

Surface emission of neutron stars

NS Radii

- A NS with homogeneous surface temperature and local blackbody emission

$$L = 4\pi R^2 \sigma T^4$$

$$F = \frac{L}{4\pi D^2} = (R/D)^2 \sigma T^4$$

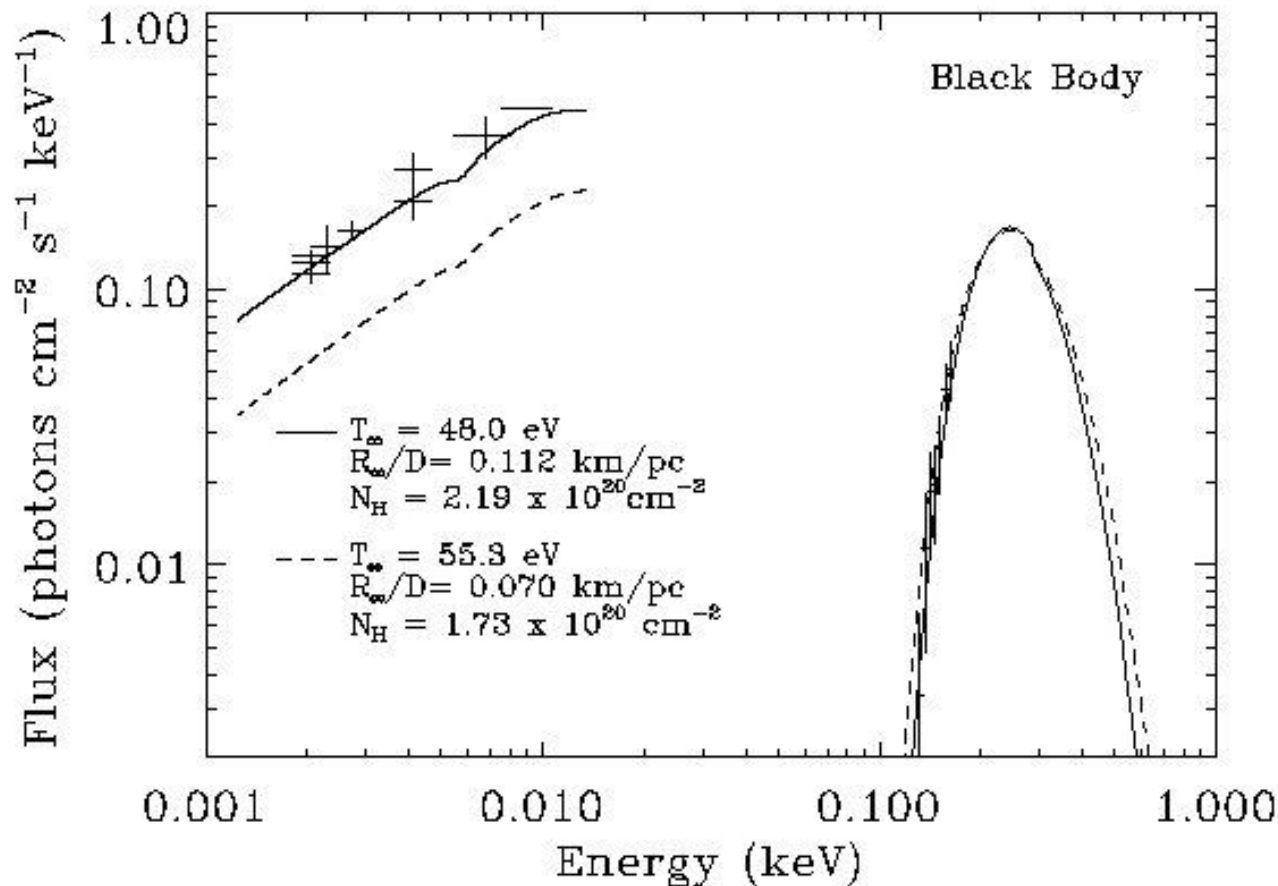
From dispersion
measure

From X-ray
spectroscopy

NS Radii - II

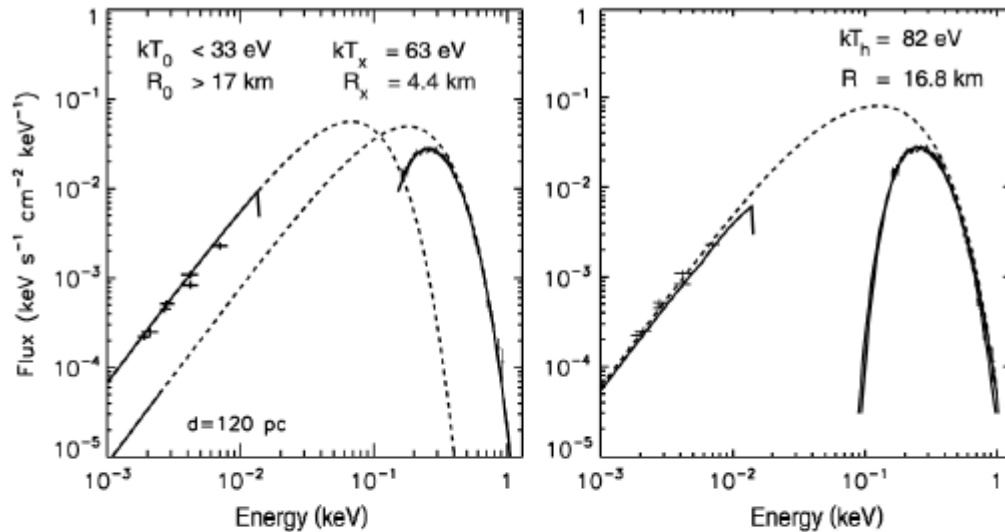
- Real life is a trifle more complicated...
Atmospheres.
- Because of the strong B field
 - Photon propagation different
 - Surface temperature is not homogeneous
 - Local emission may be not exactly planckian
- Gravity effects are important

Uncertainties in temperature

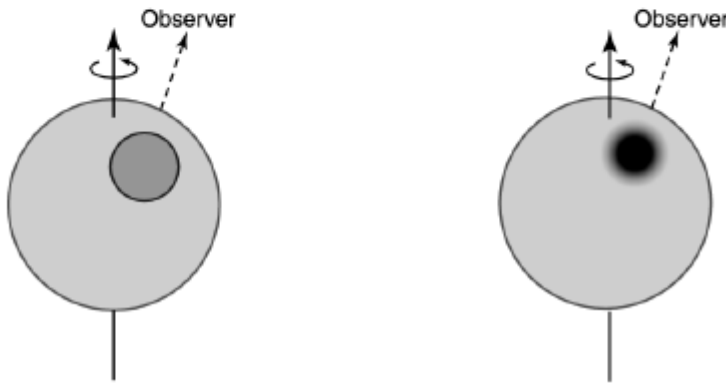


- Atmospheres (composition)
- Magnetic field
- Non-thermal contributions to the spectrum
- Distance
- Interstellar absorption
- Temperature distribution

Non-uniform temperature distribution

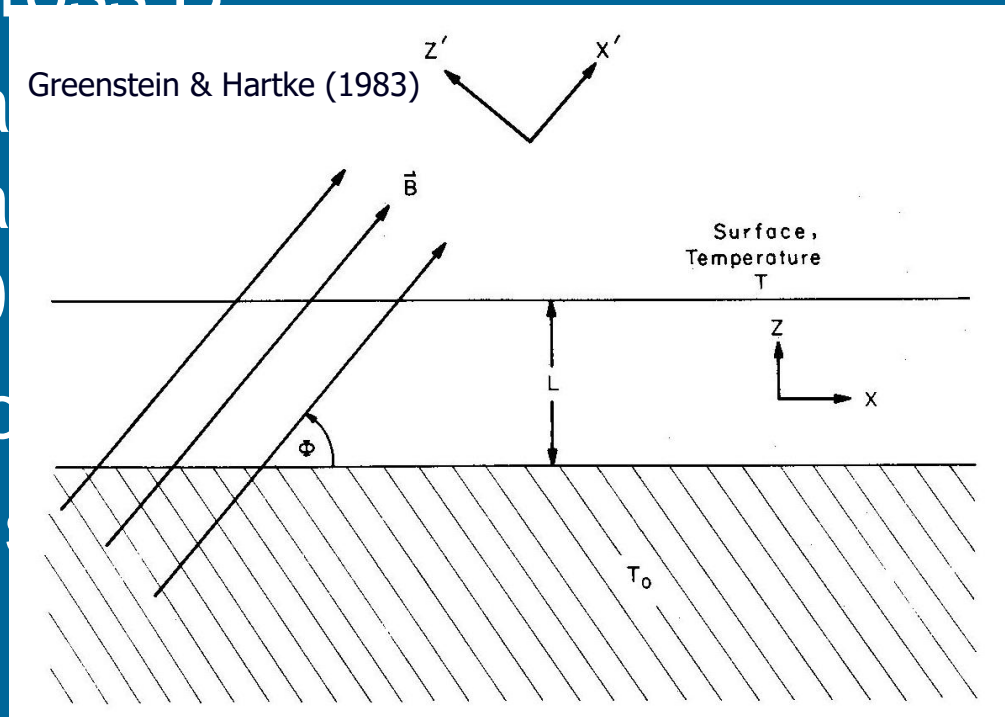


In the case of RX J1856 because of significant (~ 6) optical excess it was proposed that there is a spot, or there is a continuous temperature gradient.



NS Thermal Maps

- Electrons move much more easily along B than across B
- Thermal conductivity inside a metal is $\rho \gg 10^{-8} \Omega \cdot \text{cm}$
- Envelope of the thermal map is $B \sim \cos \theta$



$$T_s = \left[\cos^2 \Theta + \left(K_{\text{perp}} / K_{\text{par}} \right) \sin^2 \Theta \right]^{1/4} T_{\text{pole}}$$

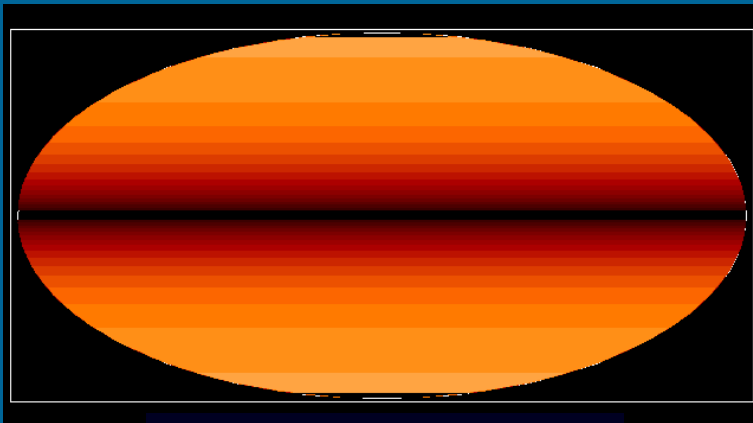
$$K_{\text{perp}} / K_{\text{par}} \ll 1$$

K - conductivity

$$T_s = |\cos \Theta|^{1/2} T_{\text{pole}}$$



Valid for strong fields: $K_{\text{perp}} \ll K_{\text{par}}$



Core centered dipole



Core centered quadrupole

Local Surface Emission

- Much like normal stars NSs are covered by an atmosphere
- Because of enormous surface gravity,
 $g \approx 10^{14} \text{ cm/s}^2$, $h_{\text{atm}} \approx 1\text{-}10 \text{ cm}$ ($h_{\text{atm}} \sim kT/mg$)
- Spectra depend on g , chemical composition and magnetic field
- Plane-parallel approximation (locally)

Atmospheric composition

A_1 The lightest

A_2 Light

A_3 Heavy

A_4 The heaviest



As $h \ll R$ we can consider only flat layers.

Due to strong gravity an atmosphere is expected to be separated: lighter elements on top.

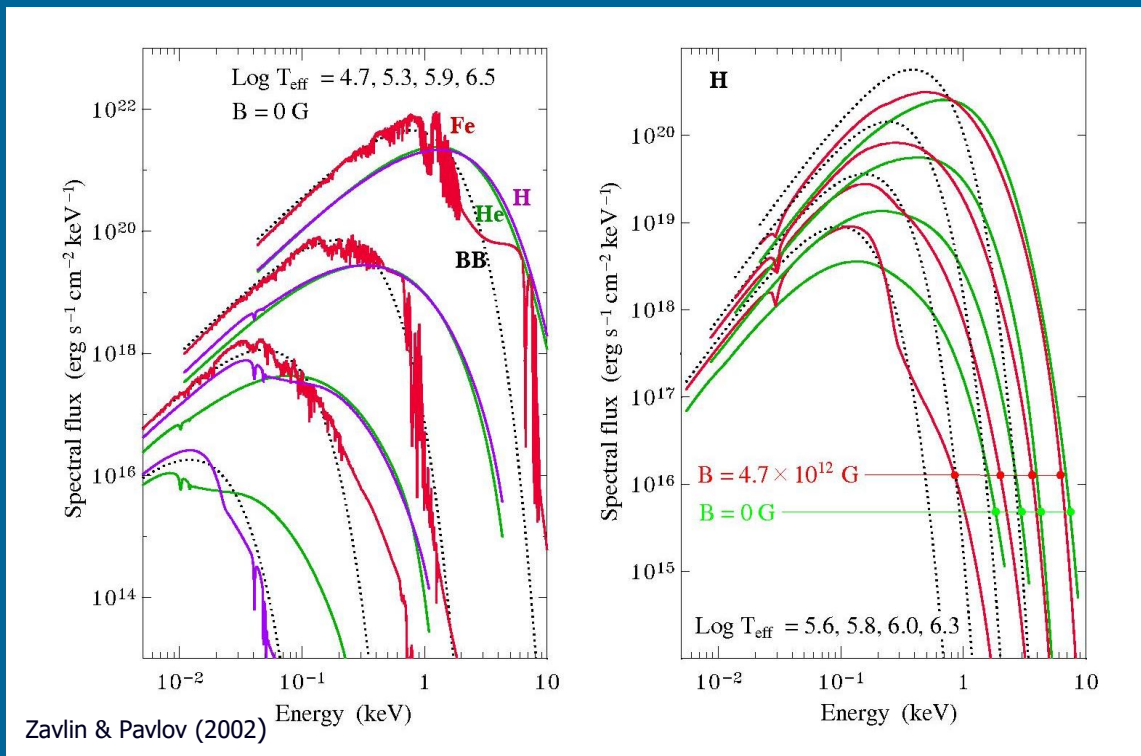
Because of that even a small amount of light elements (hydrogen) results in its dominance in the properties of the atmosphere.

10^{-20} solar mass of hydrogen is enough to form a hydrogen atmosphere.

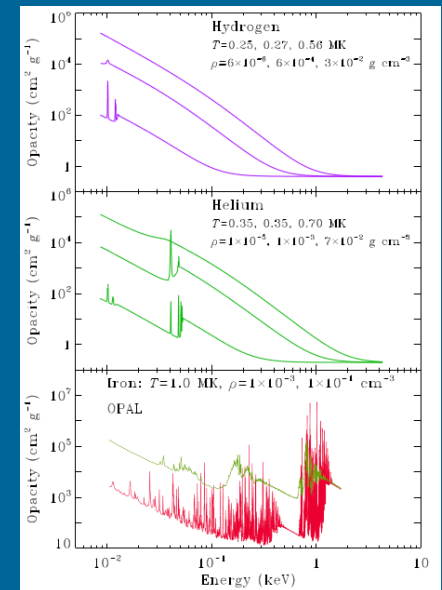
- Free-free absorption dominates

$$\kappa_\nu \propto \nu^{-3}, h\nu \gg kT$$

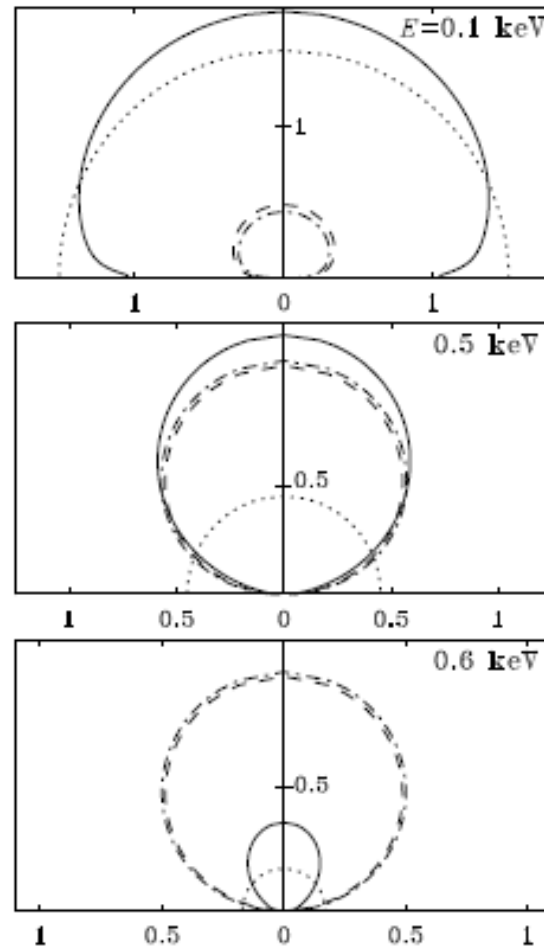
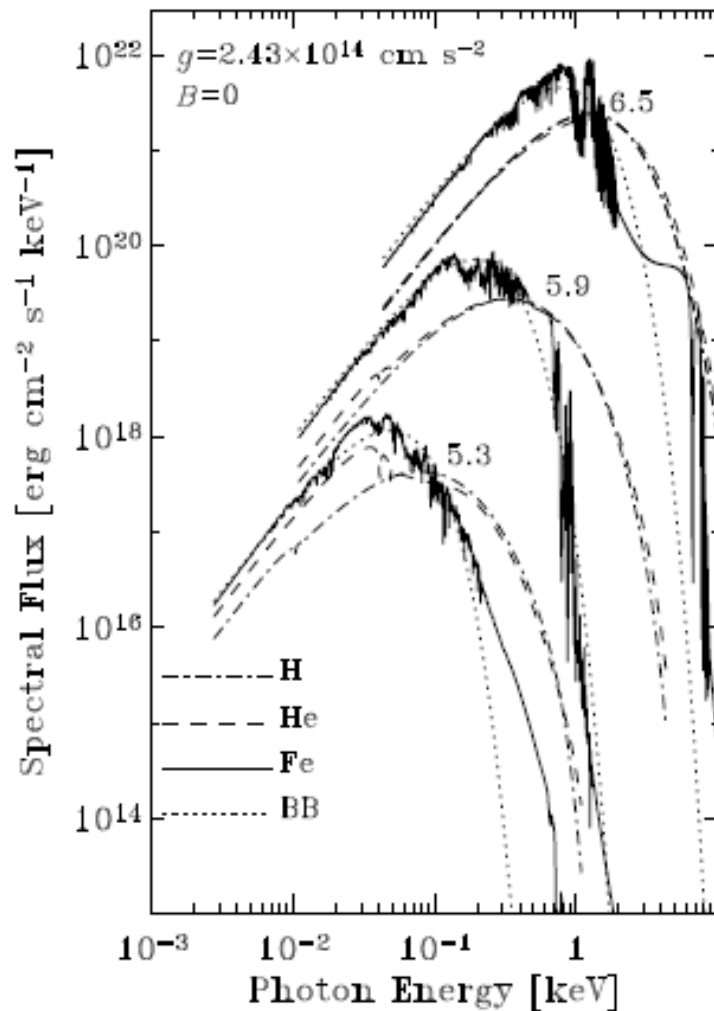
- High energy photons decouple deeper in the atmosphere where T is higher



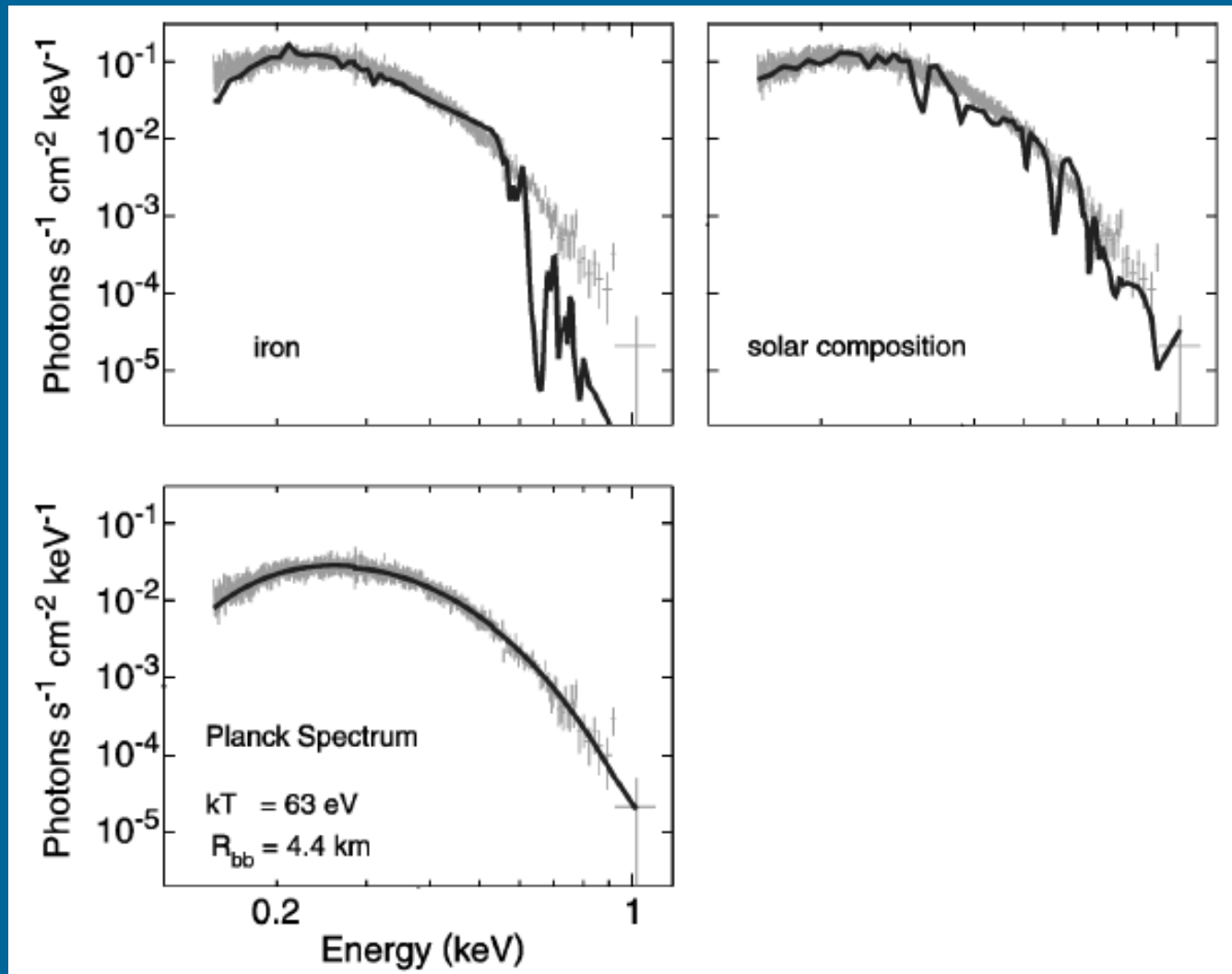
Rapid decrease of the light-element opacities with energy ($\sim E^{-3}$)



Emission from different atmospheres



Fitting the spectrum of RX J1856



Different fits

PARAMETERS FROM MULTIWAVELENGTH FITS^a

Model	n_{H} (10^{20} cm^{-2})	T_{∞} (eV)	R_{∞}/D (km pc ⁻¹)	$T_{\infty}(R_{\infty}/D)^2$ [eV (km pc ⁻¹) ²]	Luminosity ^b ($10^{31} \text{ ergs s}^{-1}$)	P_{ox}^c
BB	$2.2^{+0.3}_{-0.4}$	48 ± 2	0.11 ± 0.01	$0.60^{+0.05}_{-0.4}$	$1.55^{+0.23}_{-0.17}$	3×10^{-4}
H	1.0 ± 0.1	26 ± 1	0.27 ± 0.01	1.94 ± 0.01	0.6 ± 0.01	$< 10^{-14}$
Fe.....	1.8 ± 0.2	44 ± 1	0.13 ± 0.01	0.75 ± 0.05	$1.41^{+0.08}_{-0.06}$	7×10^{-7}
Si-ash.....	$1.9^{+0.3}_{-0.2}$	45^{+2}_{-1}	0.13 ± 0.01	$0.74^{+0.04}_{-0.05}$	$1.63^{+0.14}_{-0.21}$	0.53

^a 3 σ ranges, assuming $z = 0.305$. Weighting of the data is discussed in the text.

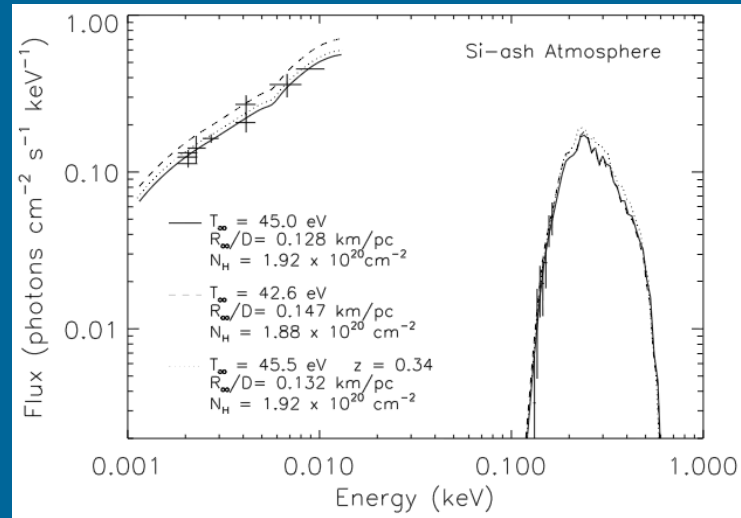
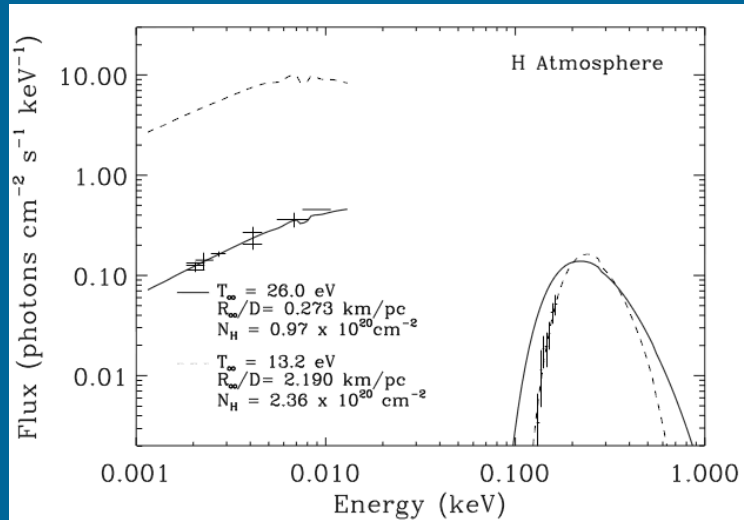
^b Uncertainty does not include uncertainty in distance.

^c The likelihood that the X-ray and optical parameters are the same.

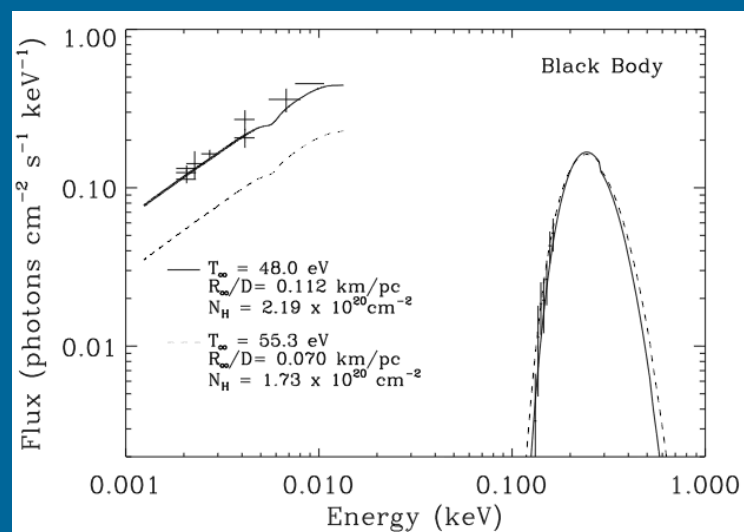
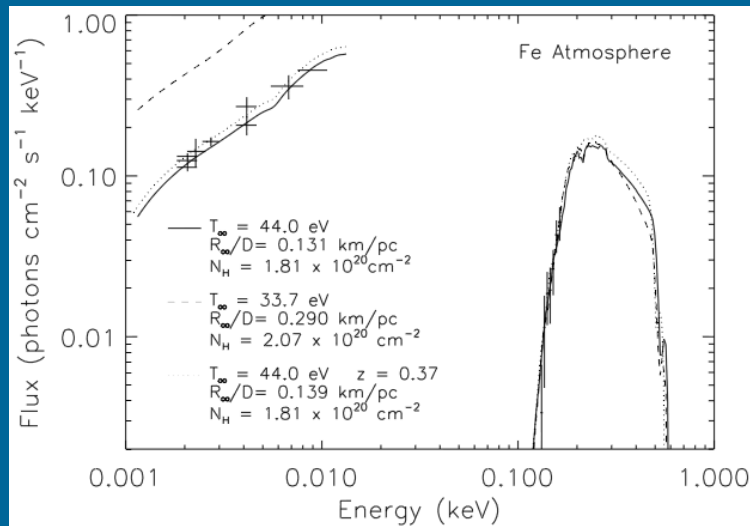
Fits of realistic spectra of cooling NSs give higher temperature (and so smaller emitting surfaces) for blackbody and heavy element atmospheres (Fe, Si).

$$T_{\text{BB}} \sim 2T_{\text{H}}$$

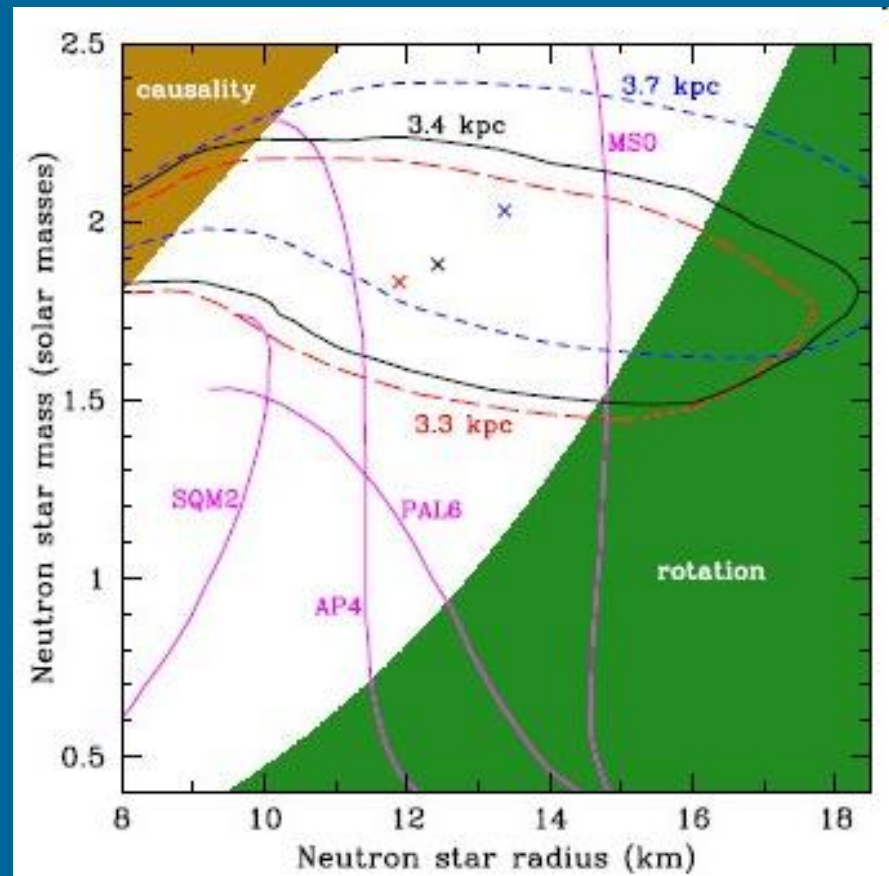
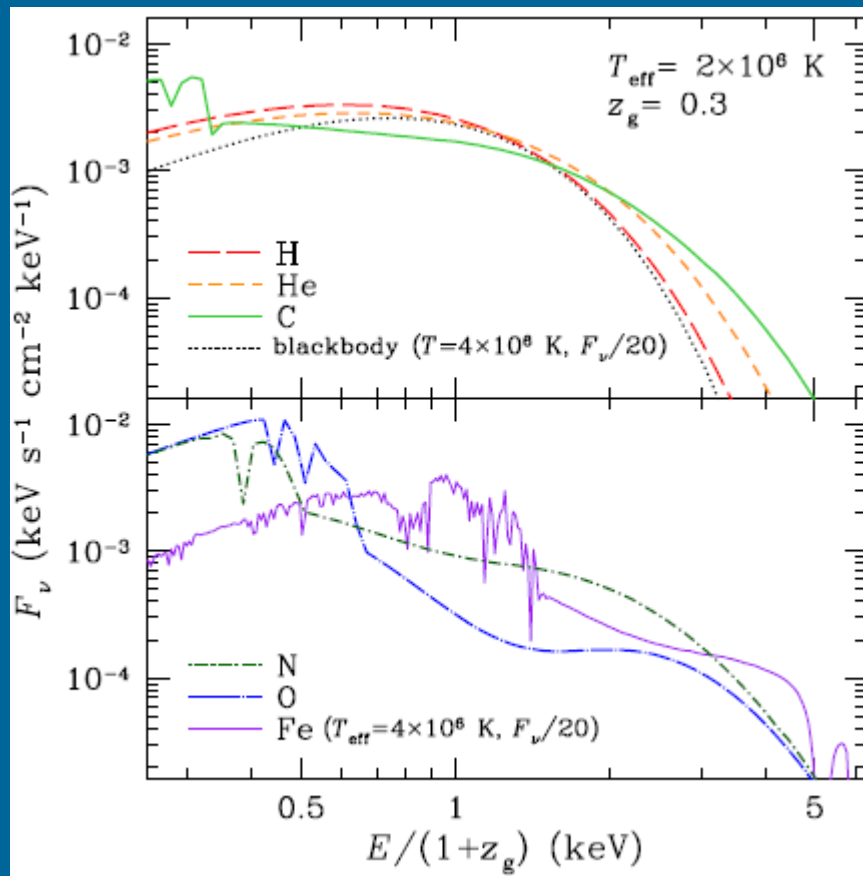
Different fits



$$T_{\text{bb}} \sim T_{\text{Fe}} > T_{\text{H}}$$



Cas A carbon atmosphere



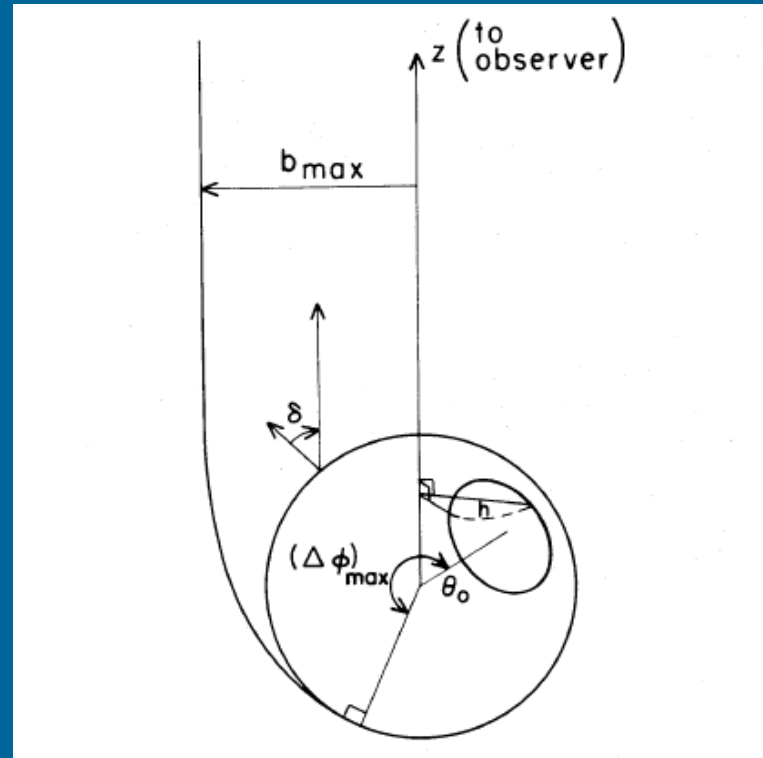
Low-field carbon atmosphere can fit the data.
Before all fits provided a very small emitting area.

Gravity Effects

- Redshift
- Ray bending

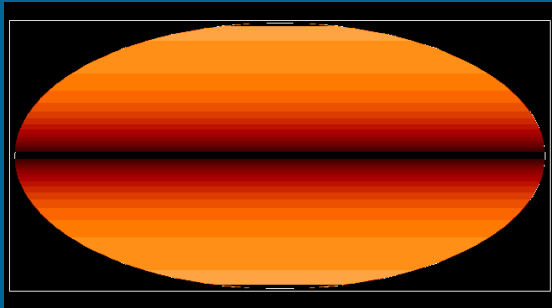
$$L_{\infty} = 4\pi R_{\infty}^2 \sigma T_{\infty}^4$$

$$4\pi\sigma T_{\infty}^4 \rightarrow \int_0^{2\pi} d\gamma \int_0^{2\pi} d\Phi \int_0^1 du^2 \int_{E_{\infty,1}}^{E_{\infty,2}} dE_{\infty} I(E, B, \cos \Theta, T_s, \gamma)$$



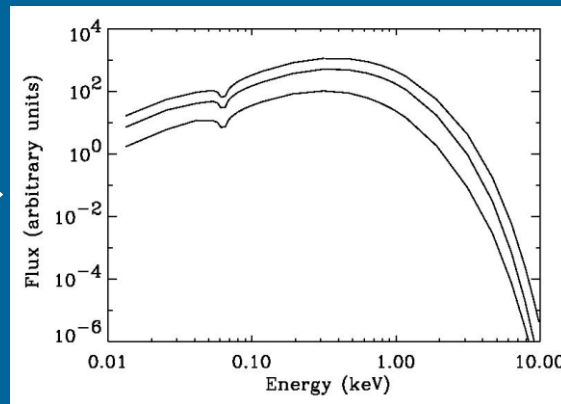
STEP 1

Specify viewing geometry and B-field topology; compute the surface temperature distribution



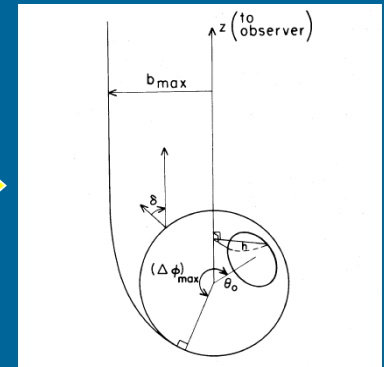
STEP 2

Compute emission from every surface patch



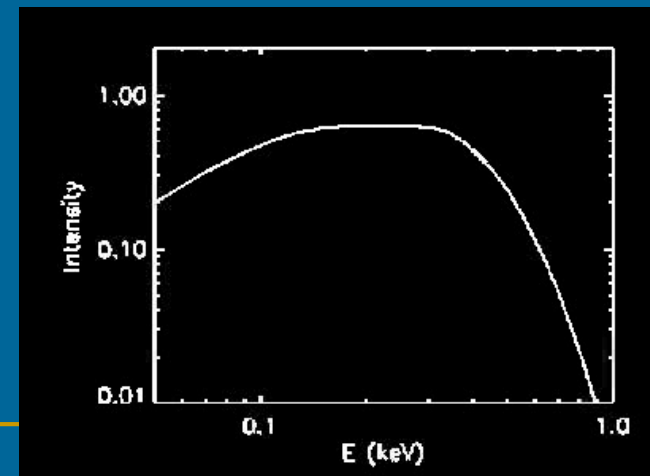
STEP 3

GR ray-tracing to obtain the spectrum at infinity



STEP 4

Predict lightcurve and phase-resolved spectrum
Compare with observations



The Seven X-ray dim Isolated NSs

- Soft thermal spectrum ($kT \approx 50\text{-}100$ eV)
- No hard, non-thermal tail
- Radio-quiet, no association with SNRs
- Low column density ($N_H \approx 10^{20} \text{ cm}^{-2}$)
- X-ray pulsations in all (but one?) sources ($P \approx 3\text{-}10$ s)
- Very faint optical counterparts
- Broad spectral features

ICoNS: The Perfect Neutron Stars

ICoNS are key in neutron star astrophysics:
these are the only sources for which we have
a “clean view” of the star surface

- Information on the thermal and magnetic surface distributions
- Estimate of the star radius (and mass ?)
- Direct constraints on the EOS

ICoNS: What Are They ?

- ICoNS *are* neutron stars
- Idea number 1: Powered by ISM accretion?
 $\dot{M}_{\text{Bondi}} \sim n_{\text{ISM}}/v^3$ if $v < 40$ km/s and $D < 500$ pc
(e.g. Treves et al 2000)
- Measured proper motions imply $v > 100$ km/s
- Just cooling NSs

Simple Thermal Emitters ?

Recent detailed observations of ICoNS allow direct testing of surface emission models

“STANDARD MODEL” thermal emission from the surface of a neutron star with a dipolar magnetic field and covered by an atmosphere

The optical excess

ICoNS lightcurves

The puzzle of RX J1856.5-3754

Spectral evolution of RX J0720.4-3125

Note a claim for an excess at harder (keV) X-rays: 1703.05995

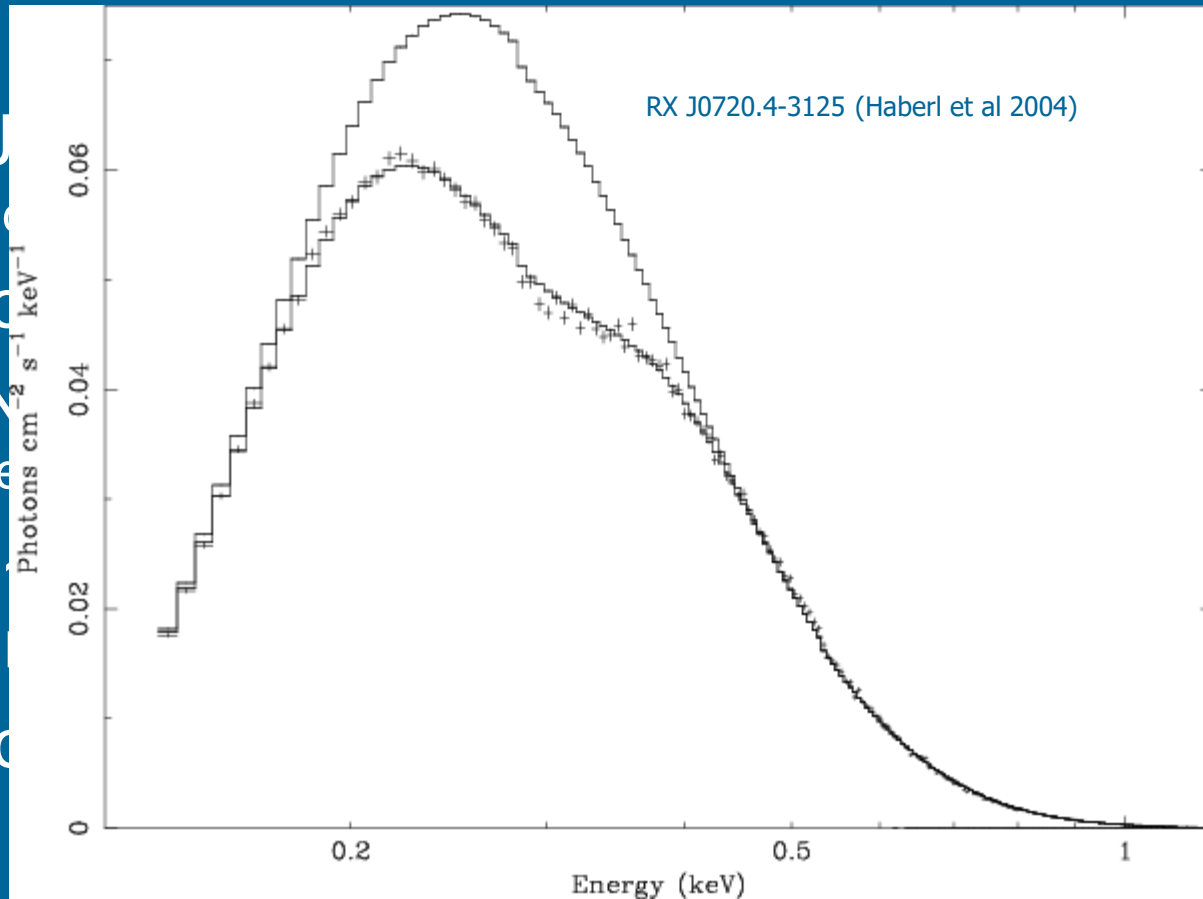
The Magnificent Seven

Source	kT (eV)	P (s)	Amplitude/2	Optical
RX J1856.5-3754	60	7.06	1.5%	V = 25.6
RX J0720.4-3125 (*)	85	8.39	11%	B = 26.6
RX J0806.4-4123	96	11.37	6%	UV
RX J0420.0-5022	45	3.45	13%	B = 26.6
RX J1308.6+2127 (RBS 1223)	86	10.31	18%	$m_{50\text{CCD}} = 28.6$
RX J1605.3+3249 (RBS 1556)	96	3.39?	??	$m_{50\text{CCD}} = 26.8$
1RXS J214303.7+065419 (RBS 1774)	104	9.43	4%	B=27.4

(*) variable source

Featureless ? No Thanks !

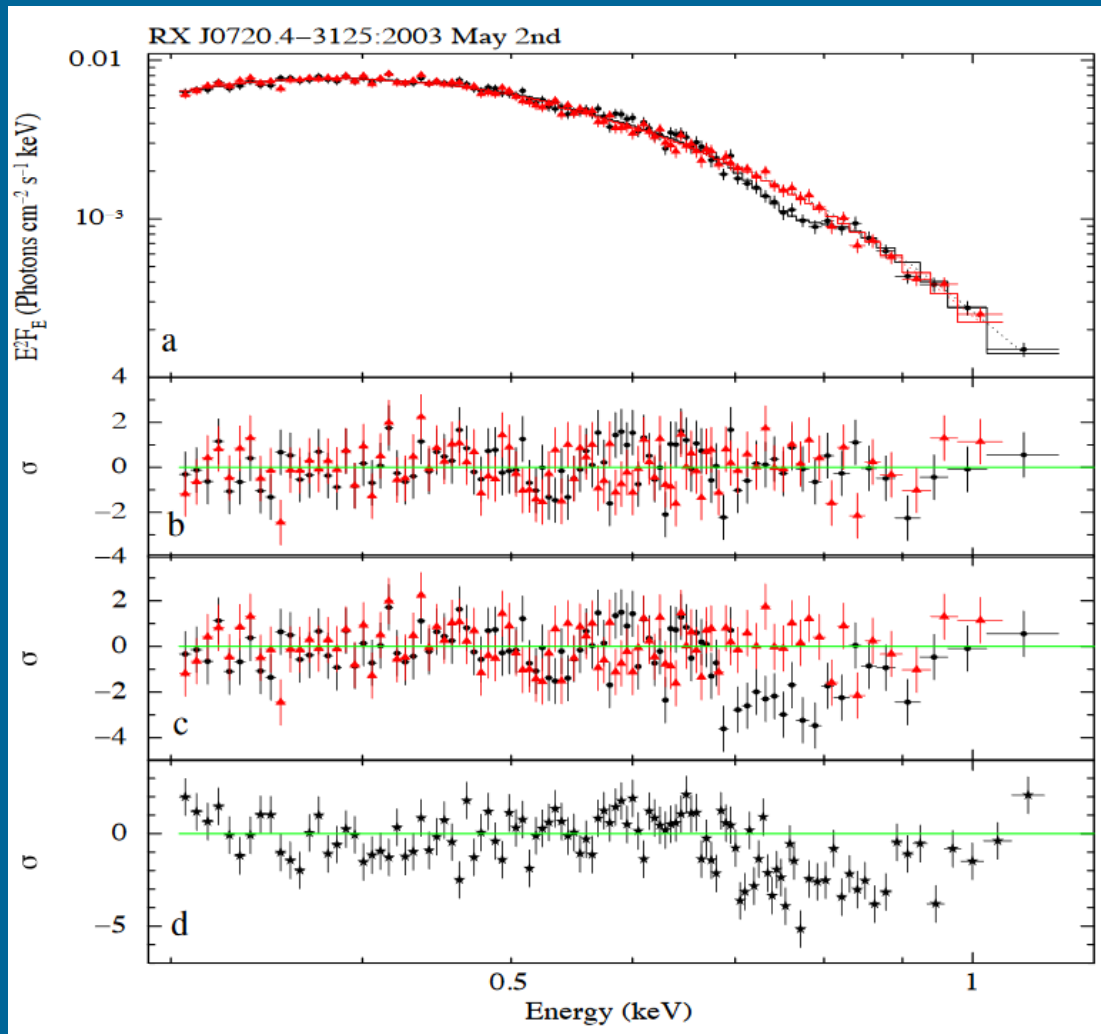
- RX J0720.4-3125 (Chandra)
- A broad peak
- ICoN model
Zane et al 2004
- $E_{\text{line}} = 2E_2$ in
Proton
- ?



S
her
al 2004;
th $E_1 \sim$
high B

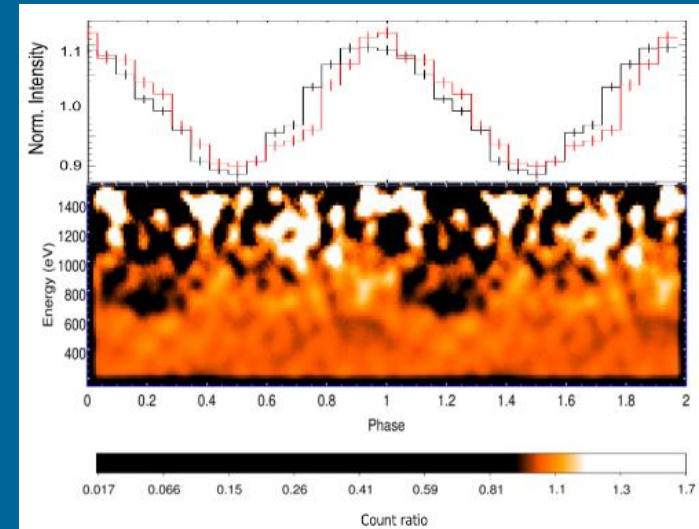
Source	Energy (eV)	EW (eV)	B_{line} (B_{sd}) (10^{13} G)	Notes
RX J1856.5-3754	no	no	?	-
RX J0720.4-3125	270	40	5 (2)	Variable line
RX J0806.4-4123	460	33	9	-
RX J0420.0-5022	330	43	7	-
RX J1308.6+2127	300	150	6 (3)	-
RX J1605.3+3249	450	36	9	-
1RXS J214303.7+065419	700	50	14	-

Phase variable spectral feature



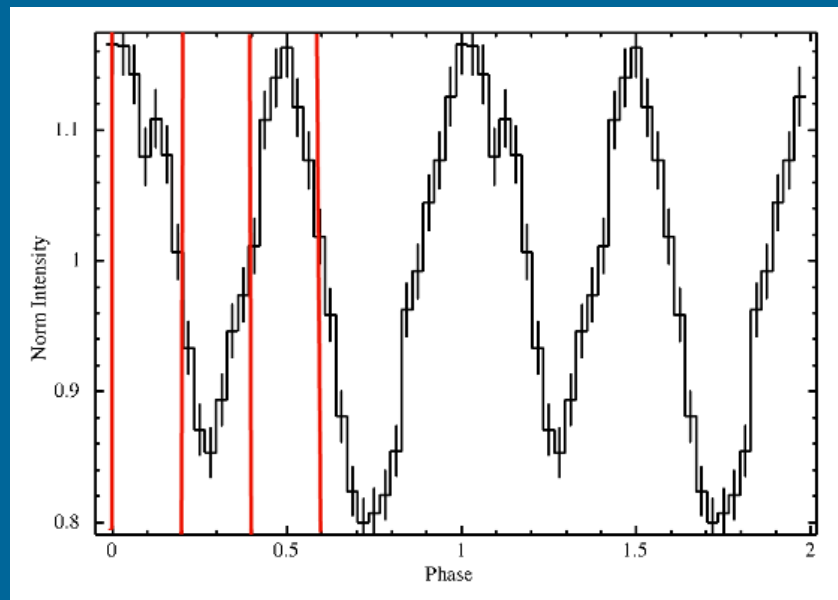
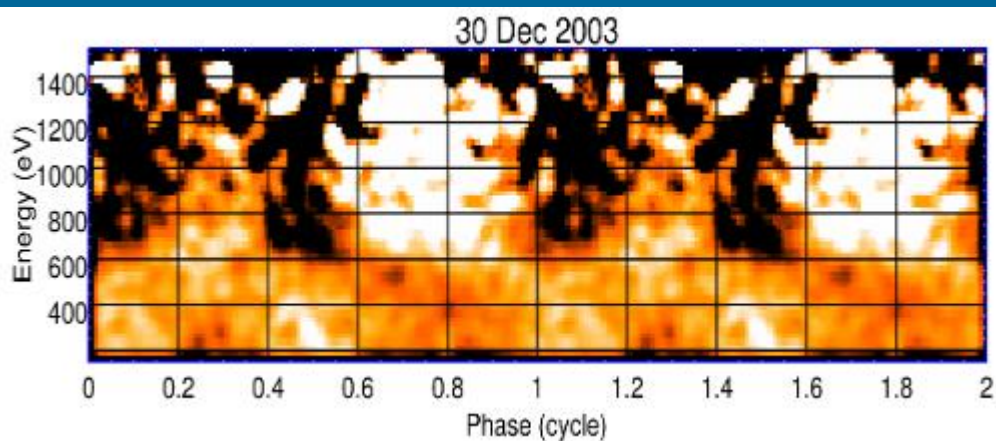
RX J0720.4-3125

Black: phase 0.1-0.3
red: phase 0.5-0.7



More phase-dependent features in M7

RX J1308.6+2127

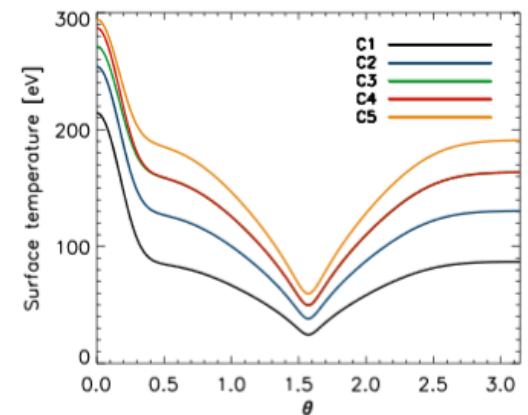
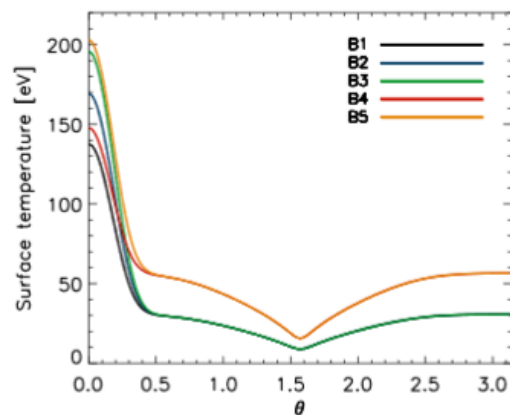
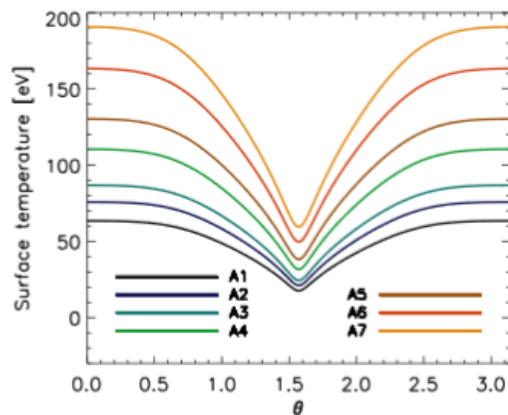


Parameter ^a	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1
BB+GAUSS					
kT _{BB} (eV)	77.7 ^{+1.8} _{-2.0}	75.4 ^{+2.2} _{-2.5}	84.9 ^{+1.3} _{-1.4}	75.6 ^{+2.1} _{-2.7}	84.9 ^{+1.8} _{-2.0}
R _{BB} (km)	4.3±0.5	5.6±1.0	2.6±0.1	5.8±1.1	3.4±0.3
Flux ^b	3.34 ^{+0.04} _{-0.09}	3.67 ^{+0.15} _{-0.09}	3.10 ^{+0.05} _{-0.07}	3.68 ^{+0.07} _{-0.06}	3.69±0.06
Unabs. Flux ^b	7.42±1.10	7.69 ^{+1.70} _{-1.01}	6.63 ^{+0.63} _{-0.36}	8.26 ^{+1.35} _{-1.39}	7.77 ^{+0.55} _{-0.76}
E ₁ (eV)	173 ⁺³² ₋₃₉	107 ⁺⁴⁴ ₋₅₄	256 ⁺²² ₋₂₈	109 ⁺⁴¹ ₋₅₉	198 ⁺³⁰ ₋₃₆
σ ₁ (eV)	143 ⁺¹³ ₋₁₂	169 ⁺¹⁵ ₋₁₄	105 ⁺¹¹ ₋₁₁	168 ⁺¹⁶ ₋₁₃	146 ⁺¹⁴ ₋₁₂
Eq Width ₁ (eV)	182 ⁺² ₋₈	204 ⁺² ₋₃₅	128 ⁺¹⁰ ₋₁₄	203 ⁺² ₋₅	171 ⁺¹¹ ₋₂₉
NHP ^c	1.6×10 ⁻¹	1.5×10 ⁻¹	5.4×10 ⁻²	1.3×10 ⁻¹	2.8×10 ⁻³
χ _ν ²	1.12	1.12	1.20	1.13	1.35
dof	141	149	139	147	150

1703.05336

Non-uniform temperature distribution

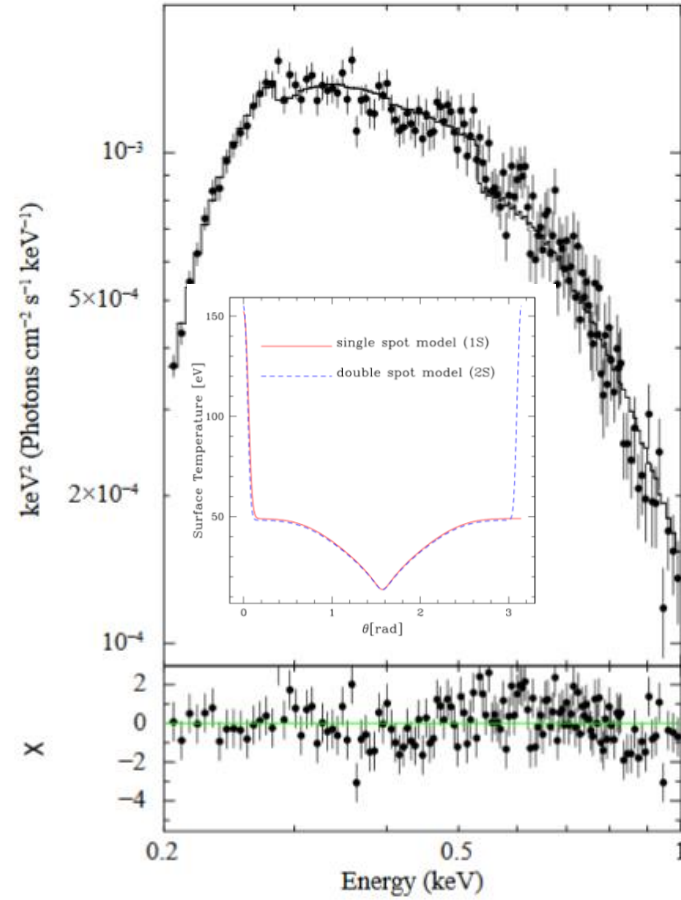
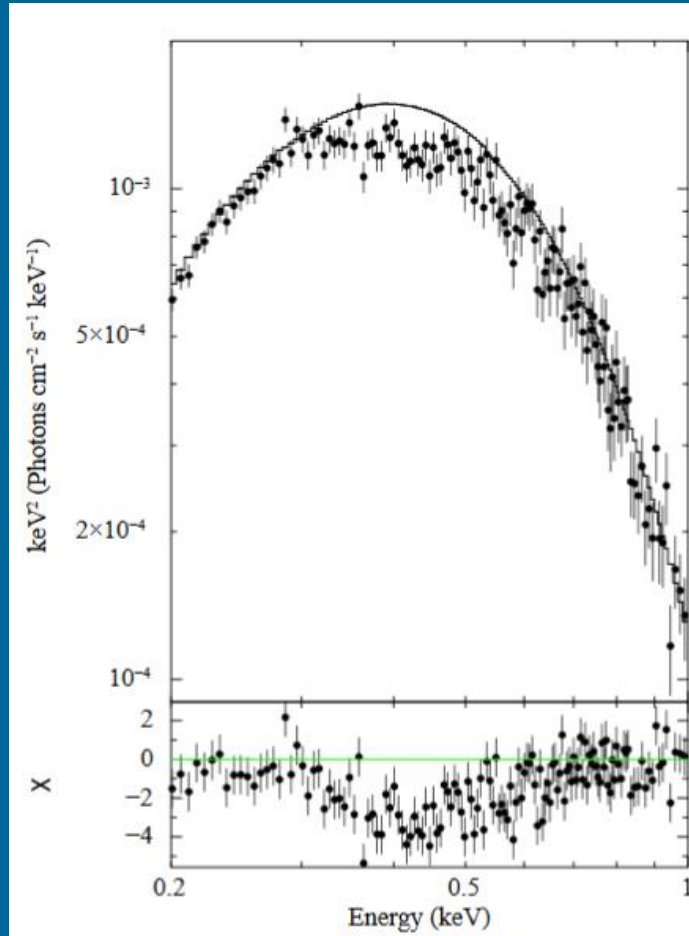
Source	Class	B_{dip} [10^{12} G]	N_H [10^{20} cm $^{-2}$]	kT_{bb} [eV]	E_0 [eV]	$ E_w $ [eV]	PF %	Refs.
RX J0720.4-3125	XINS	49	1.0	84-94	311*	0-70	11	[1]
RX J0806.4-4123	XINS	51	0.9	95	486*	30	6	[2]
RX J1308.6+2127	XINS	68	3.7	93	390*	150	18	[3]
RX J1605.3+3249	XINS	148 [†]	0	99	400*	70	5 [†]	[4]
RX J2143.0+0654	XINS	40	2.3	104	750	50	4	[5]
2XMM J1046-5943 [‡]	?	?	26	135	1350*	90	<4	[6]
1E 1207.4-5209	CCO	0.2	13	155,290	740,1390	60,100	4-14**	[7]
PSR J1740+1000	RPP	37	9.7	94	550-650	50-230	30	[8]
PSR J1819-1458	RPP	100	124	112	1120*	400	34	[9]
XTE J1810-197	MAG	410	73	300	1150	35	17-47**	[10]



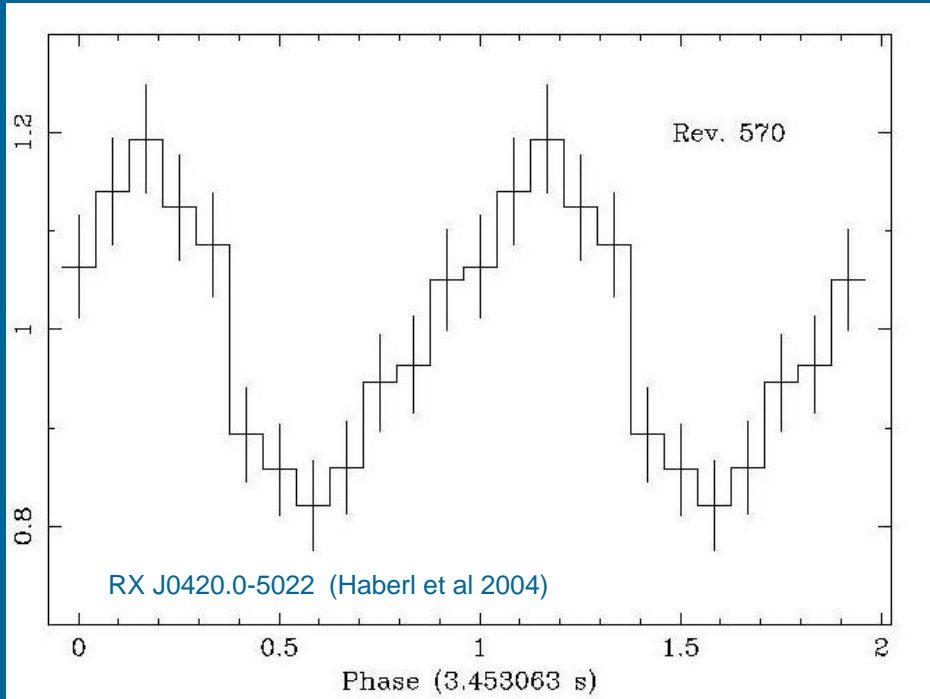
RX J0806.4-412

BB+line

Non-uniform distribution



Pulsating ICoNS - I



- Quite large pulsed fractions
- Skewed lightcurves
- Harder spectrum at pulse minimum
- Phase-dependent absorption features

Pulsating ICoNS - II

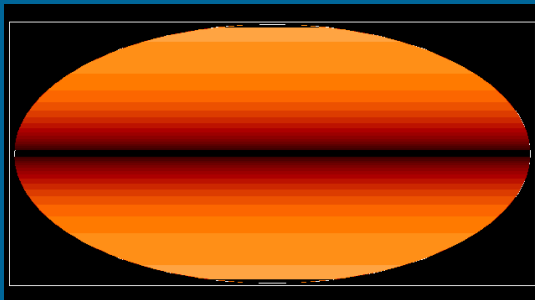
Core-centred
dipole field

+

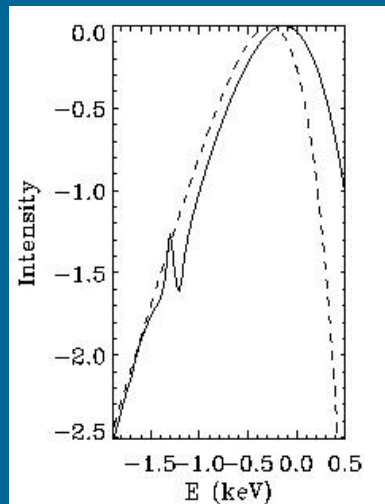
Atmosphere
emission

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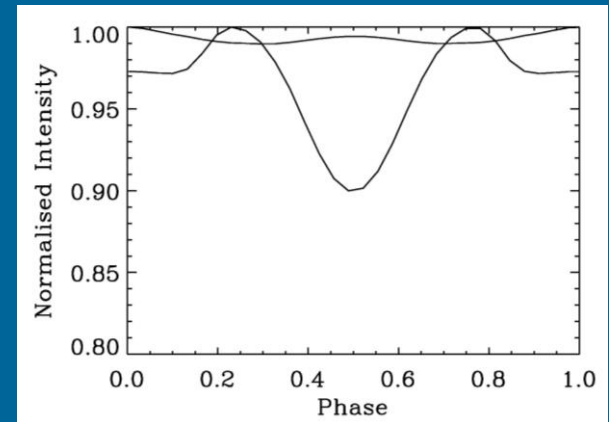
Too small
pulsed fractions
Symmetrical
pulse profiles
(Zane & Turolla 2006)



+

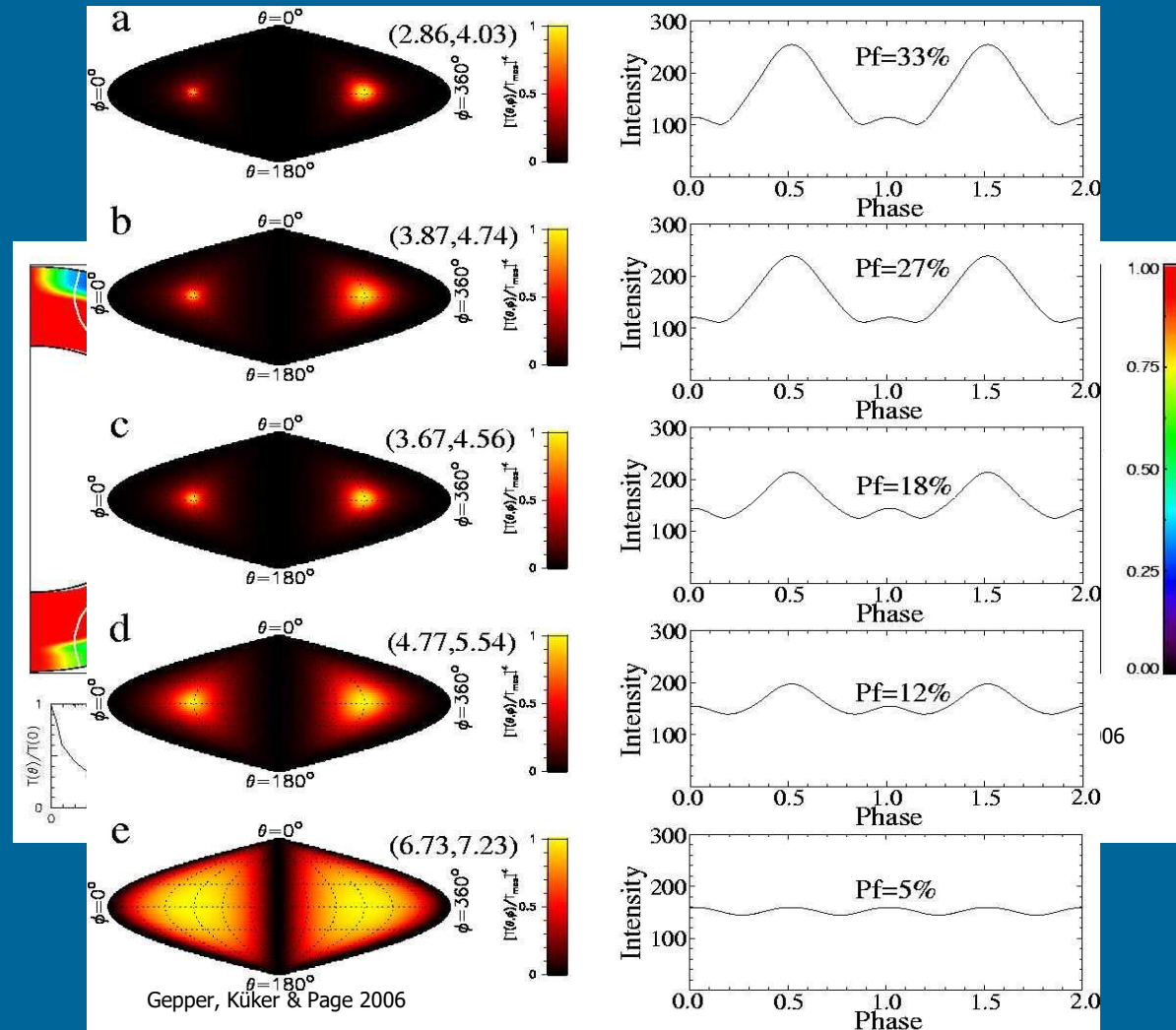


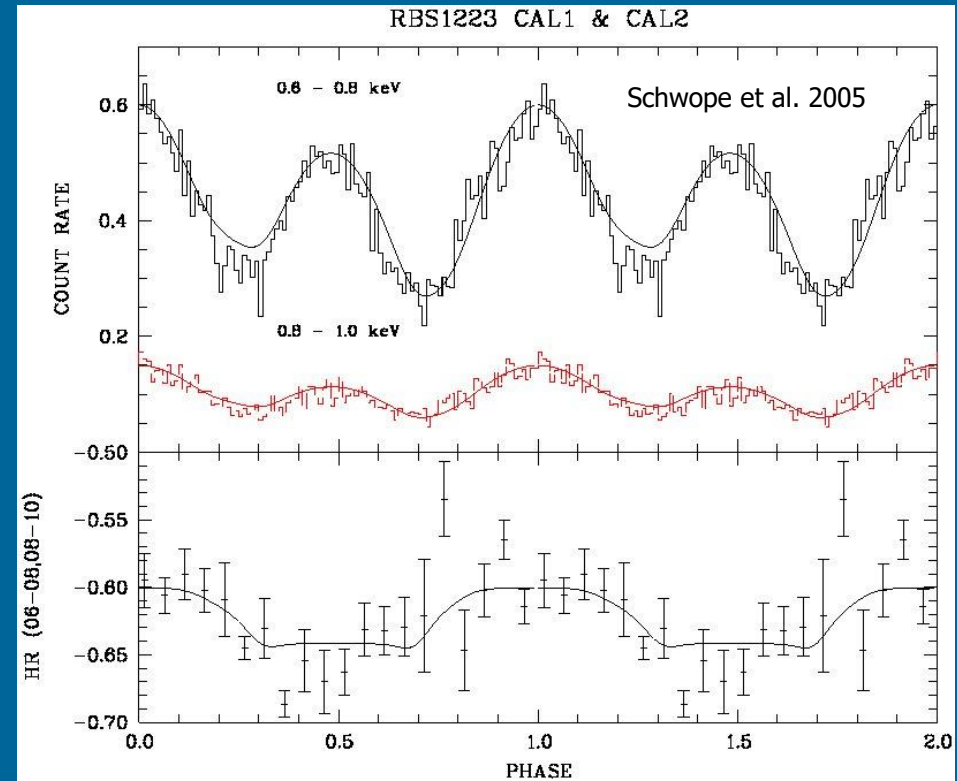
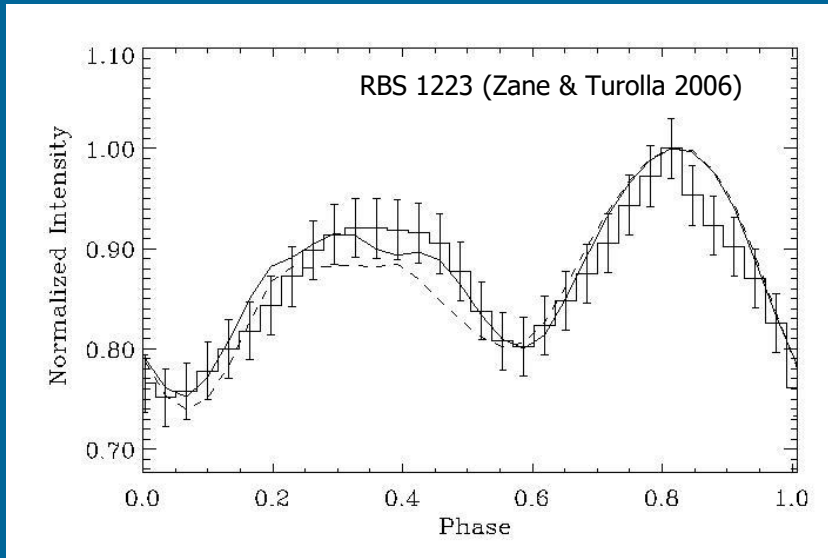
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Crustal Magnetic Fields

- Star centred dipole + poloidal/toroidal field in the envelope (Geppert, Küker & Page 2005; 2006)
- Purely poloidal crustal fields produce a steeper meridional temperature gradient
- Addition of a toroidal component introduces a N-S asymmetry



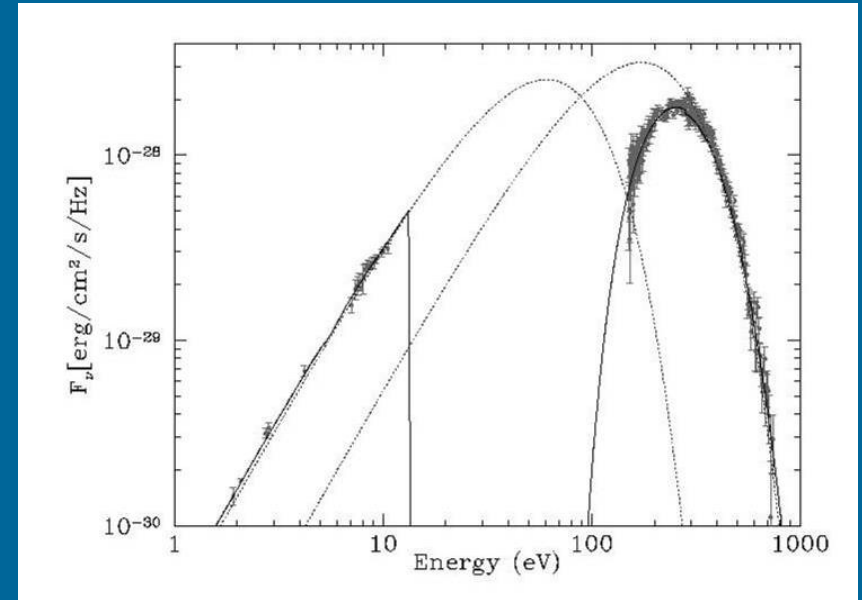


Indications for non-antipodal caps (Schwope et al 2005)

Need for a non-axisymmetric treatment of heat transport

RX J1856.5-3754 - I

Blackbody featureless spectrum in the 0.1-2 keV band (Chandra 500 ks DDT, Drake et al 2002); possible broadband deviations in the XMM 60 ks observation (Burwitz et al 2003)



RX J1856 multiwavelength SED (Braje & Romani 2002)

Thermal emission from NSs is not expected to be a featureless BB ! H, He spectra are featureless but only blackbody-like (harder). Heavy elements spectra are closer to BB but with a variety of features

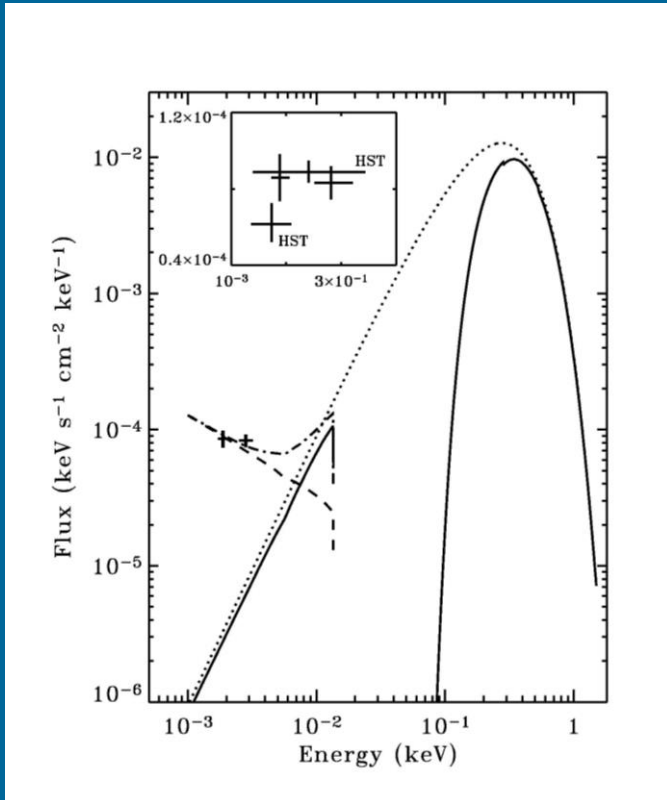
RX J1856.5-3754 - II

What spectrum ?
The optical excess ?

- A quark star (Drake et al 2002; Xu 2002; 2003)
- A NS with hotter caps and cooler equatorial region (Pons et al 2002; Braje & Romani 2002; Trümper et al 2005)
- A bare NS (Burwitz et al 2003; Turolla, Zane & Drake 2004; Van Adelsberg et al 2005; Perez-Azorin, Miralles & Pons 2005)

A perfect BB ?

The Optical Excess

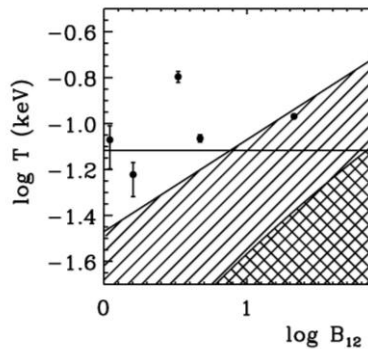
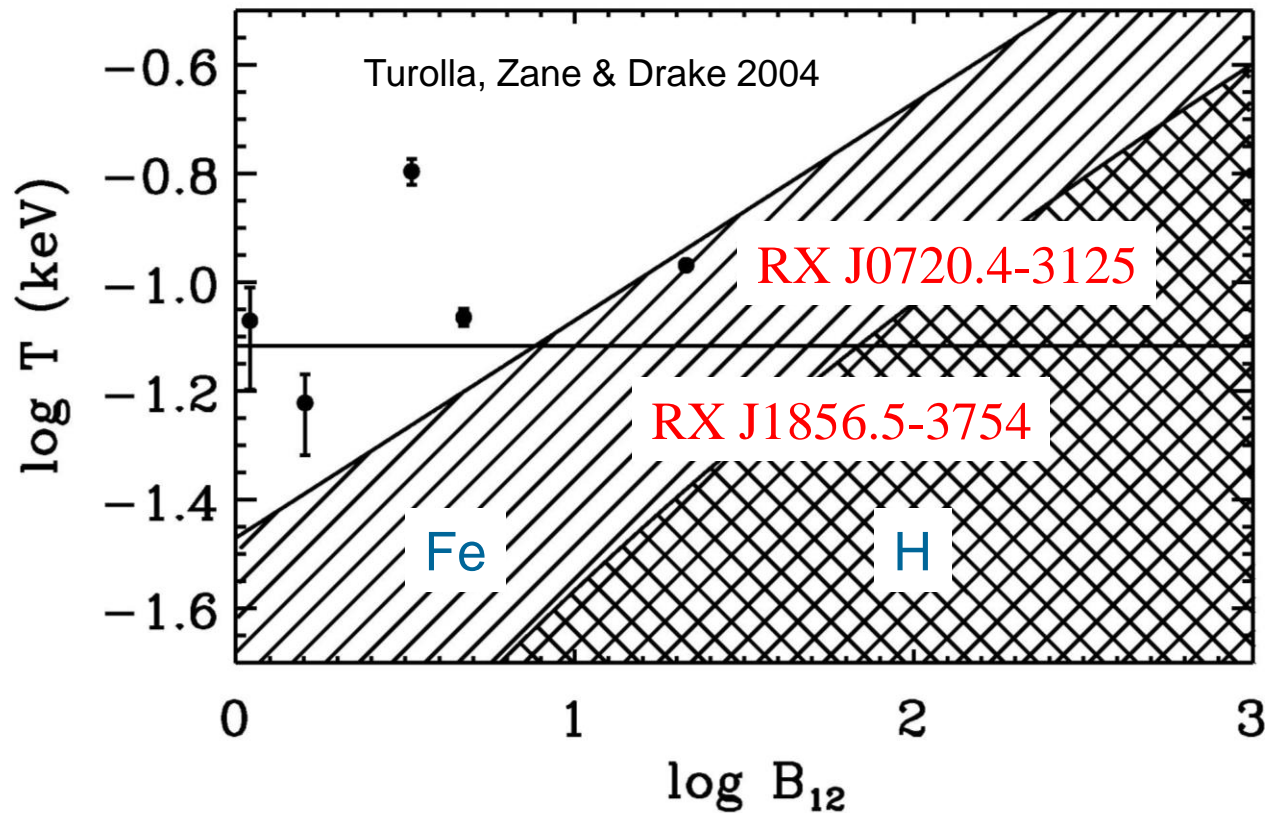


RX J1605 multiwavelength SED (Motch et al 2005)

- In the most of the sources with a confirmed optical counterpart $F_{\text{opt}} \approx 5-10 \times B_{\nu}(T_{\text{BB},X})$
- $F_{\text{opt}} \approx \nu^2$?
- Deviations from a Rayleigh-Jeans continuum in RX J0720 (Kaplan et al 2003) and RX J1605 (Motch et al 2005). A non-thermal power law ?

Bare Neutron Stars

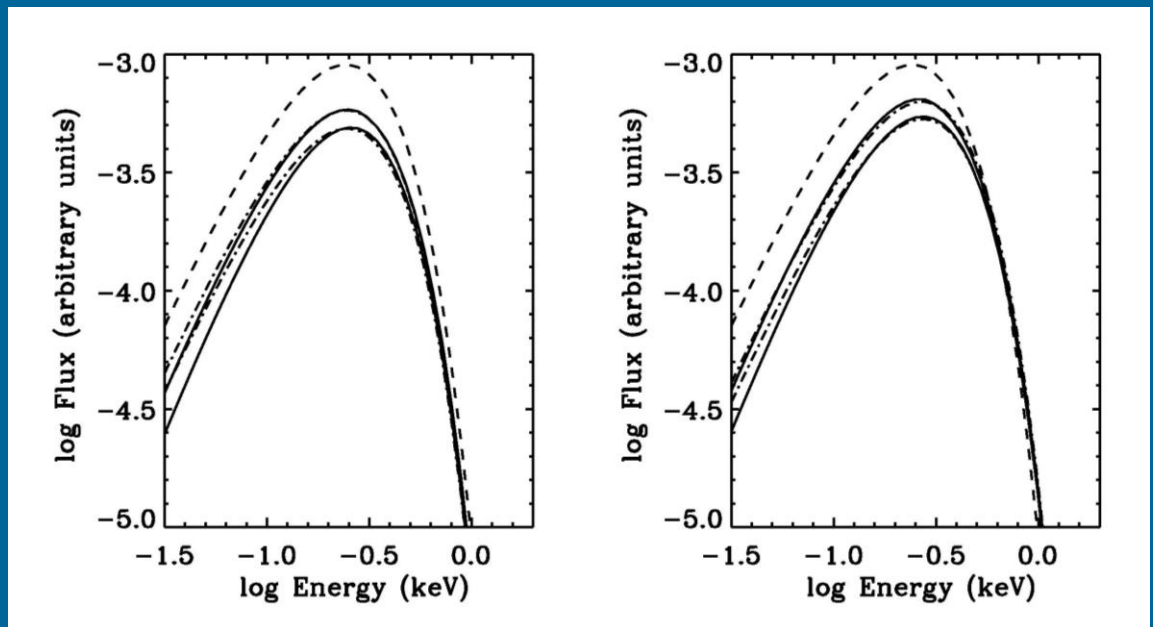
- At $B \gg B_0 \sim 2.35 \times 10^9$ G atoms



Spectra from Bare NSs - I

The cold electron gas approximation. Reduced emissivity expected below ω_p (Lenzen & Trümper 1978; Brinkmann 1980)

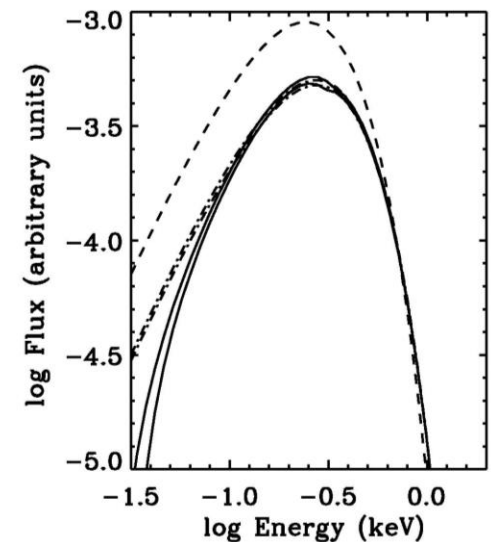
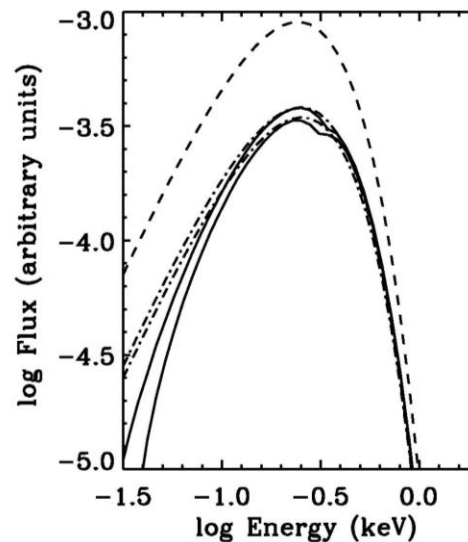
Spectra are very close to BB in shape in the 0.1 - 2 keV range, but depressed wrt the BB at T_{eff} . Reduction factor $\sim 2 - 3$.



Spectra from Bare NS - II

Proper account for damping of free electrons by lattice interactions (e-phonon scattering; Yakovlev & Urpin 1980; Potekhin 1999)

Spectra deviate more from BB. Fit in the 0.1 – 2 keV band still acceptable. Features may be present. Reduction factors higher.



Is RX J1856.5-3754 Bare ?

- Fit of X-ray data in the 0.15-2 keV band acceptable
- Radiation radius problem eased
- Optical excess may be produced by reprocessing of surface radiation in a very rarefied atmosphere (Motch, Zavlin & Haberl 2003; Zane, Turolla & Drake 2004; Ho et al. 2006)
- Details of spectral shape (features, low-energy behaviour) still uncertain

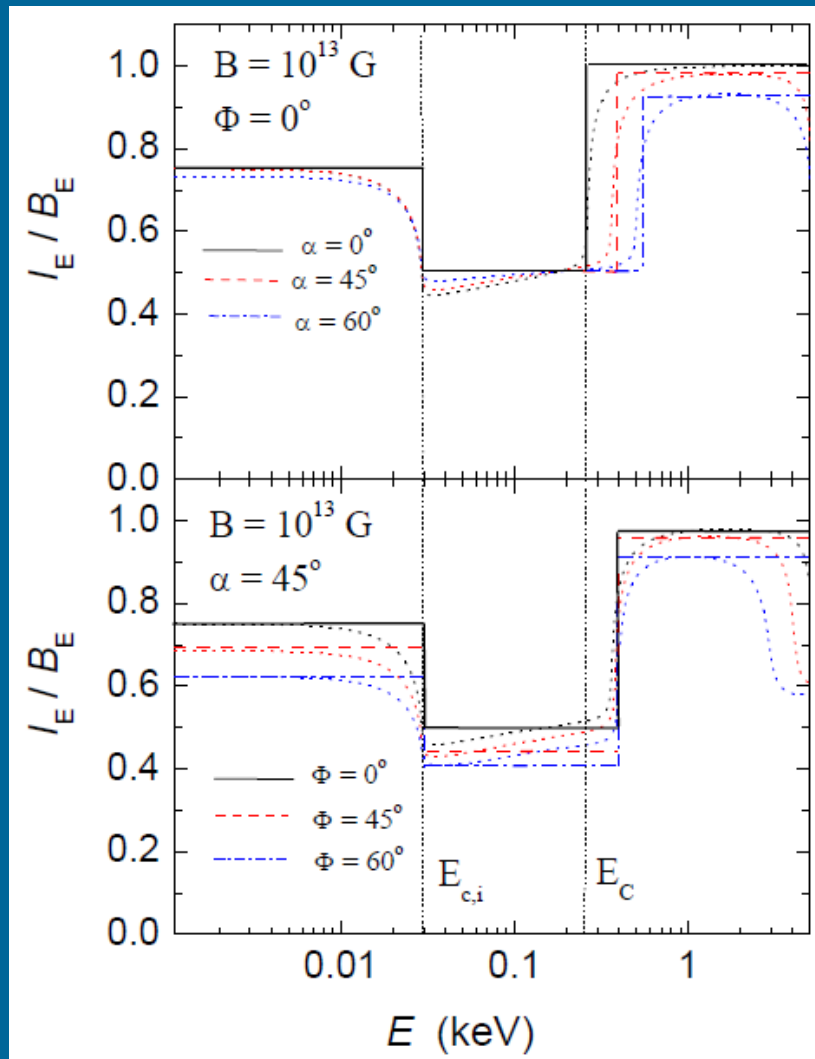
$$R_{\infty} = 4.25 f_E^{-1/2} \left(\frac{D}{100 \text{ pc}} \right) \left(\frac{T_{BB}}{60 \text{ keV}} \right)^{-2} \text{ km}$$

Does the atmosphere keep the star surface temperature ?



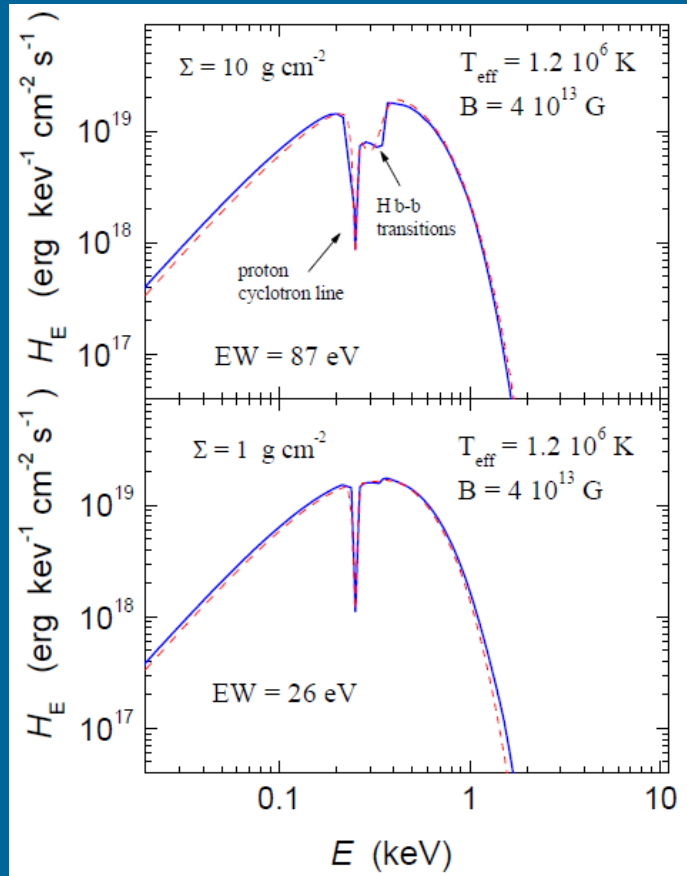
What is the ion contribution to the dielectric tensor ?
(Van Adelsberg et al. 2005; Perez-Azorin, Miralles & Pons 2005)

Condensed iron surface emissivity

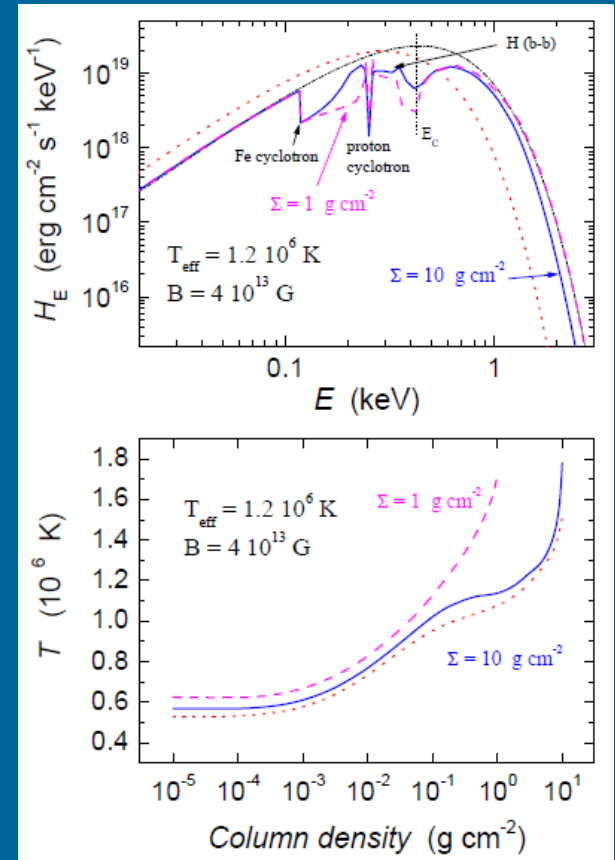


Free ions approximation.

Thin hydrogen magnetized atmosphere above blackbody and iron condensed surface

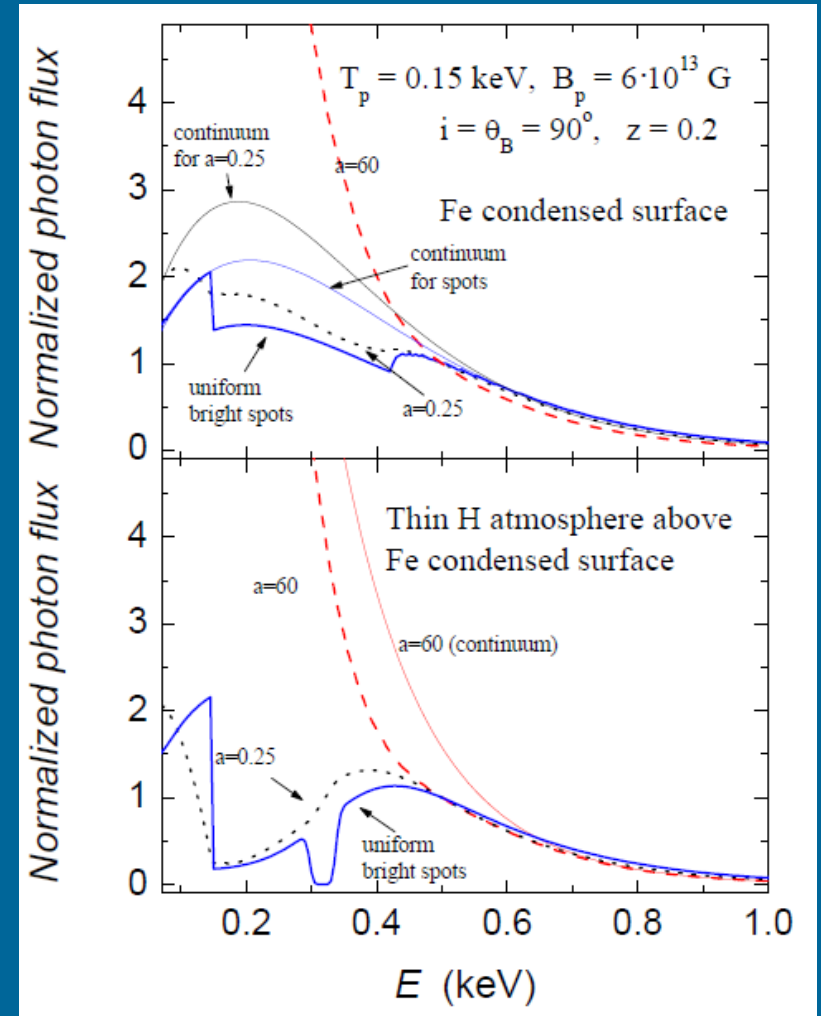
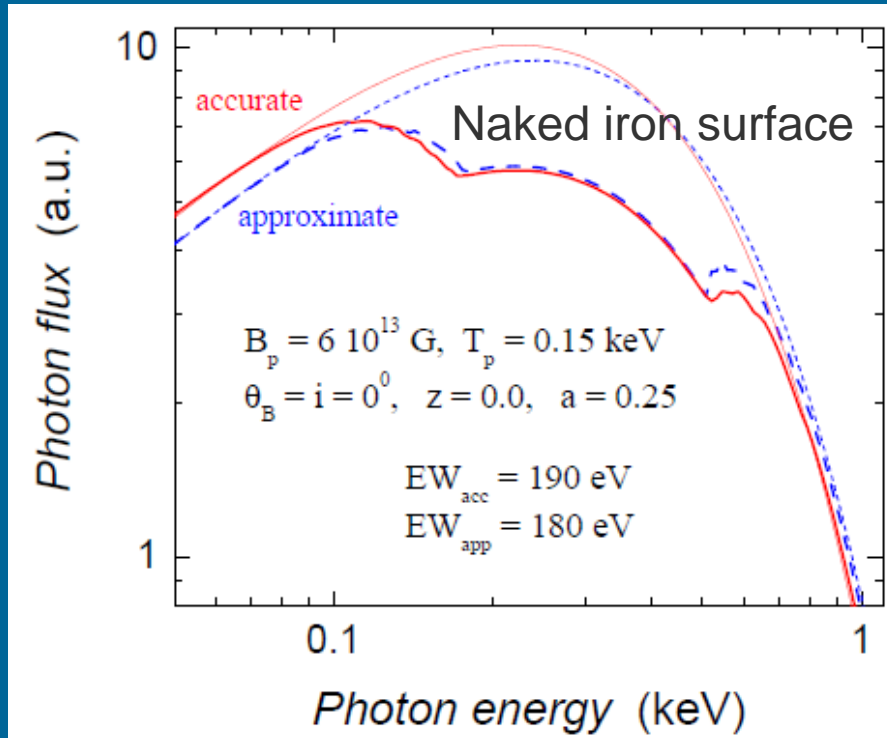


Below atmosphere was a blackbody spectrum



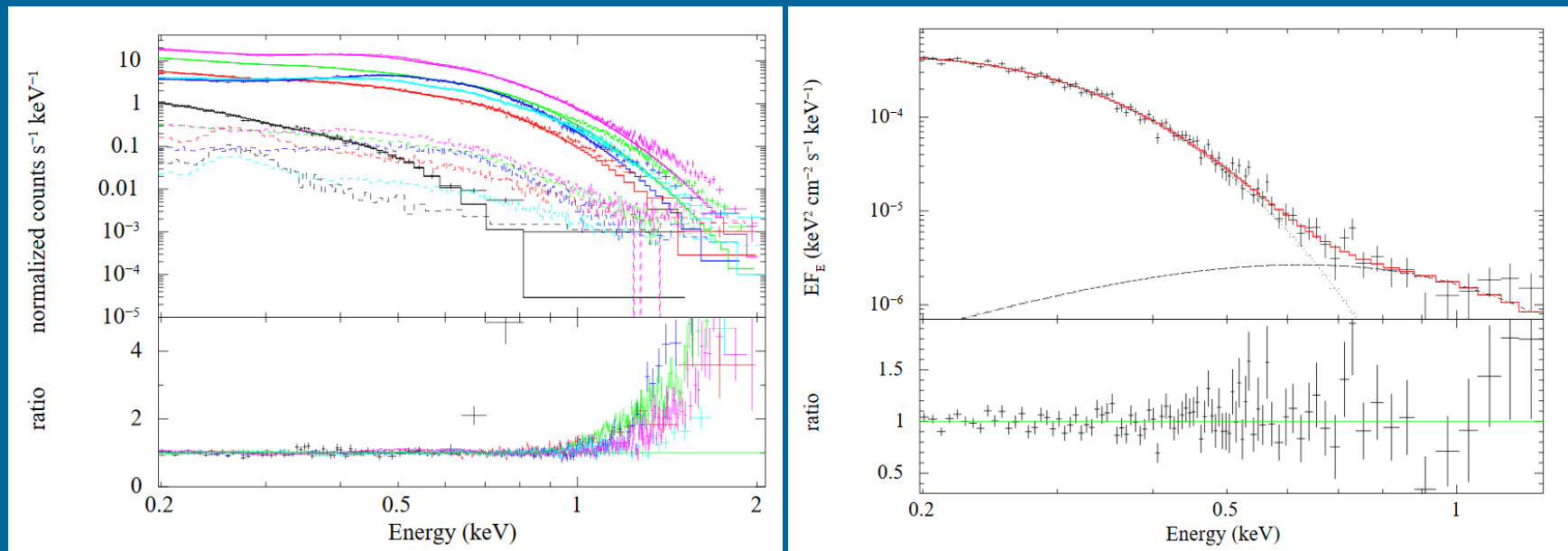
Below – iron condensed surface

Let us make it realistic

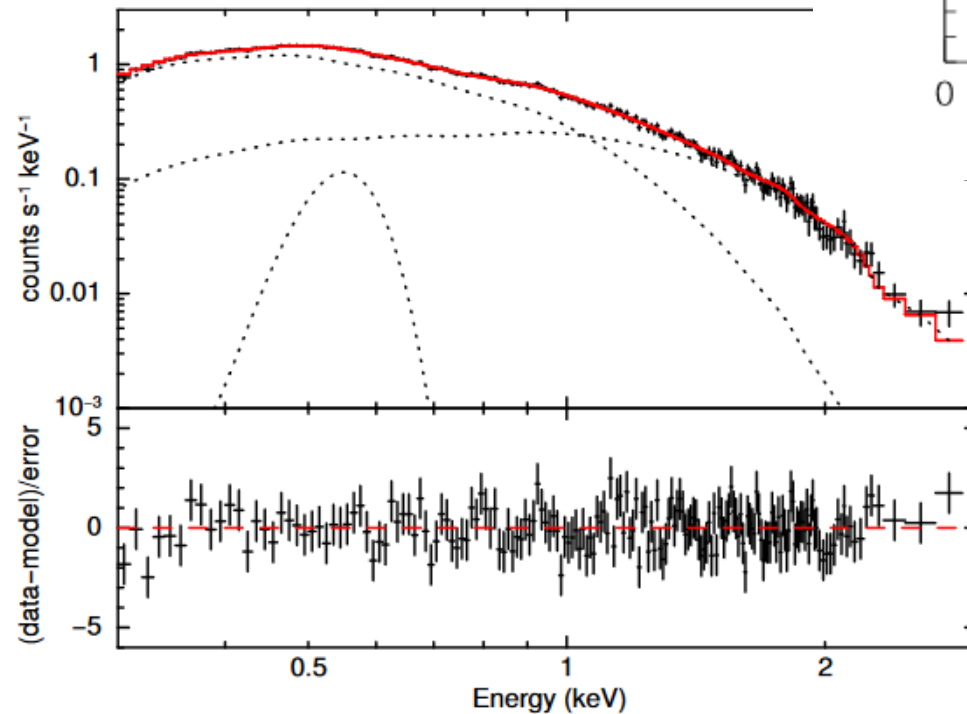
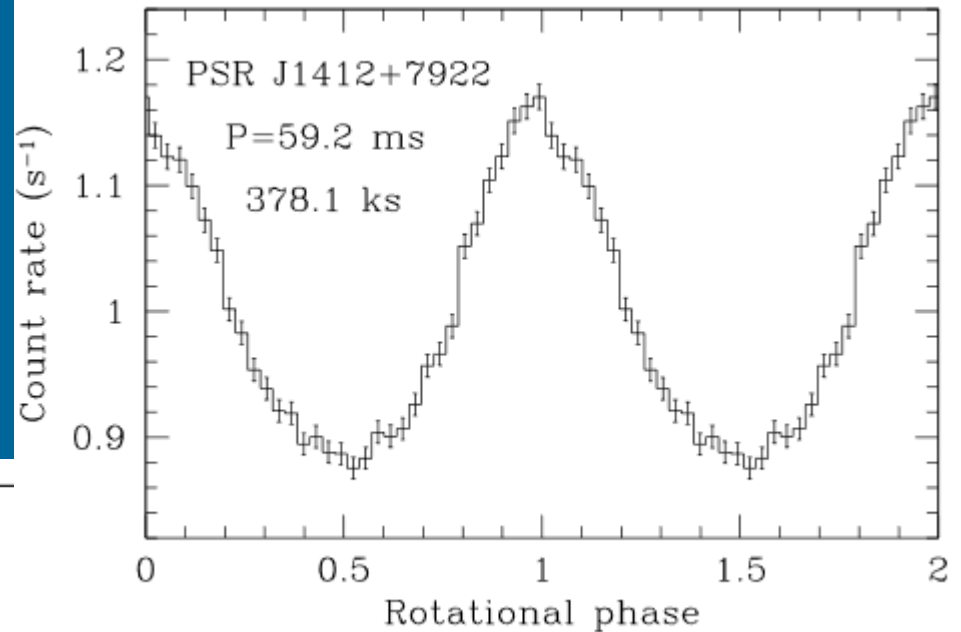


Excess at >1 keV?

Analysis of spectra of M7 demonstrated a strange excess at energies > 1 keV. This is somehow similar to what magnetars demonstrate.

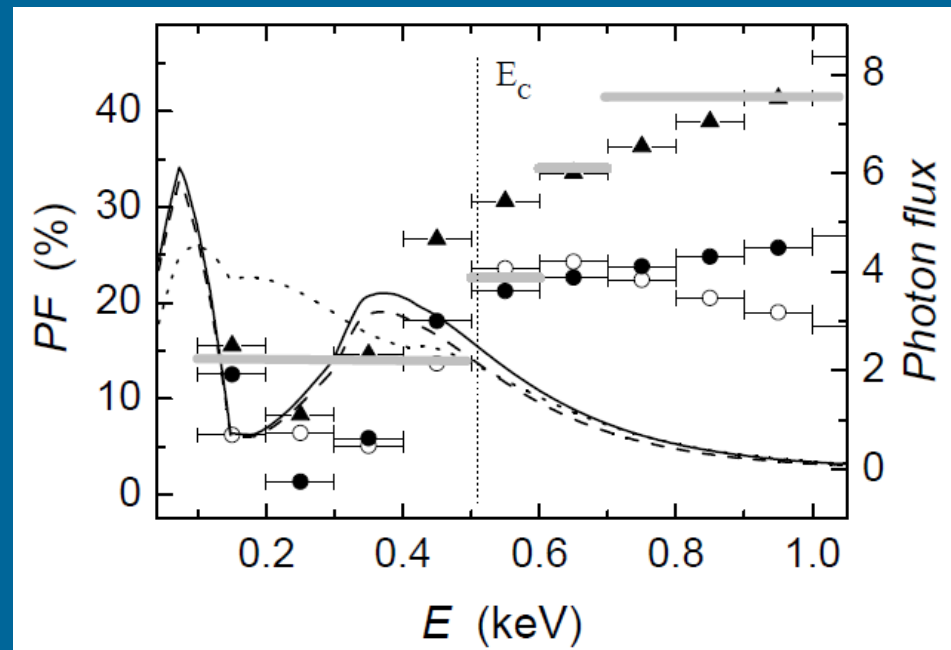
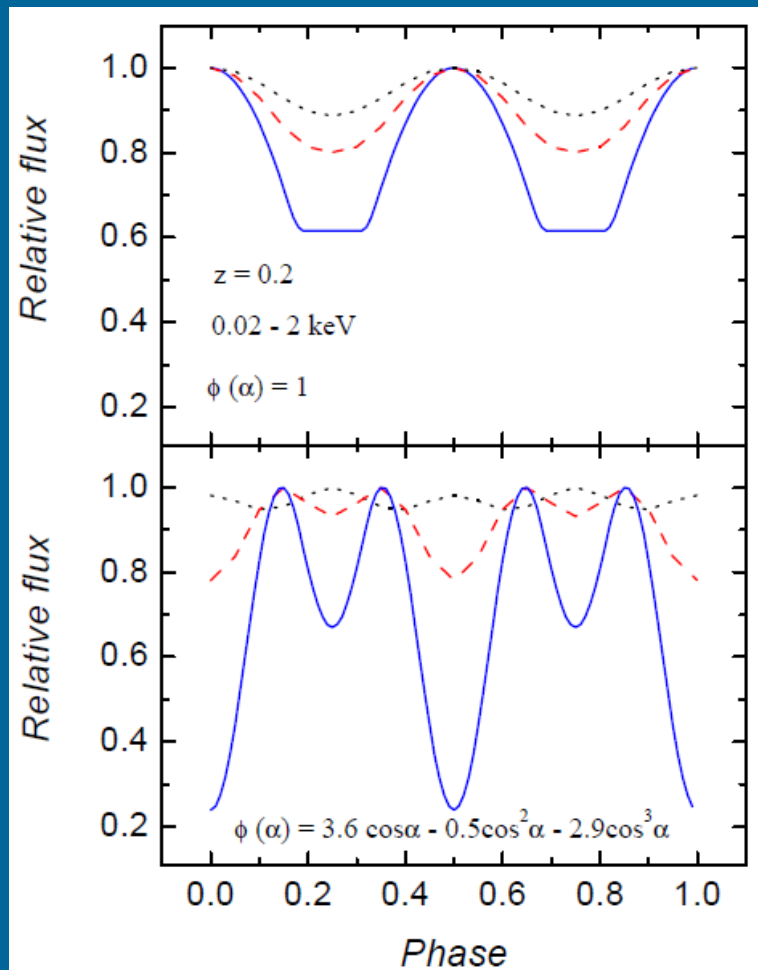


Calvera spectrum



kT_1 (keV)	0.154 ± 0.004
R_1 (km) ^b	$2.21^{+0.08}_{-0.07}$
kT_2 (keV)	$0.319^{+0.013}_{-0.012}$
R_2 (km) ^b	0.37 ± 0.04

Light curves and pulsed fraction



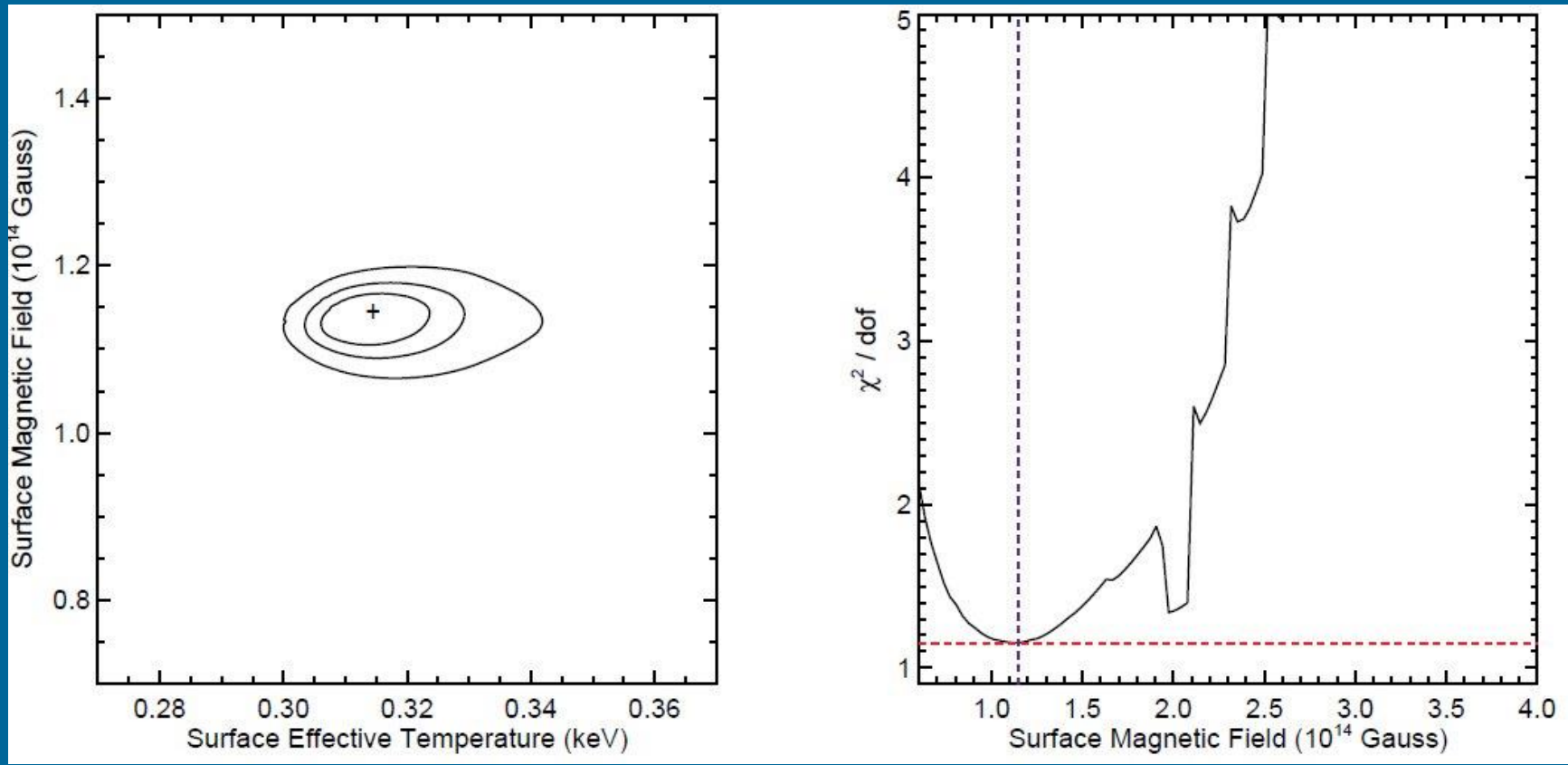
1010.0125

1006.3292

Low-field magnetar SGR 0418+5729

Fitting parameters of the magnetized atmosphere it is possible to show, that the low-field solution is not acceptable.

This can be due to non-dipolar field components.



Conclusions

- Emission from cooling NSs is more complicated than a simple blackbody
- Light bending (gravity)
- Atmospheres
- Magnetic field distribution - effects on properties of atmospheres and emission
- Magnetic field (including toroidal) in the crust – non-uniform temp.distr.
- Condensate
- Rotation at \sim msec periods can smear spectral lines

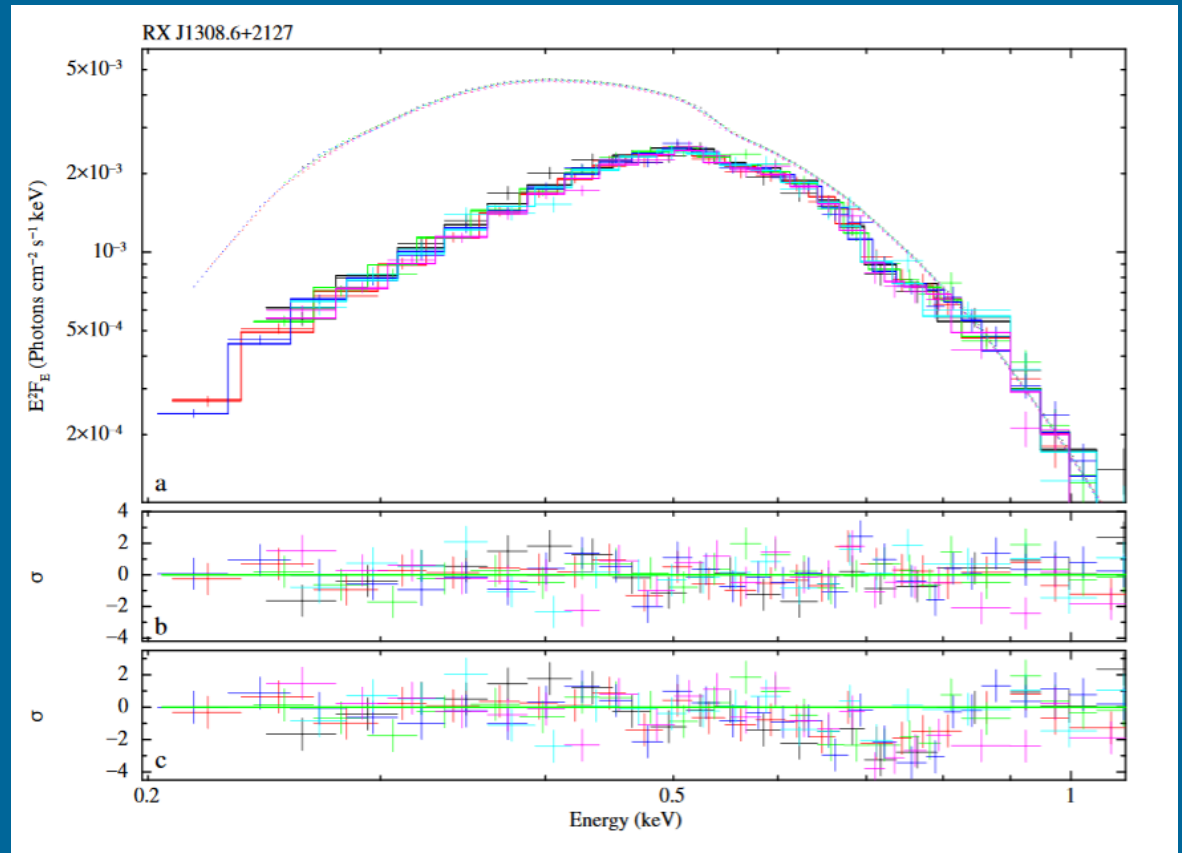
Papers to read

- [astro-ph/0702426](#) ←
- [arXiv: 0801.1143](#)
or [astro-ph/0609066](#) } Reviews on the M7
- [astro-ph/0206025](#) ←
- [arXiv: 0905.3276](#) } Recent calculations of spectra from magnetized atmos.
- [arXiv: 1006.3292](#) }
- [arXiv: 1210.0916](#) – review
- [arXiv: 1409.7666](#) - review

Phase-resolved spectra and features

RX J1308.6+2127

A feature at the energy of ~ 740 eV
and an equivalent width of ~ 15 eV

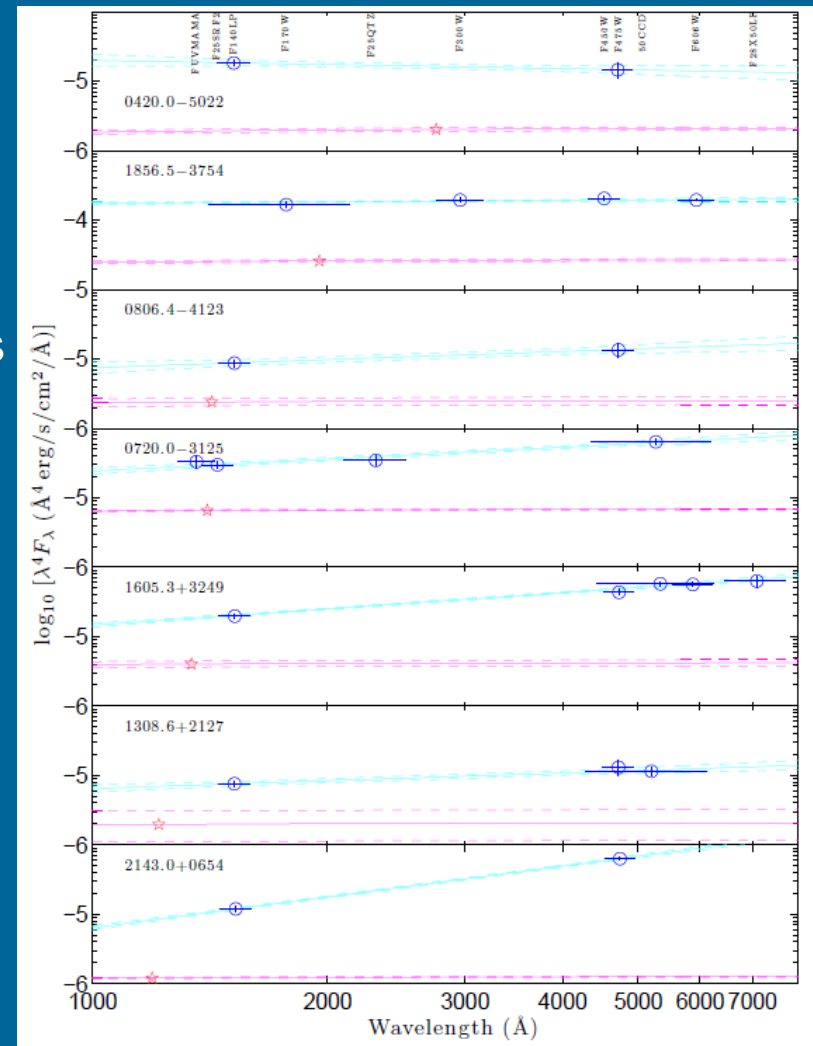


All in optics and UV

All seven objects have confirmed optical and ultraviolet counterparts.

The Rayleigh-Jeans tail would be flat.
The best-fit power-laws with $\pm 1\sigma$ uncertainties are shown by the cyan lines.
The extrapolations of the X-ray blackbodies with $\pm 1\sigma$ uncertainties are shown by the magenta lines.

kT \downarrow



New data: Kaplan et al. 1105.4178

Is RX J1856.5-3754 Bare ?

- Fit of X-ray data in the 0.15-2 keV band acceptable
- Radiation radius problem eased
- Optical excess may be produced by reprocessing of surface radiation in a very rarefied atmosphere (Motch, Zavlin & Haberl 2003; Zane, Turolla & Drake 2004; Ho et al. 2006)
- Details of spectral shape (features, low-energy behaviour) still uncertain

$$R_{\infty} = 4.25 f_E^{-1/2} \left(\frac{D}{100 \text{ pc}} \right) \left(\frac{T_{BB}}{60 \text{ eV}} \right)^{-2} \text{ km}$$

Does the atmosphere keep the star surface temperature ?

