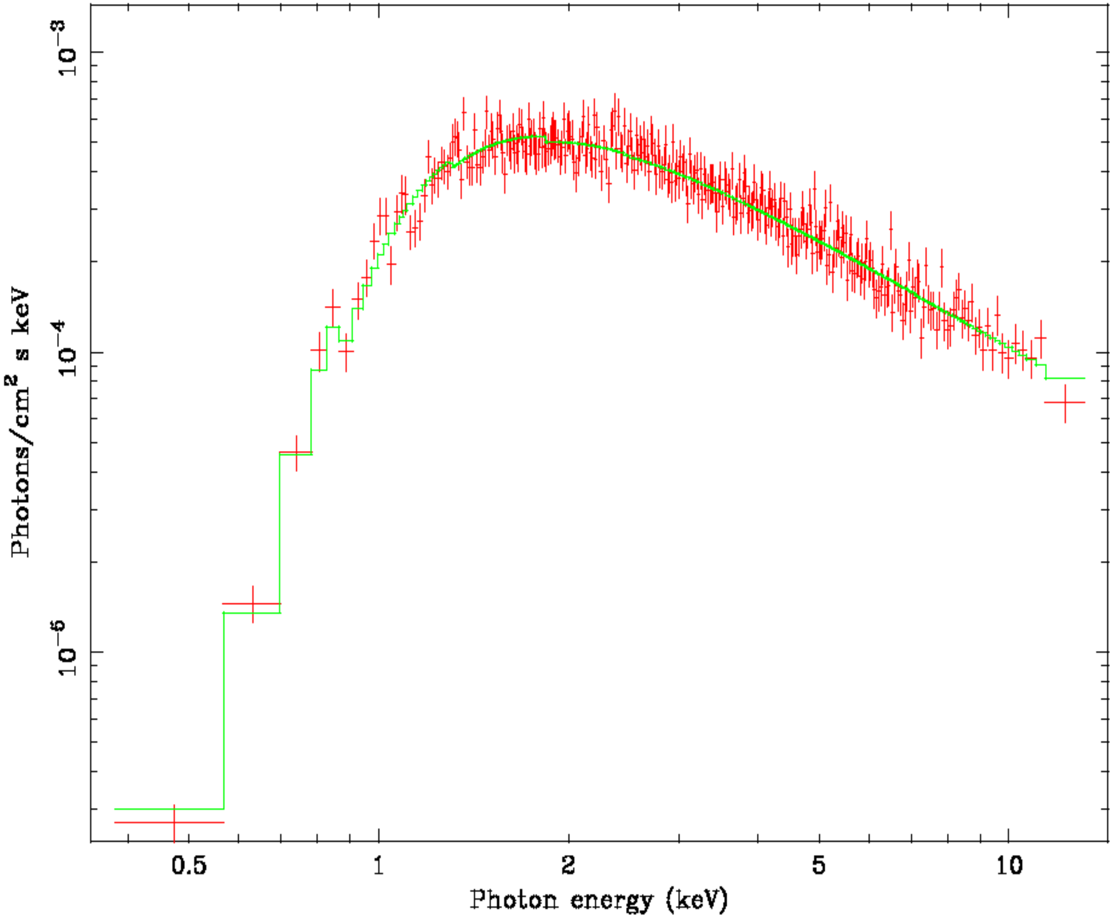
None excluded, only observations can tell.

Can be different in different NSs (similar to **DA, DB, DC white dwarfs**)

# Observations

Most of the observed NSs are active pulsars, with a strong magnetospheric component in their spectra → no direct information on the NS surface

Example: X-ray spectrum of the young PSR B1509-58

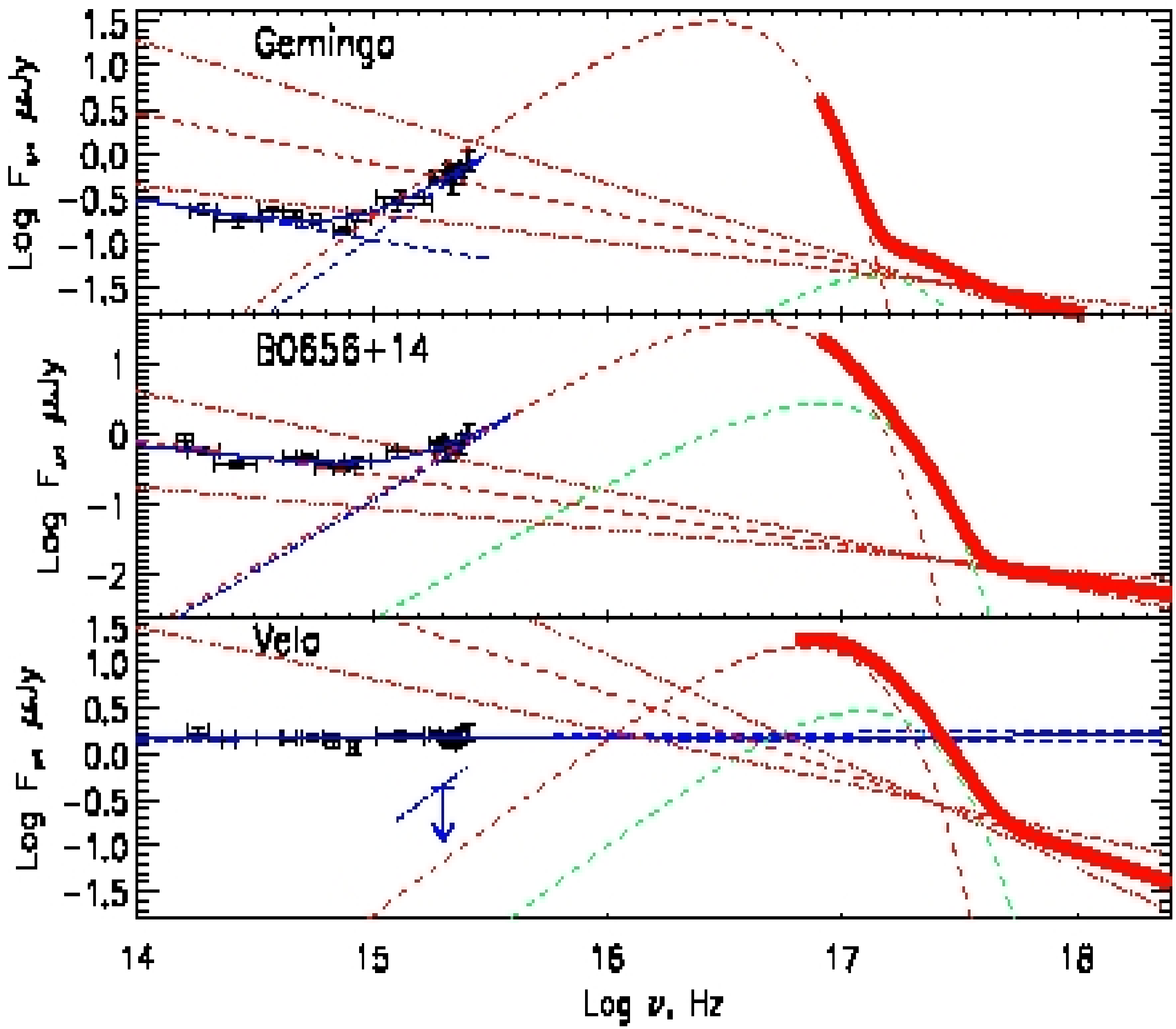



Absorbed power law spectrum with photon index $\Gamma$ = 1.3, hydrogen column density NH = 9e21 cm$^{-2}$

In some pulsars, however, we do see **thermal component from NS surface**, in soft X-rays and, in some of them, in UV.

Example:

Optical-Xray spectra for 3 middle-aged pulsars

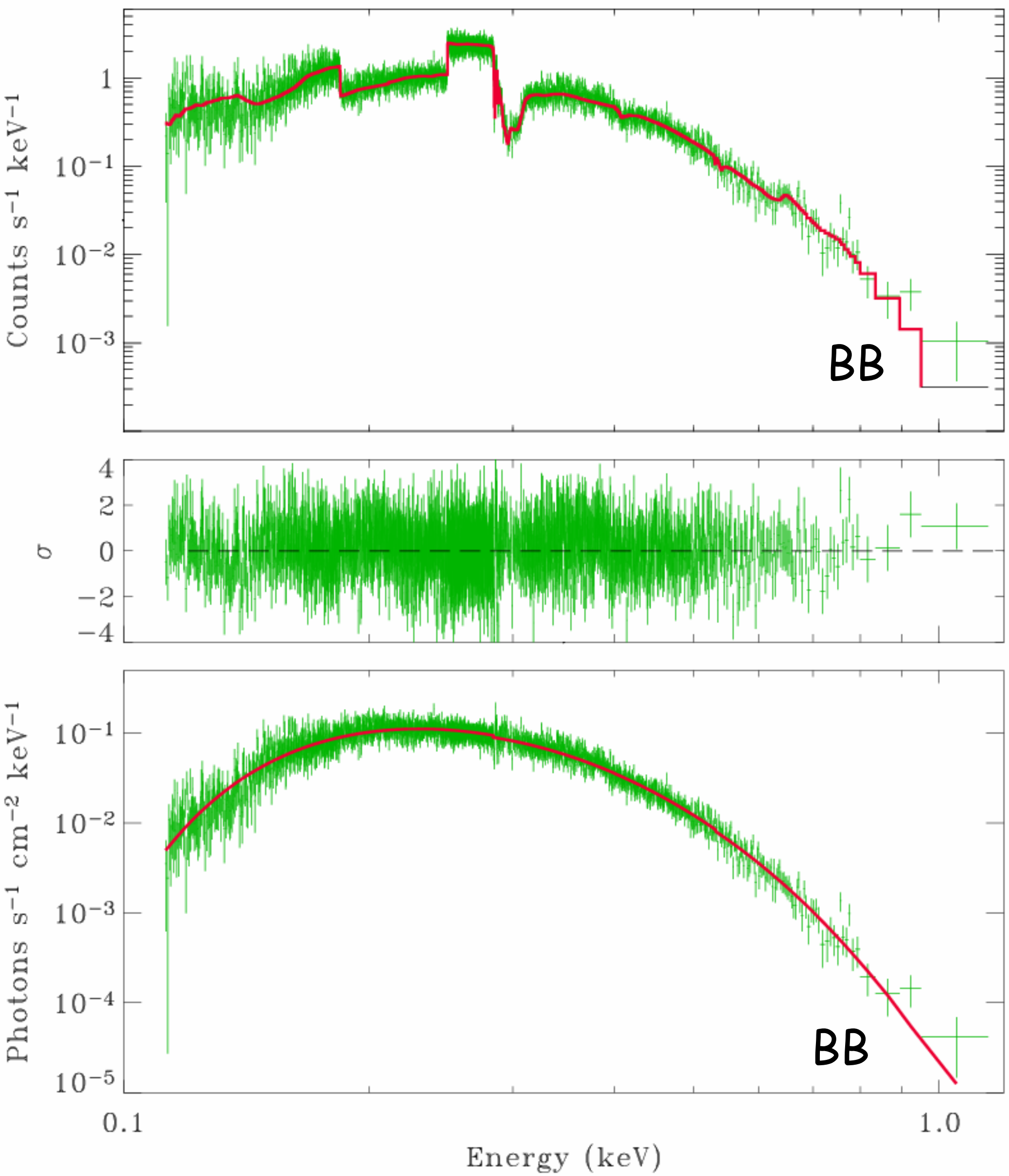


Even better in this respect are radio-quiet NSs (‘dead pulsars’), without magnetospheric activity, as they show uncontaminated spectra from the surface (atmosphere)

**“The only good pulsar is a dead one”.** (GP, 2000)

However, first X-ray observations with high energy resolution (*Chandra, XMM*) showed featureless (close to blackbody) spectra, no spectral lines → hard to infer chemical composition.

# 500 ks of Chandra LETGS on RX J1856-3754



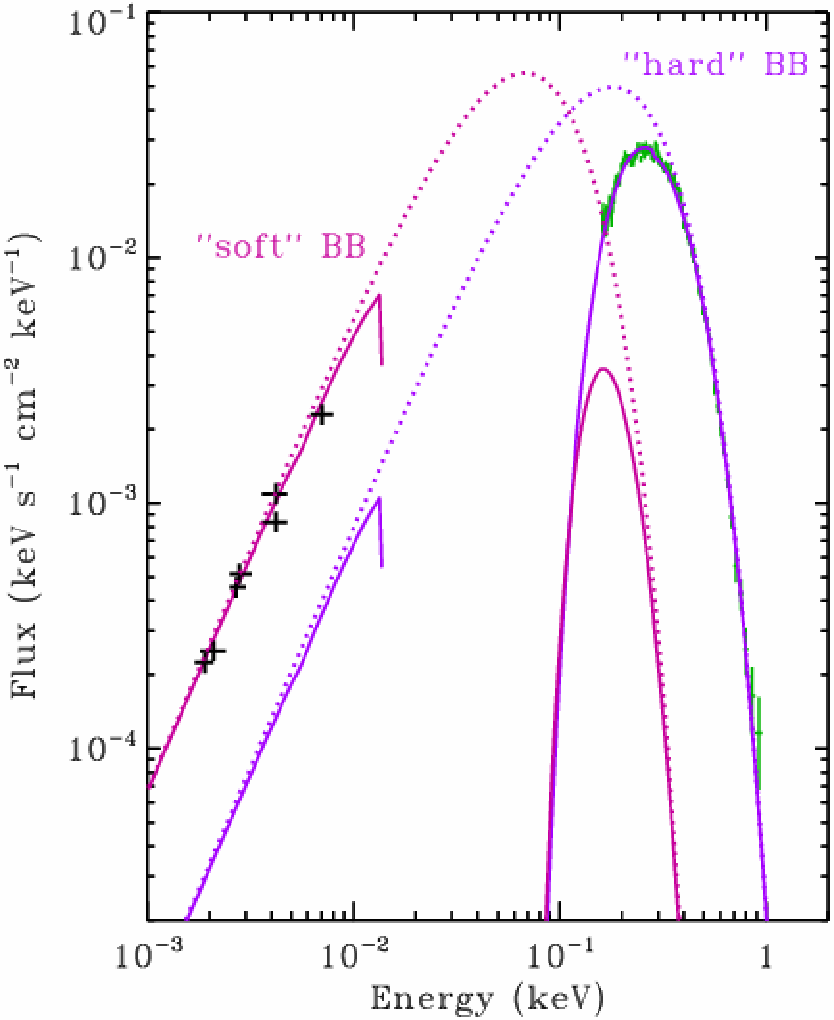

(talks by F. Haberl, S. Zane)

(almost) perfect BB fit
For the X-ray spectrum:

$T^{\infty} \approx 0.7$ MK

$R^{\infty} \approx 6$ km (for d=160 pc)

no spectral features




# RX J1856-3754

distance ~ 160 pc

spin period ~**7 sec ?**

"hard" $T^{\infty}$ 0.7 MK

"soft" $T^{\infty}$ 0.3 MK

"hard" $R^{\infty}$ ~6 km

"soft" $R^{\infty}$ ~20 km

blackbody model inapplicable?

H/He atmospheres: too small R/d, too large optical fluxes

Heavy-element atmospheres do not fit the X-ray data

Condensed surface? Problem with optical emission (talk by S. Zane)

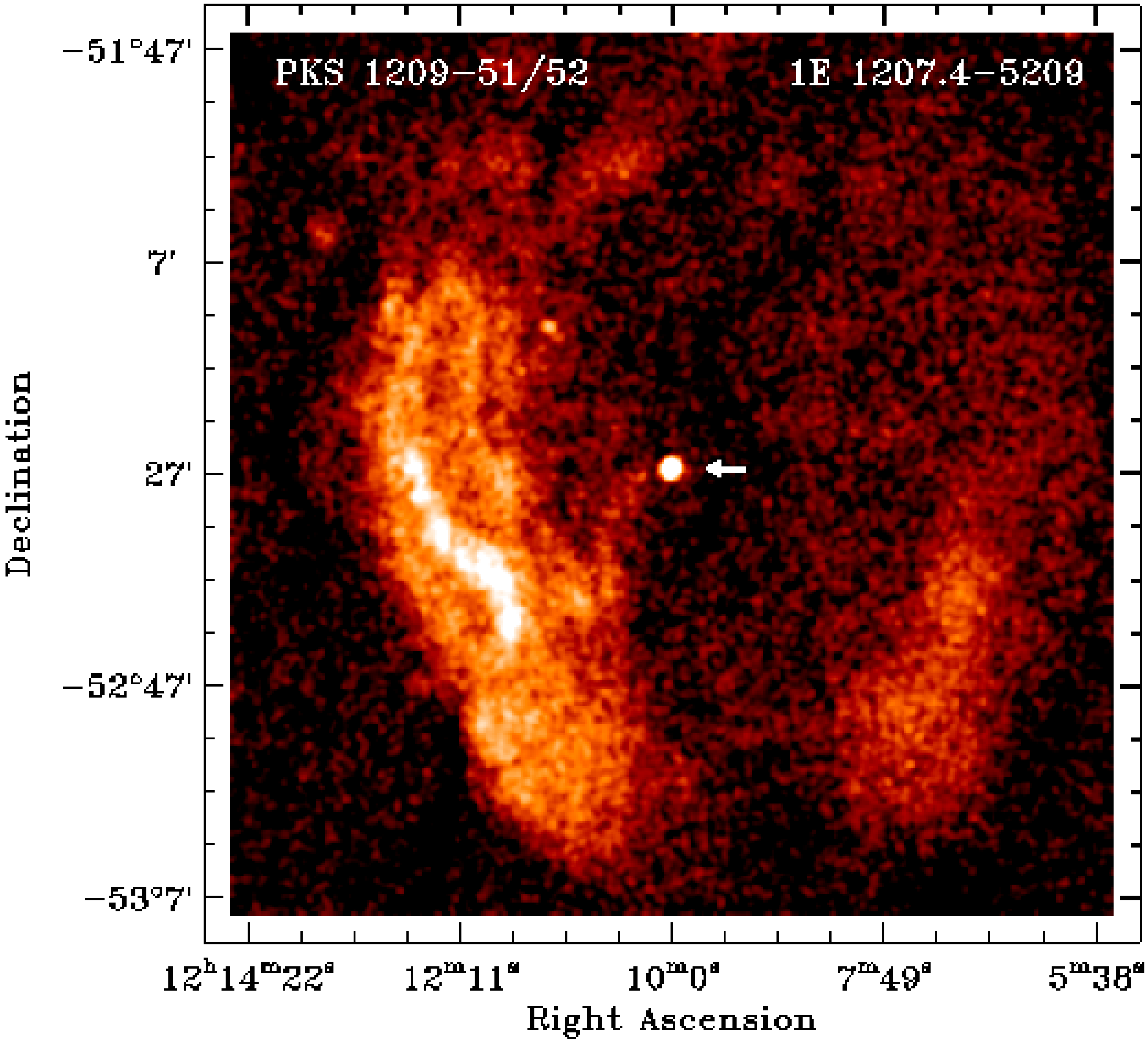
Spectral lines are needed to

- understand chemical composition,
- measure magnetic field,
- measure gravitational redshift (M/R)
- measure gravitational acceleration (M/R^2)
- understand E.O.S. and composition of NS interiors

(talk by D. Page)

First spectral lines in an isolated NS spectrum were discovered with *Chandra* in **1E 1207.5-5209**,
a radio-quiet neutron star at the center of
SNR PKS 1209-51/52 (a.k.a. G296.5+10.0)
(Sanwal, GP, Zavlin & Teter 2002)

# 1E 1207.5-5209 in G296.5+10.0:




**SNR**:
Age ~7 kyr,
D ~ 2 kpc

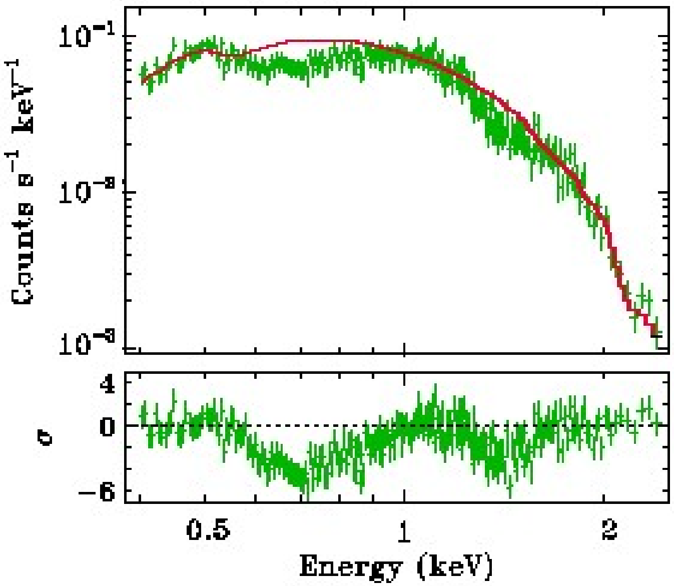
**Central Compact Object**:

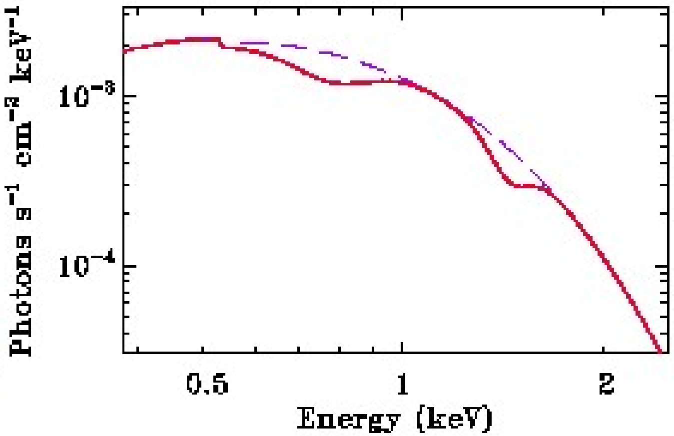
P=424 ms → neutron star (Zavlin et al 2001)

P/(2 Pdot) = 300 kyr from 2 epochs → PSR born with a long period ? (Pavlov et al. 2002)

P,Pdot →
Edot = 1e34 erg/s,
B=3e12 G

## Two Chandra observations → absorption features at 0.7 and 1.4 keV




**Electron cyclotron lines** in B = 8e10 G ? -- unlikely (too small B, too strong harmonic for so low temperature, $kT/m_ec^2 \sim E_{cyc}/m_ec^2 < 0.001$)

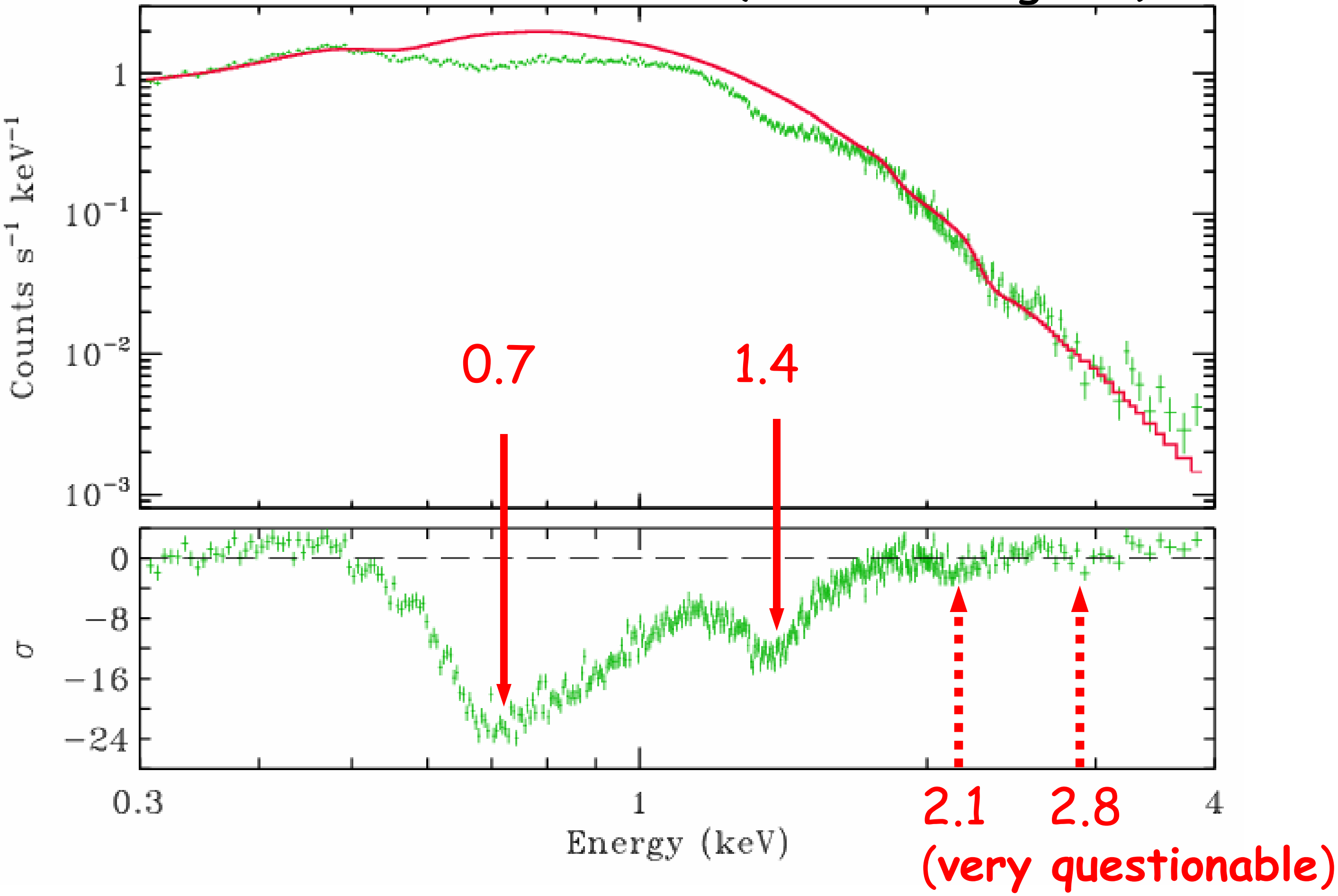
**Atomic hydrogen lines**? Firmly excluded (no such pair of lines at any B)

Could be transitions in **once-ionized He** in B = 2e14 G – this B is much stronger than 3e12 G from P,Pdot, but not unlikely for a decentered dipole. If true, gravitational redshift z =0.28 → R = 11 km/(1.4Msol) (Pavlov & Bezchastnov 2005)

Could be transitions in **Oxygen ions** in B ~ $10^{12}$ G, e.g., OVII → B=6e11 G, z=0.06 -- 0.21 (Hailey & Mori 2002) or

**Hydrogen molecular ions** (Turbiner & Lopez Vieyra 2004)

1E1207: XMM-Newton (260 ks; Aug´02)

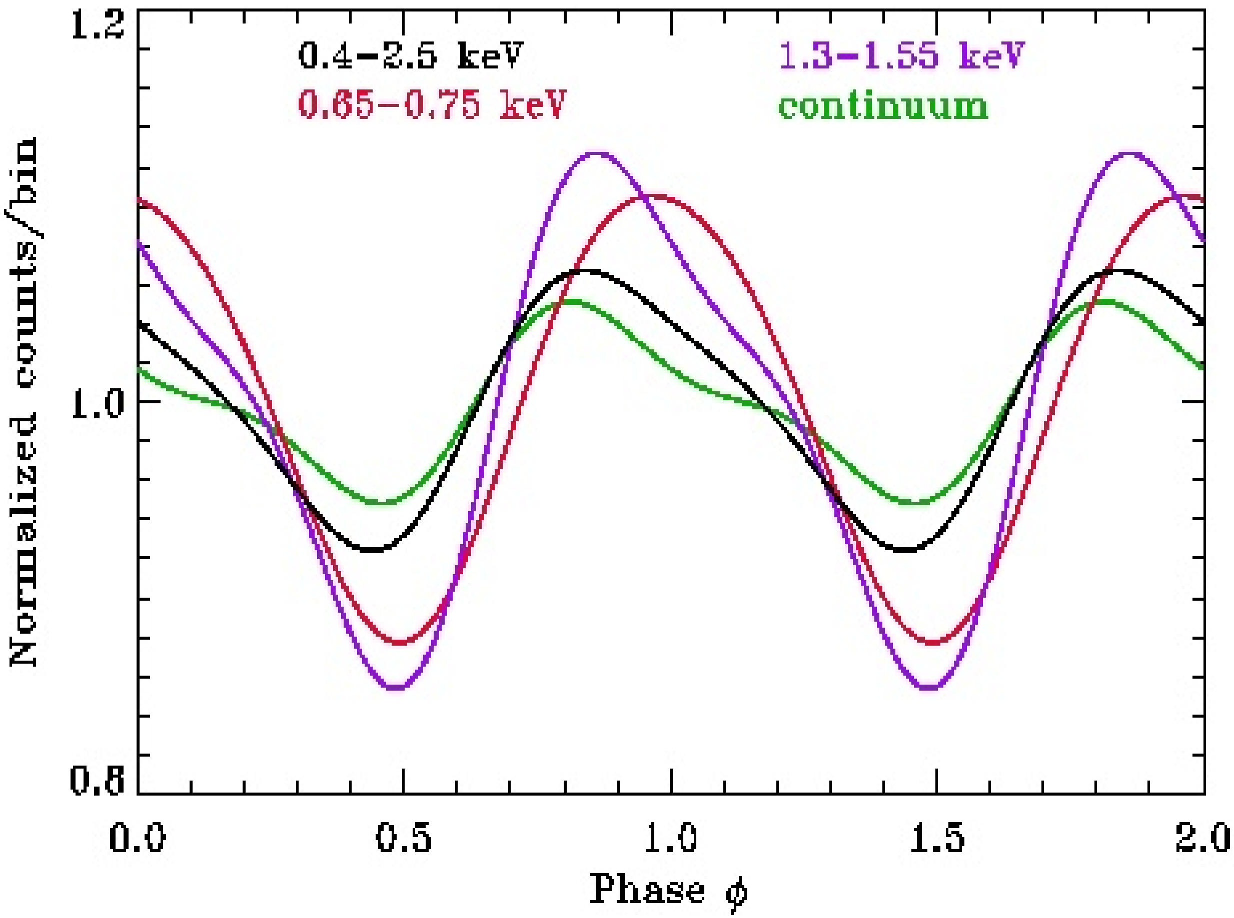



Bignami et al. (2003): indication of lines at 2.1 and 2.8 keV.

electron-cyclotron harmonics $\Rightarrow$ $B \approx 8\times10^{10}$ G

But: the harmonics should be **much** weaker at such low T and B

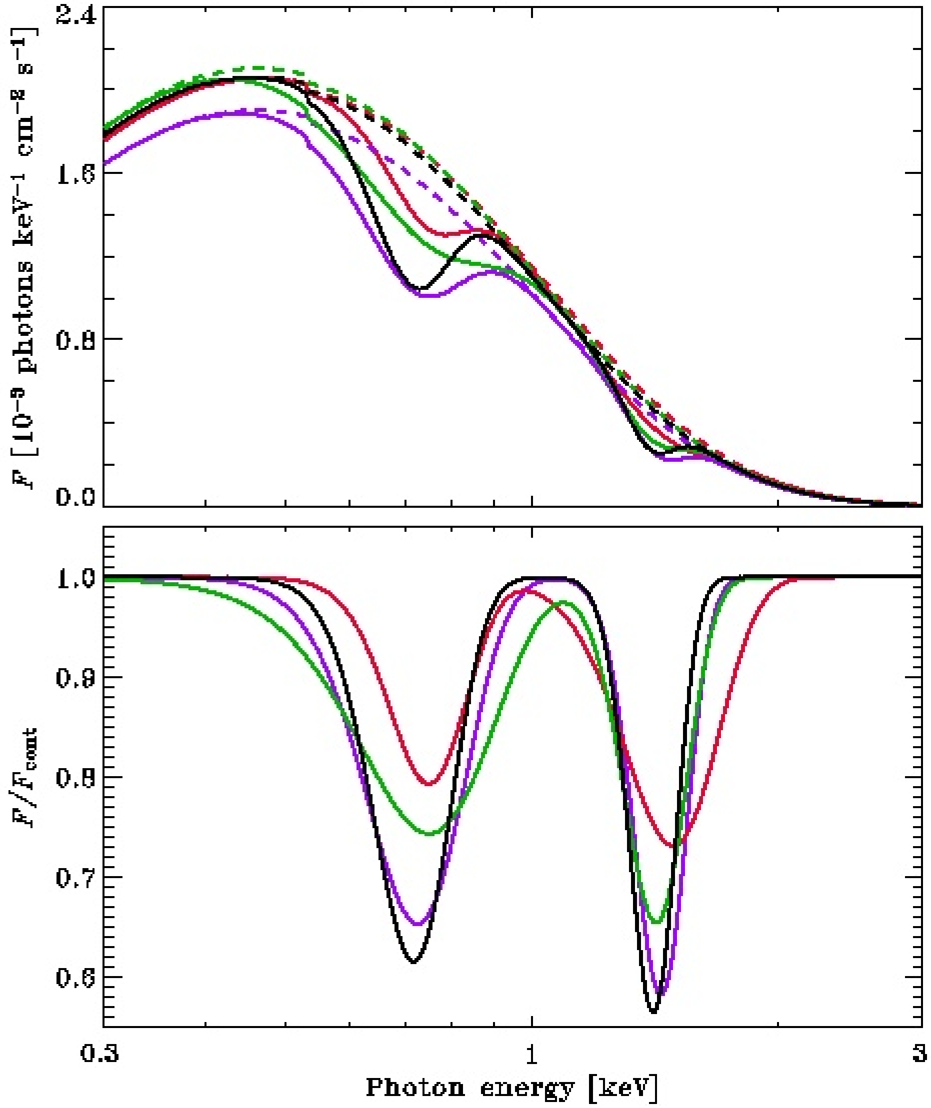
# **Pulsations in different energy bands** (XMM data of 2005)




Pulsations in lines are stronger than in the continuum → line emission more anisotropic → strong B required.

Pulse maxima at different phases → different types of transitions? The lines are formed at different sites?

# **Spectra at different phases** (XMM data of 2005)

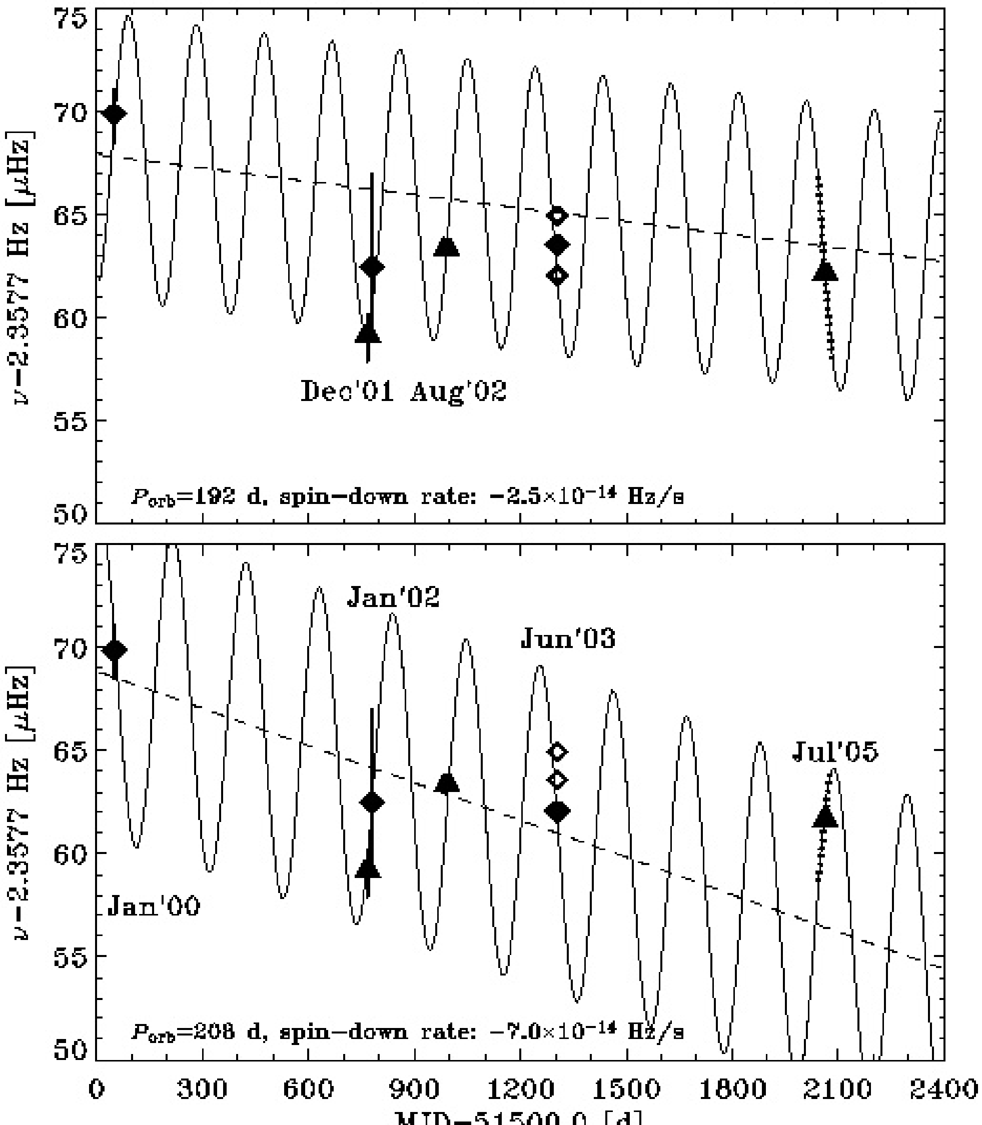



Green: 0.1 – 0.4 (pulse fall)
Purple: 0.4 – 0.6 (pulse min)
Black: 0.6 – 0.9 (pulse rise)
Red : 0.9 – 1.1 (pulse max)

Energies and positions of lines depend on pulse phase → different magnetic fields are exposed?

# **Timing puzzles** (with 6 XMM observations of 2005)

Two possible timing solutions in July 2005




Possibly a binary system with an invisible (low-mass) component

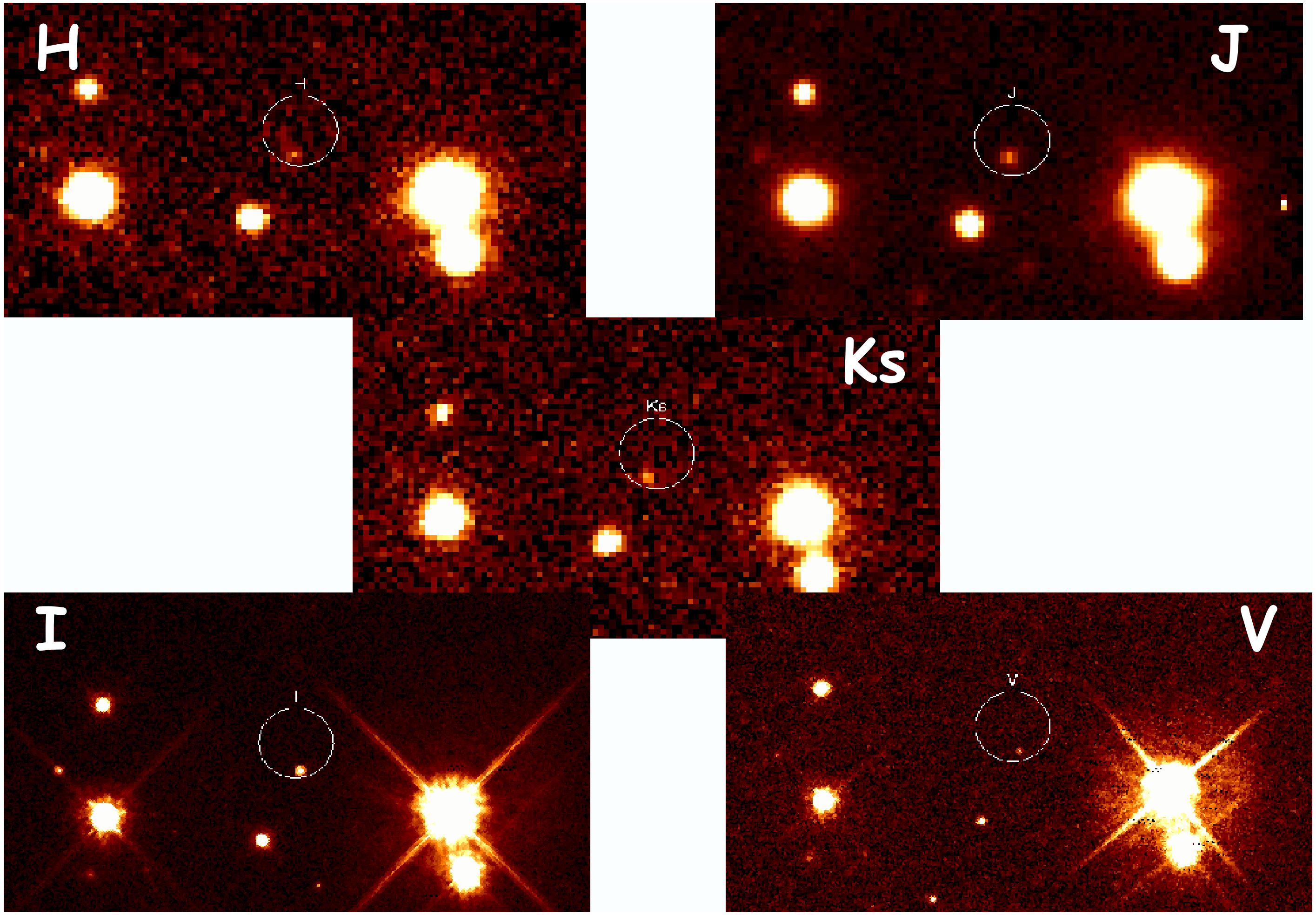
New series of observations is required to resolve the ambiguity

VLT

ISAC

HST

ACS




**Object at the boundary of the Chandra error circle:**

V=26.8, I=23.4, J=21.7, H=21.2, Ks=20.7 (too large offset)

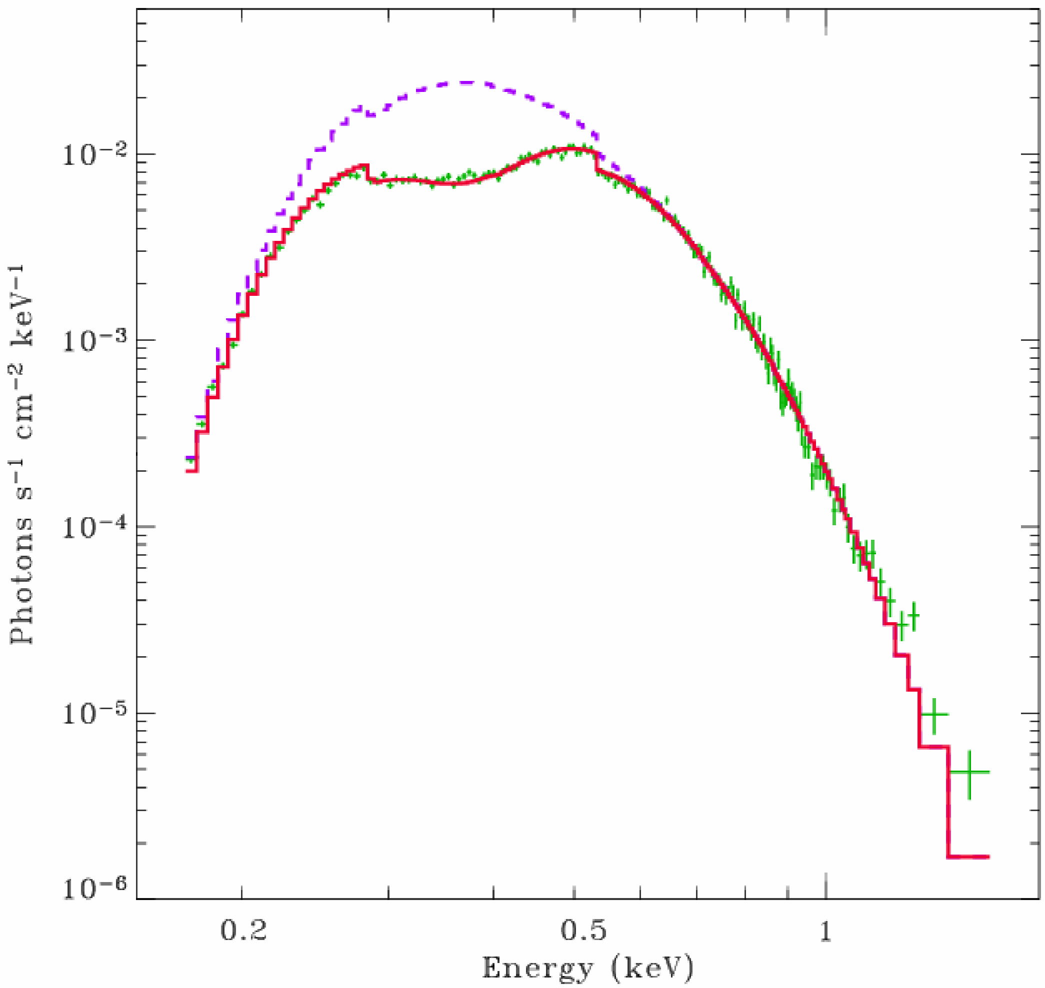
Limits: **V>28.7, I>27.8, J>23.4, Ks>22.0**

Moody, GP, Sanwal 2005

# Spectral lines have been discovered in 6 of the Magnificent Seven

(talk by Frank Haberl)

Example: XMM-Newton on RX J1308+2127 (P ≈10.3 s, $T^{\infty}$ ≈1 MK)




Broad absorption feature around 0.3 keV (Haberl et al. 2003)

Weaker features in 5(4?) other sources, possibly 2 or 3 lines in some of them, at energies **0.2 – 0.8 keV**

Overall, **absorption features**, presumably formed in a NS atmosphere, have been found in **7 (6?)** isolated (non-accreting) NSs.

Spectral continua show **“temperatures” 50 – 120 eV**;

Likely **magnetic fields up to ~10e14 G**.

Line **central energies: 0.2 – 1.4 keV**

All the lines are **very broad**, **~100 – 200 eV**,
(but fine structure possible)

**Harmonic-like structure** in some cases?

Dependence on pulse phase

# Identification?

Electron cyclotron lines → too low magnetic fields (unless produced in magnetosphere; talk by M. Ruderman)

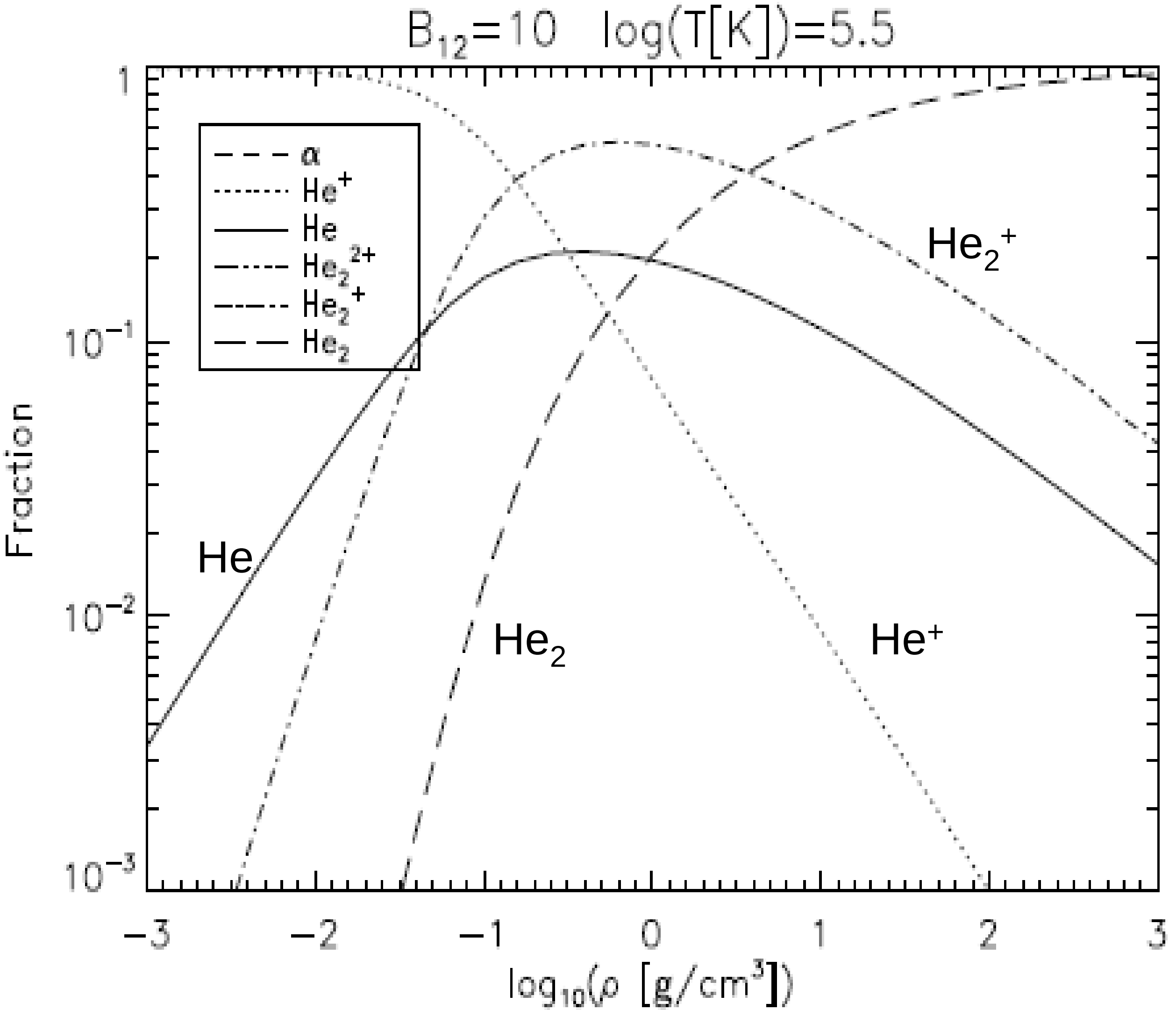
Proton cyclotron lines → harmonics should not be seen; temperatures are too low in some cases to expect strong ionization; atomic H lines should be seen simultaneously

Atomic H: may be in some cases (but certainly not in 1E 1207)

Molecular H: temperatures too high?

Could it be Helium? If yes, in which ionization/dissociation state?

**Ionization/dissociation** depends on temperature, density, and magnetic field (Mori & Heyl 2007)

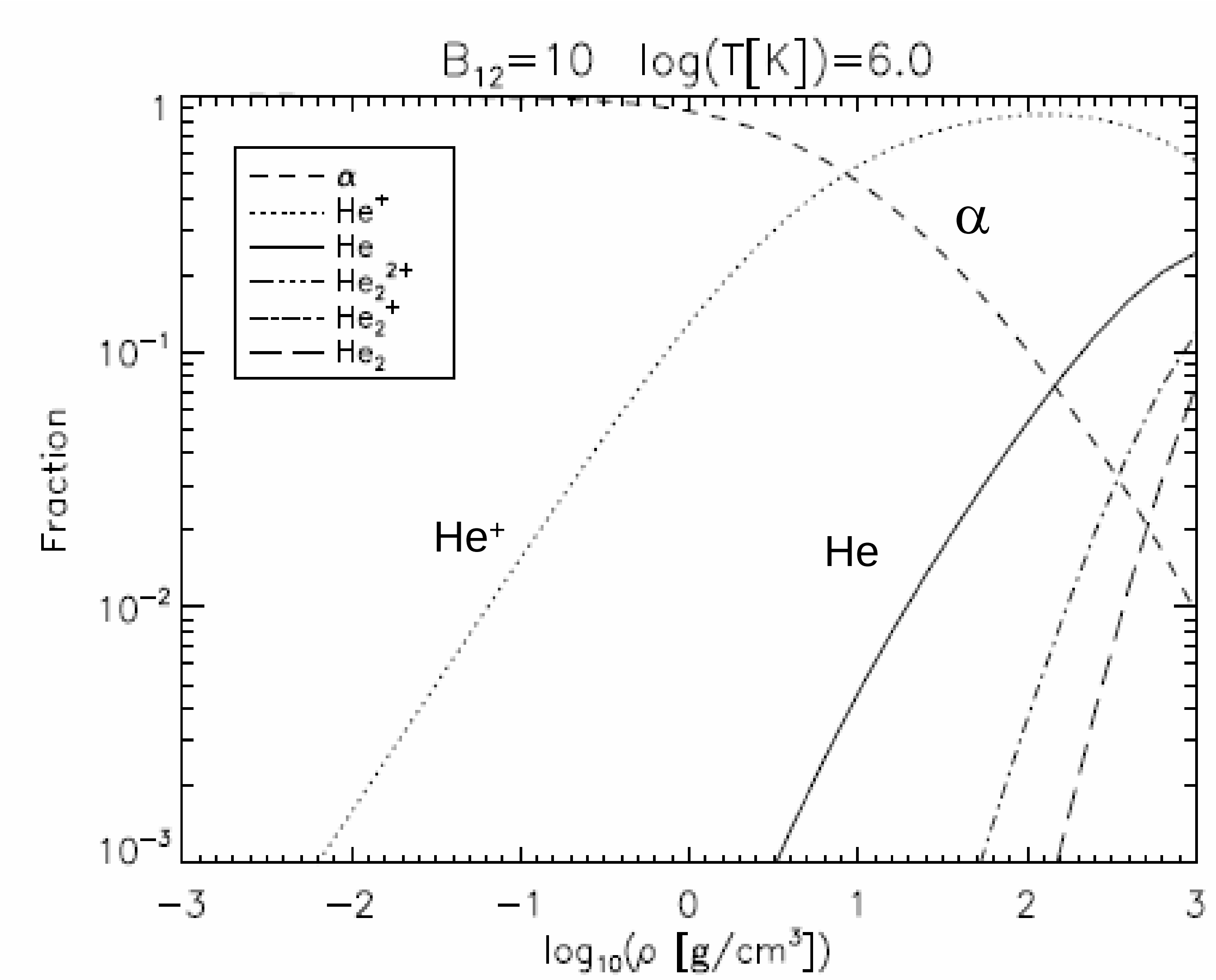



B=1e13 G,
Low T (= 26 eV)

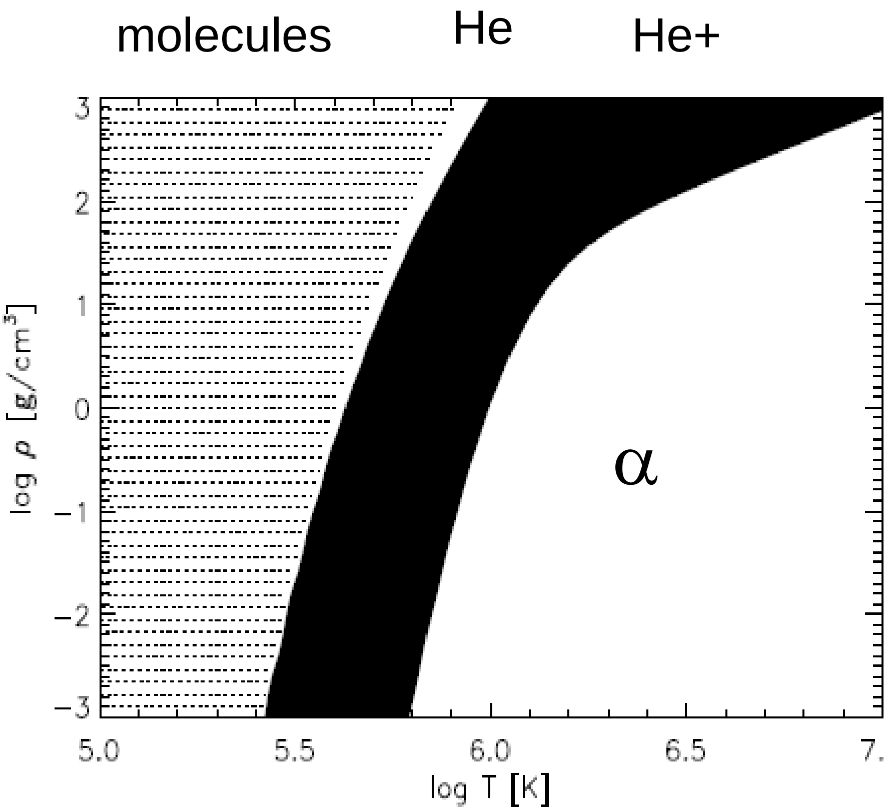
Molecules dominate at most important densities,
$He^+$ in outermost layers

B = 1e13 G,
T = 86 eV

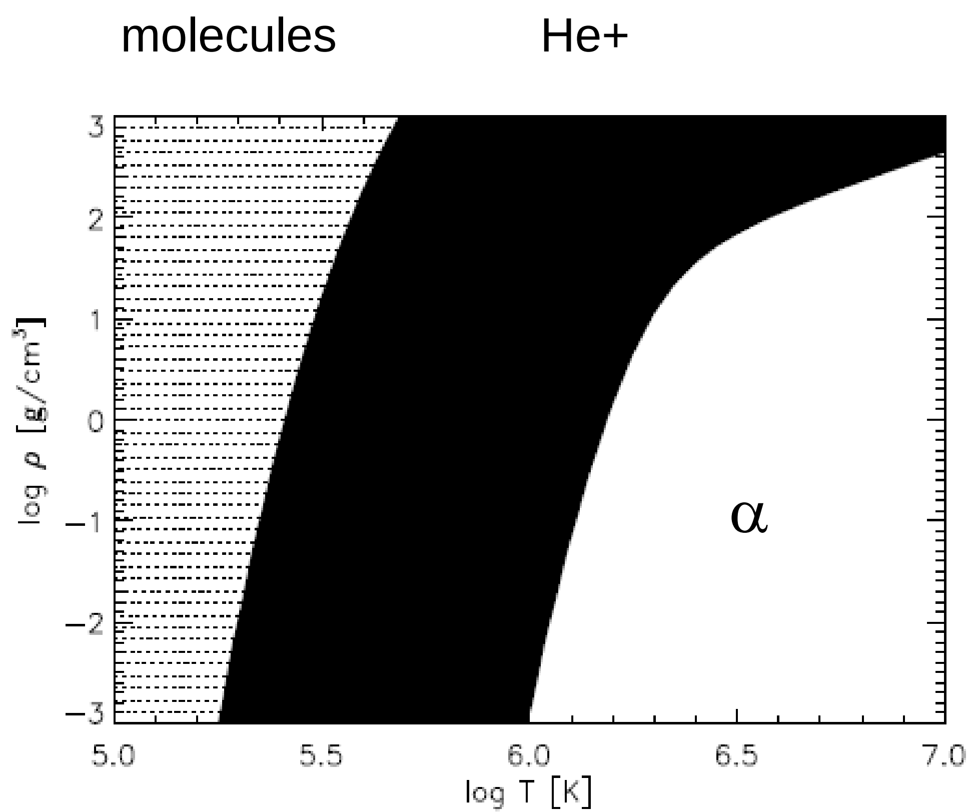
$He^+$ and $He^{++}$ dominate



# Most abundant He species




B=3e13 G




B=1e14 G

**He+** and **He molecules** are most abundant
at very high B and most interesting temperatures and densities

# He+ in strong magnetic filed

Straightforward  if we assume an infinite nucleus mass and neglect motion of the ion, for  B/Z^2  >>>  2.35e9 G   (reduces to H atom after a scaling).

When we include motion of the system,  the problem is not trivial even for H atom  because the axial symmetry is violated,  but at least the center-of-mass motion can be separated from the internal d.o.f.  using a generalized momentum and canonical transformations (Baye's group 1988-1992;  GP, Meszaros 1993; Potekhin 1996).

Energy levels depend on transverse component of total generalized momentum K_perp
Increased transverse mass at small K_perp
Decentralization at large K_perp

**The motion of the whole system cannot be separated from the internal d.o.f. if the system's charge is not zero** (Avron et al. 1978)   → we have to solve two-body (5D) problem with very different masses.

Integrals of motion for a charged ion:

Square of the total generalized momentum K_perp^2 [e.v.= $\gamma$(Z-1)(2J+1)]
Longitudinal component of the total angular momentum Lz [e.v. = - L]
Parity [e.v. = +1,-1]

Energy levels are determined by quantum numbers:

**N = 0, 1, 2, ….** -- exact quantum number, N=J+L, describes rotation of the system as a whole (at small N) and decentralization (at large N)

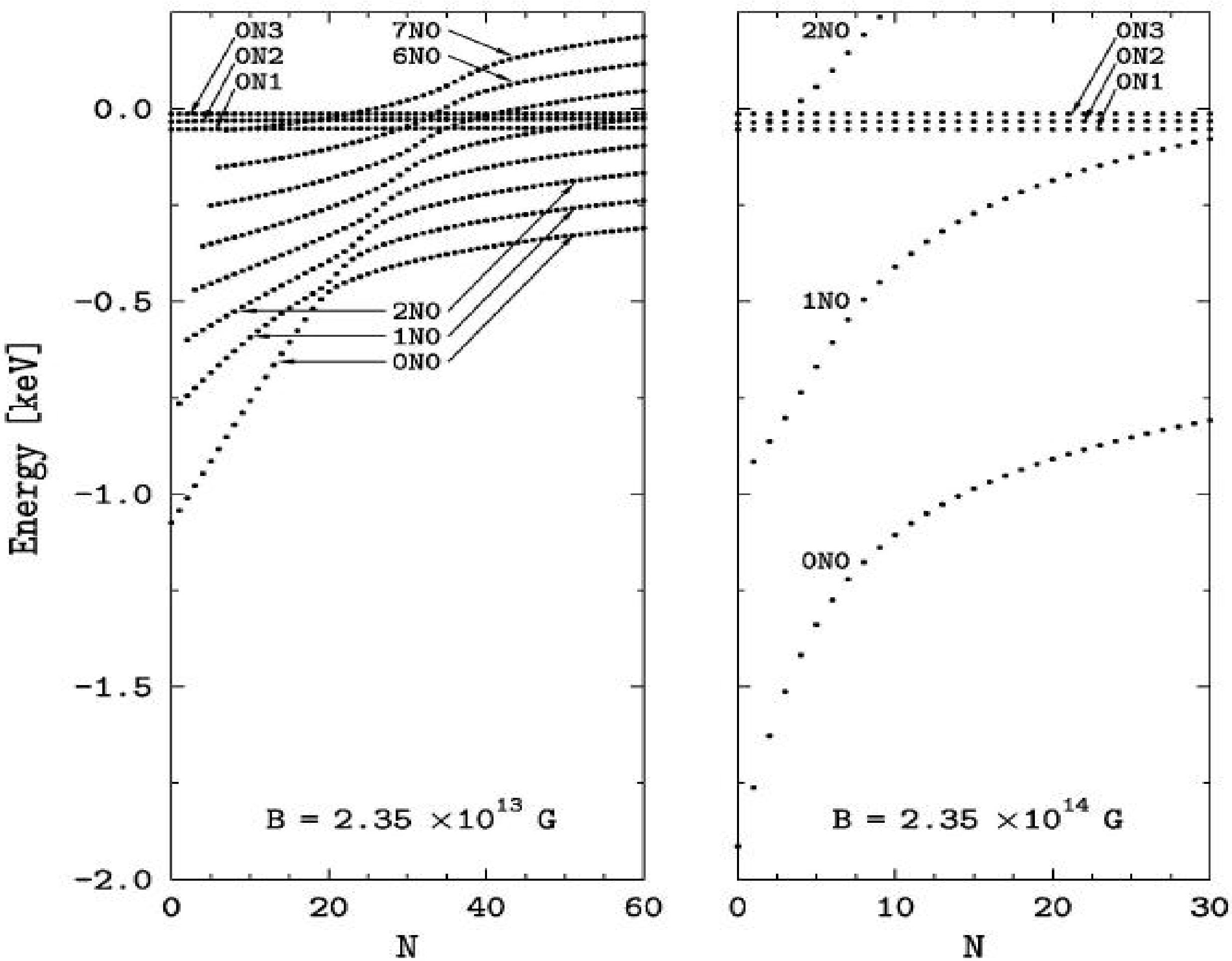
Electron Landau number n- = 0, 1, … -- good quantum number for very strong B, only **n- =0** is interesting

**$\nu$ = 0, 1, 2,...** -- longitudinal excitations; parity = $(-1)^{\nu}$; $\nu = 0$ -- tightly bound states; $\nu > 0$ – hydrogen-like states
**s = 0, 1, 2, …, N** -- transverse excitations (turns into negative of the longitudinal projection of the electron's magnetic moment in the limit of infinite nucleus mass)

Energies and wave functions can be calculated in MCHF approach with a two-particle basis

# Energy levels of He+ ion

as a function of N for two values of magnetic field




**B = 2.35e13 G**

**B = 2.35e14 G**

**sNν** – quantum numbers

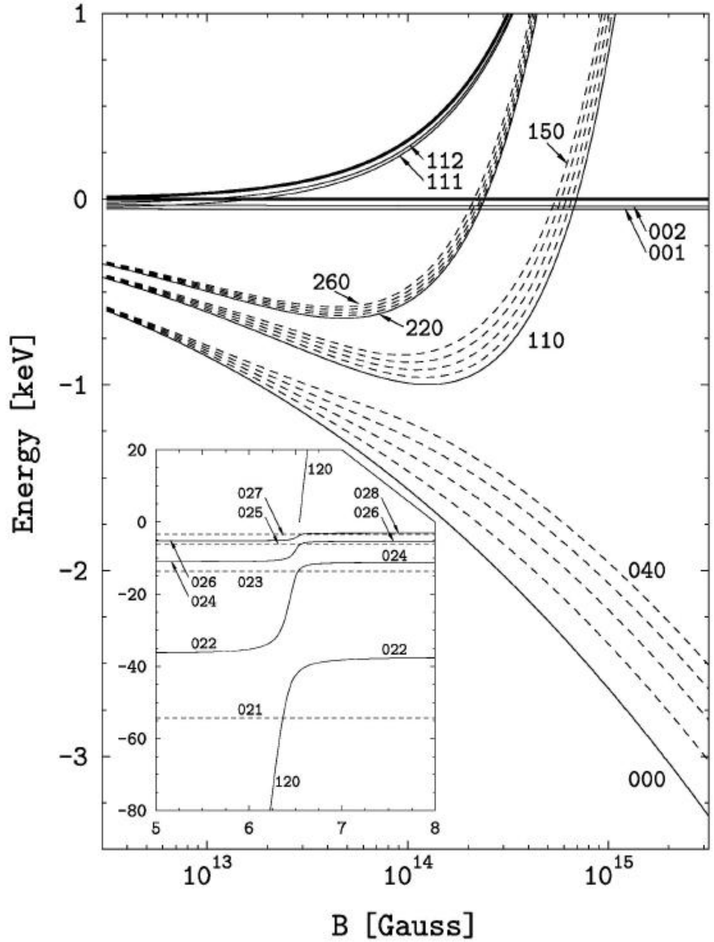
s – transverse excitation
ν – longitudinal excitation
N – rotation of ion around magnetic field

ν=0 - tightly-bound levels
ν> 0 – hydrogen-like levels

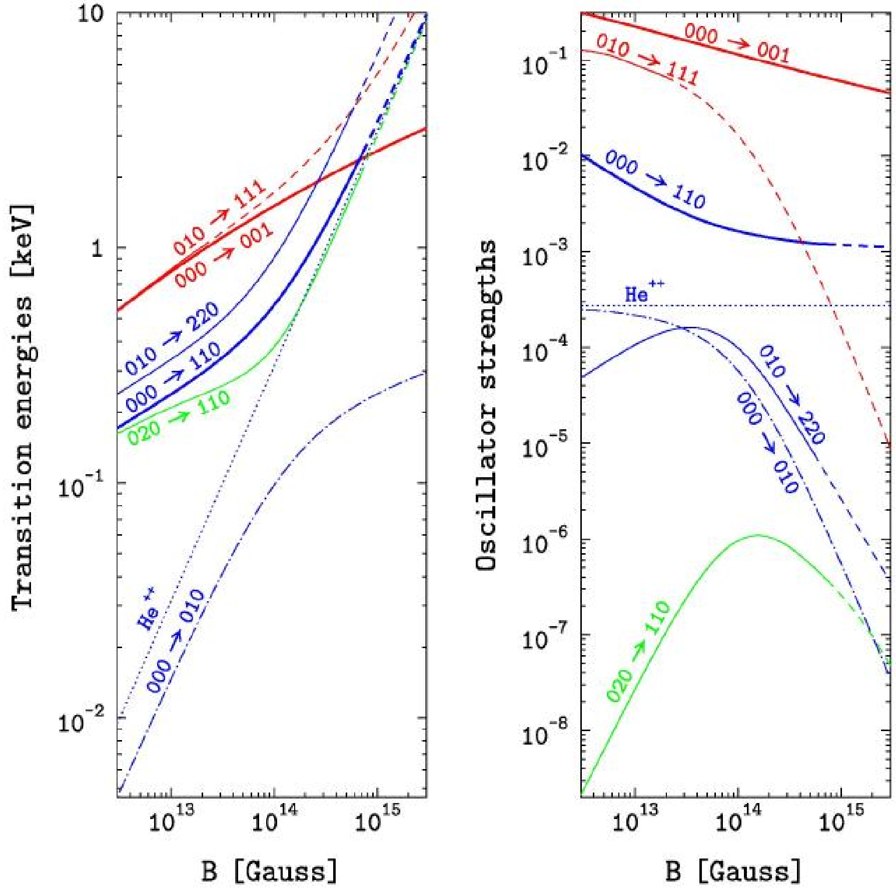
Only one truly bound s-branch remains at B > 7e14 G

GP, Bezchastnov 2005

**Energy levels** as a function of B




**Energies and oscillator strengths**
of important bound-bound transitions

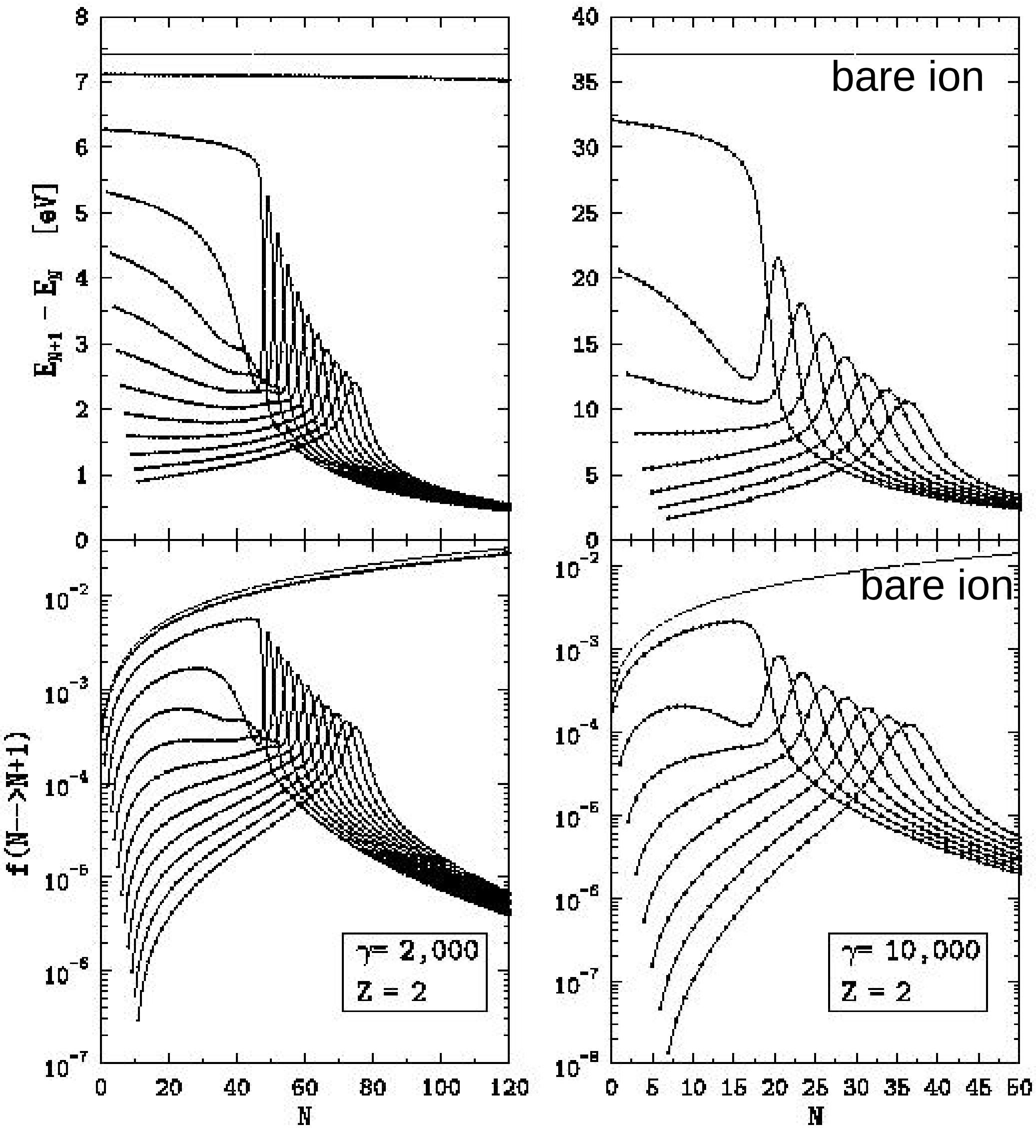



Quantization of ion rotation → **bound-ion cyclotron transitions** s,N,$\nu$→s,N+1,$\nu$
→ **fine structure** of electron transitions

He+ interpretation of two lines in 1E1207: 000→110 (0.7 keV), 000→00$\nu$ (1.4 keV)

# Bound-ion cyclotron transitions

B = 4.7e12 G    B = 2.35e13 G




**Transition energies**
(in the optical for “ordinary” NS fields; in EUV/soft-Xray In very strong B)

**Oscillator strengths**

# Summary

- It is possible that the very surface layers of some NSs are comprised of **Helium**

- The dominant He species in NSs with B ~ 1e13 – 1e14 G is **He$^+$** at the higher end of the currently observed temperatures, **He molecules** at the lower end.

- The broad absorption features detected in several INSs may be due to transitions **sN0 → s+1,N+1,0** between the s branches of tightly bound levels of He$^+$ and **sN0 → sNν** between tightly bound and hydrogen-like levels

- A new type of transitions -- **bound-ion cyclotron transitions (sN0 → s,N+1,0**) -- is due to quantization of the ion's motion as a whole. The corresponding spectral lines are in the optical-UV-EUV range, depending on B.

- The same quantization leads to a **fine structure** or strong **broadening** of the soft-Xray spectral lines.

- **To firmly identify** the observed absorption features, we need several lines detected in the same spectrum, high sensitivity and high spectral resolution of X-ray and optical **detectors** (polarization would also help), and adequate **NS atmosphere models** (work in progress).