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

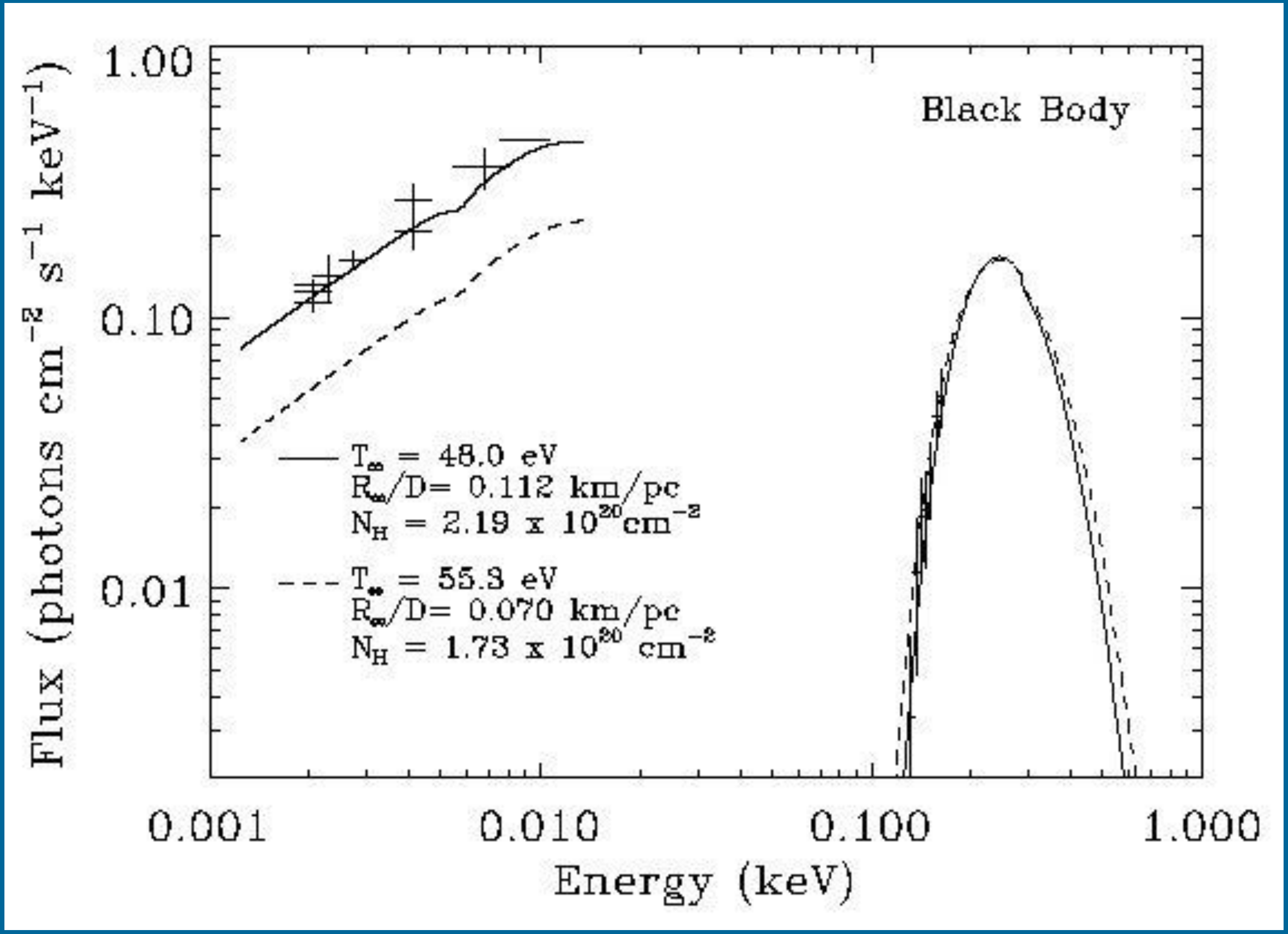
NS Radii - II

- 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

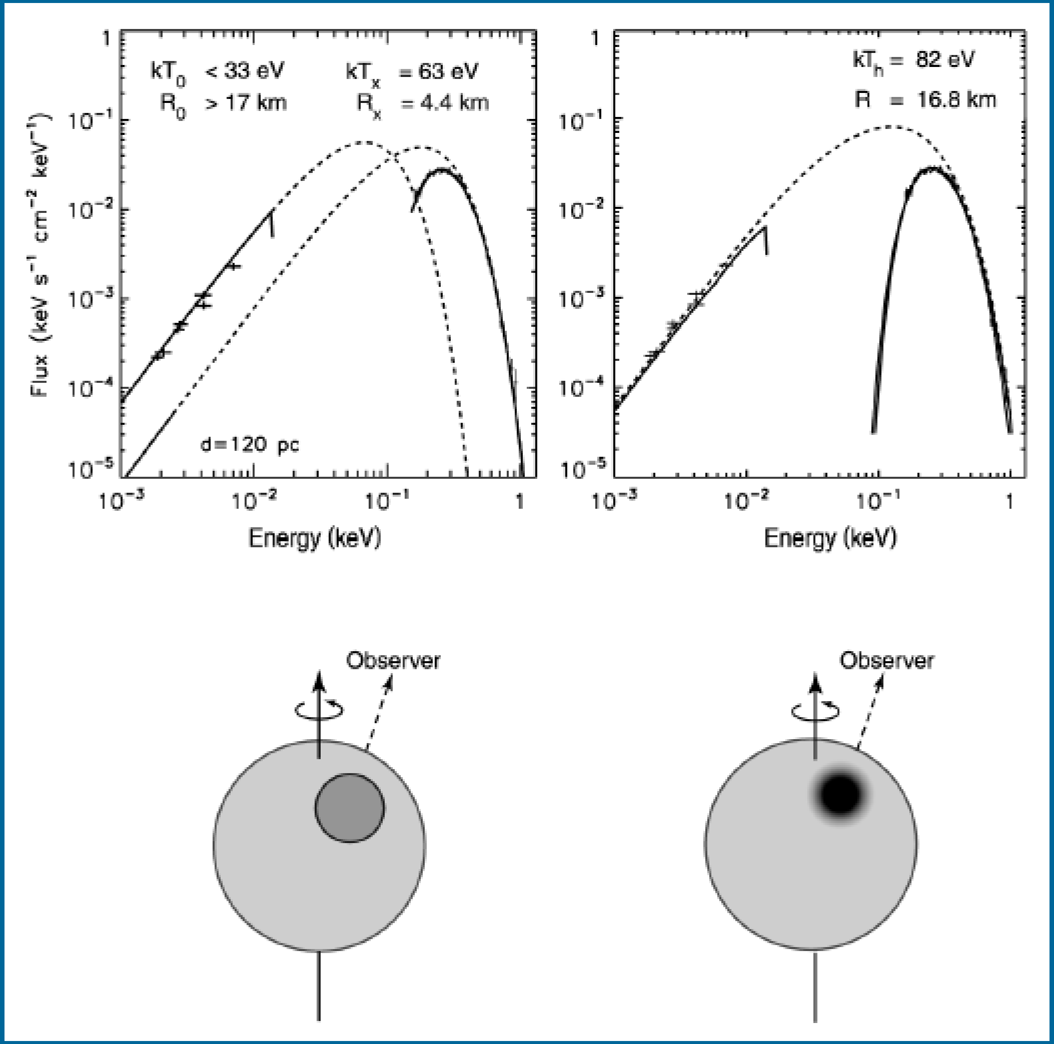
Uncertainties in temperature



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

Pons et al. astro-ph/0107404, see more about optical observations in astro-ph/0106265

Non-uniform temperature distribution



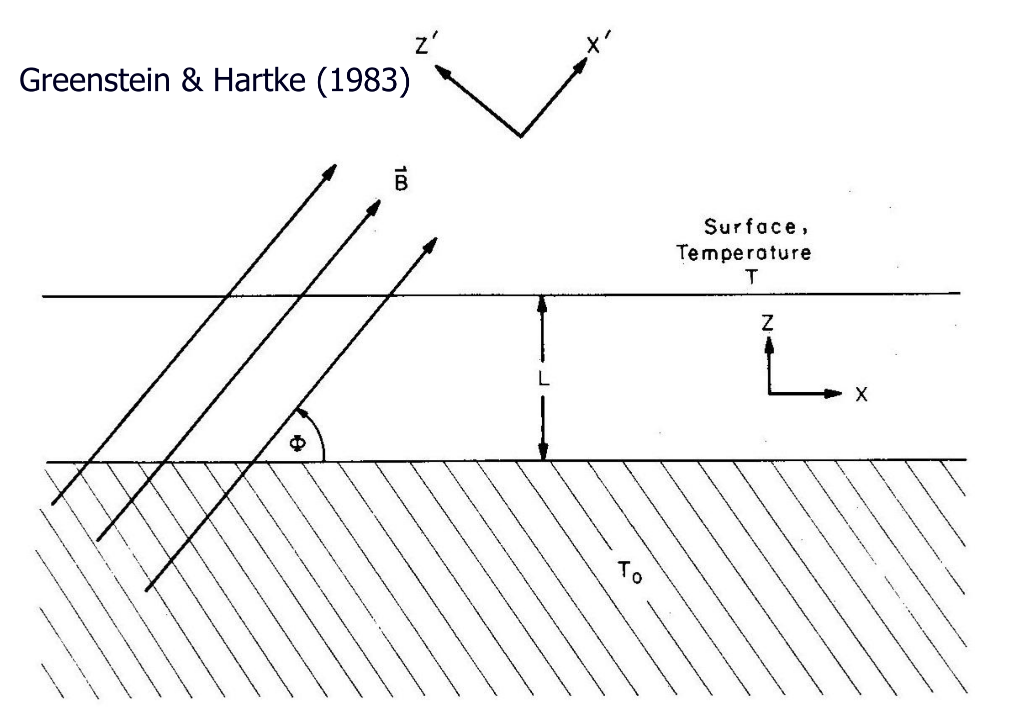
In the case of RX J1856 because of a significant (~6) optical excess it was proposed that there is a spot, or there is a continuous temperature gradient.

Trumper astro-ph/0502457

NS Thermal Maps

- Electrons move much more easily along B than across B
- Therma … opic inside a … $h\nu_B$ or ρ >> 10
- Envelop … ,

  B ~ con … 1D



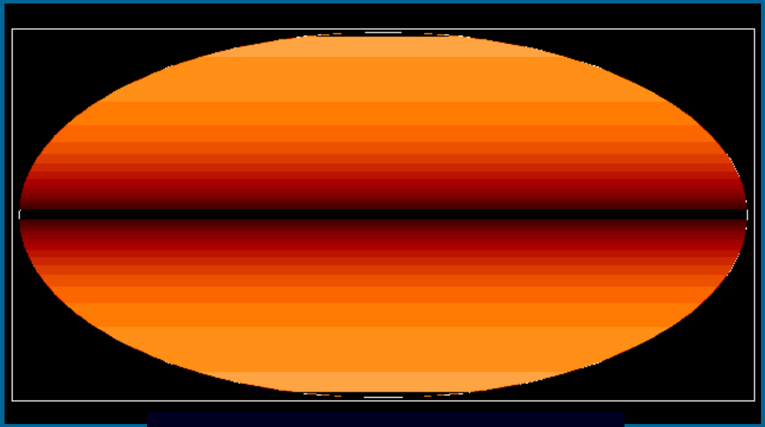
$$T_S = \left[\cos^2\Theta + \left(K_{perp}/K_{par}\right)\sin^2\Theta\right]^{1/4} T_{pole}$$

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

K - conductivity

$$T_S = \left|\cos\Theta\right|^{1/2} T_{pole}$$

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



Core centered dipole

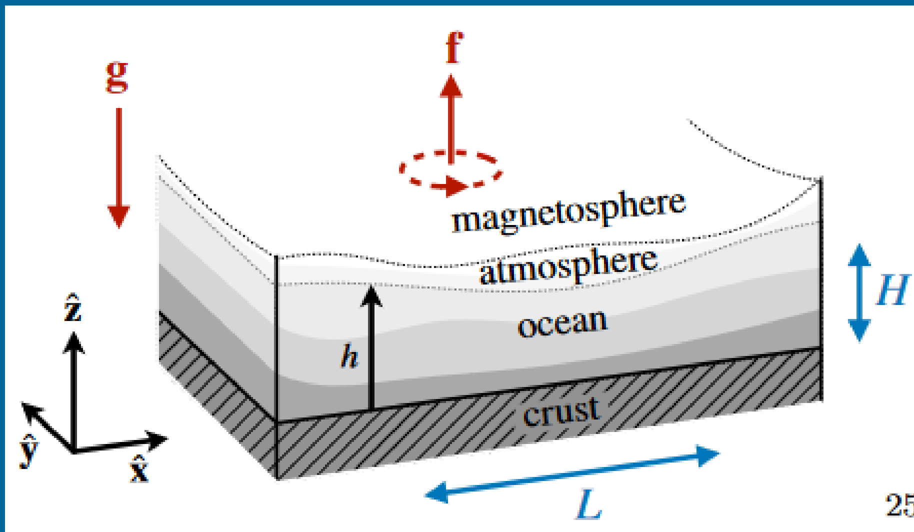
Core centered quadrupole

Zane, Turolla astro-ph/0510693

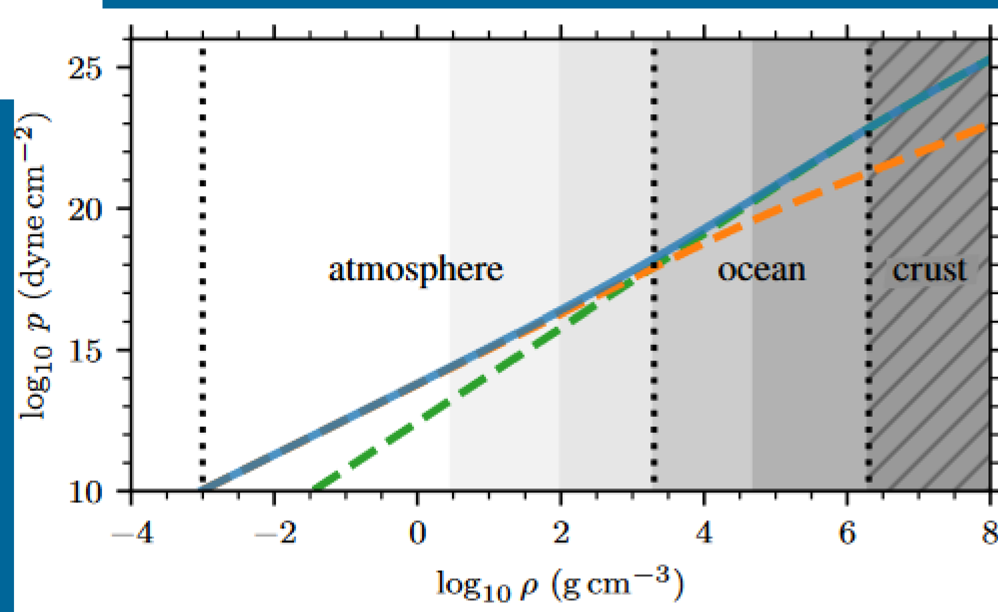
Local Surface Emission

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

Structure of external layers



$$g = \frac{GM}{R^2}\left(\frac{1}{\sqrt{1 - r_g/R}}\right) \approx 1.7 \times 10^{14}\ \mathrm{cm\ s^{-2}}$$

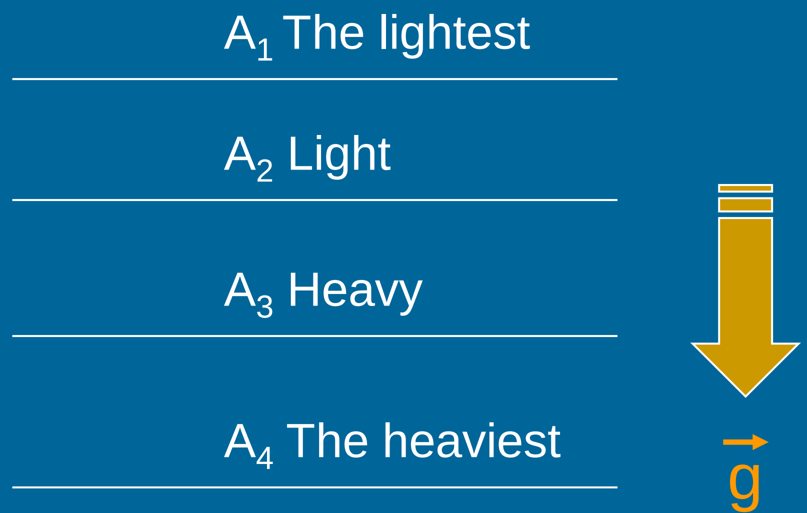


The atmosphere transitions to the ocean where the dominant agent of heat conduction changes from photons to electrons.

It corresponds to the density ~10^3g/cm^3

2306.08186

Atmospheric composition



As *h*<<*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.

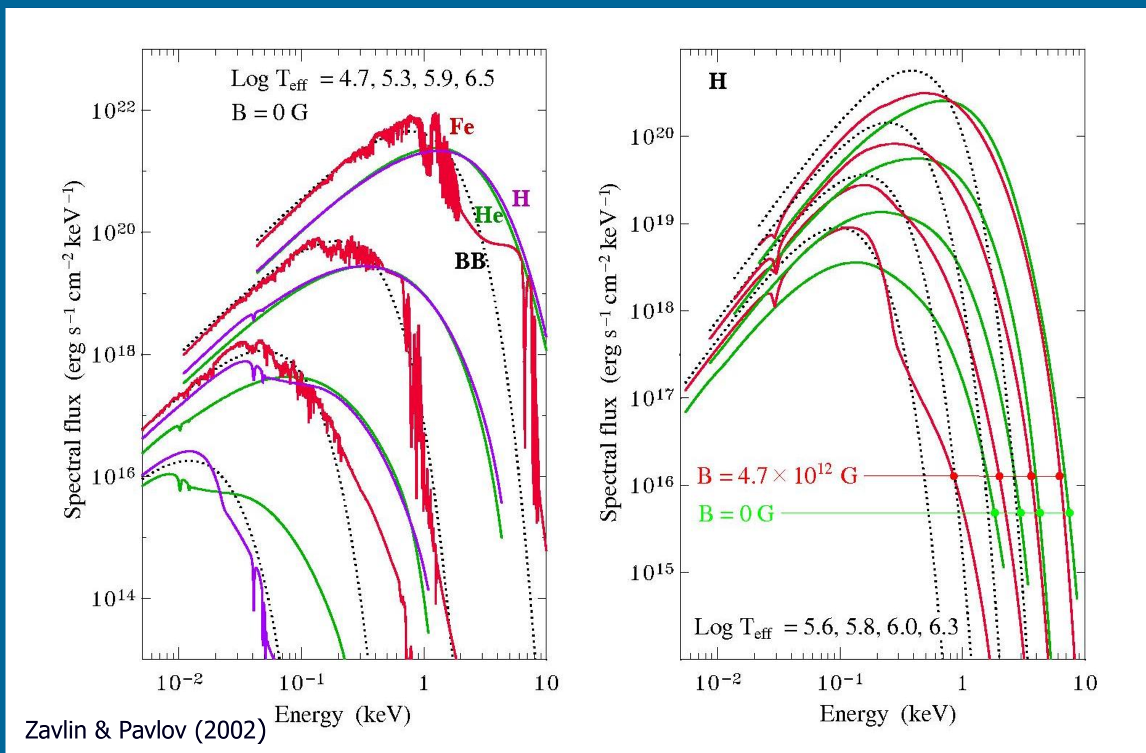
10^{-20} solar mass of hydrogen is enough to form a hydrogen atmosphere.

See astro-ph/ 0702426

- Free-free absorption dominates

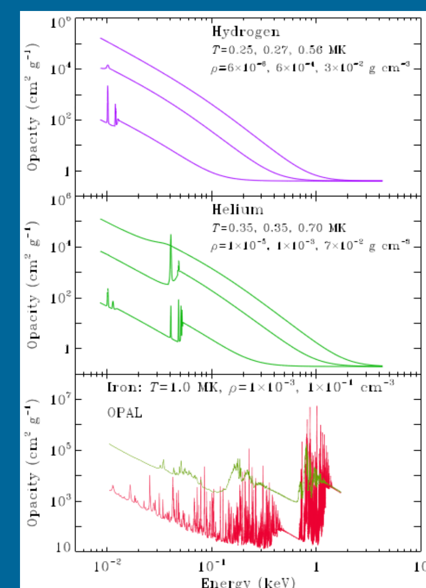
$$\kappa_\nu \propto \nu^{-3}, h\nu >> kT$$

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



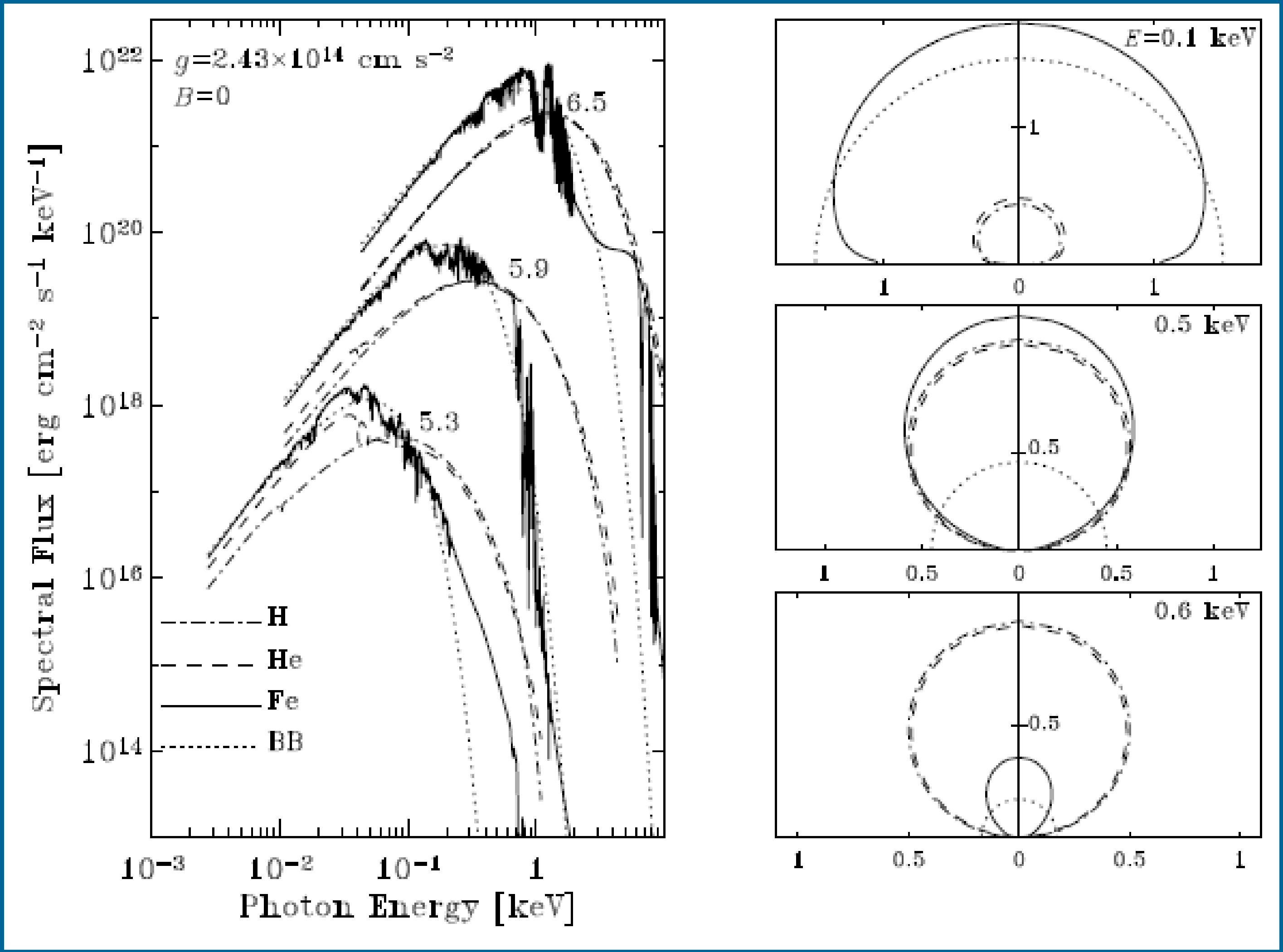
Zavlin & Pavlov (2002)

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



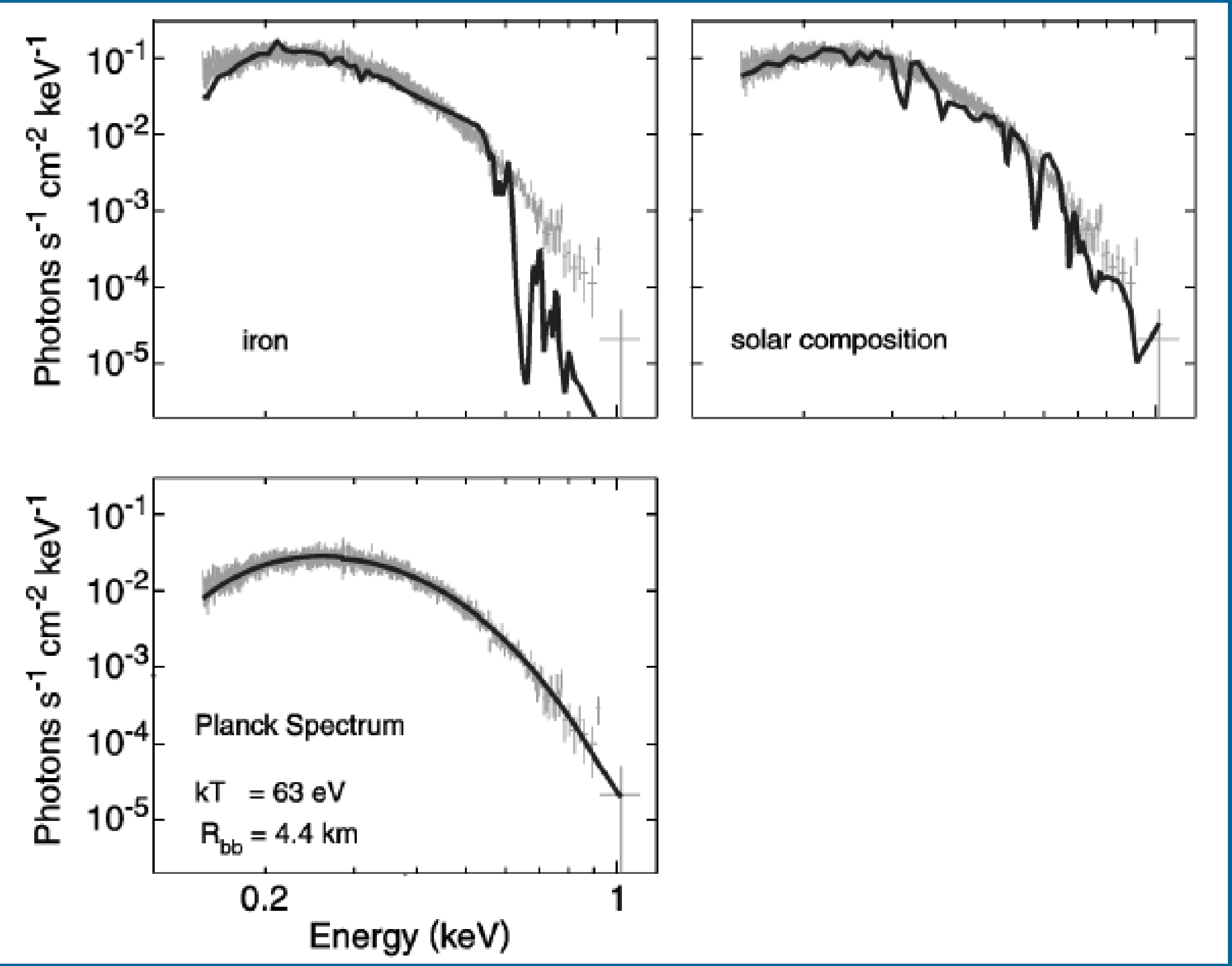
astro-ph/0206025

Emission from different atmospheres



astro-ph/0702426

Fitting the spectrum of RX J1856



Trumper astro-ph/0502457

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} ergs s^{-1})	P^c_{ox}
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

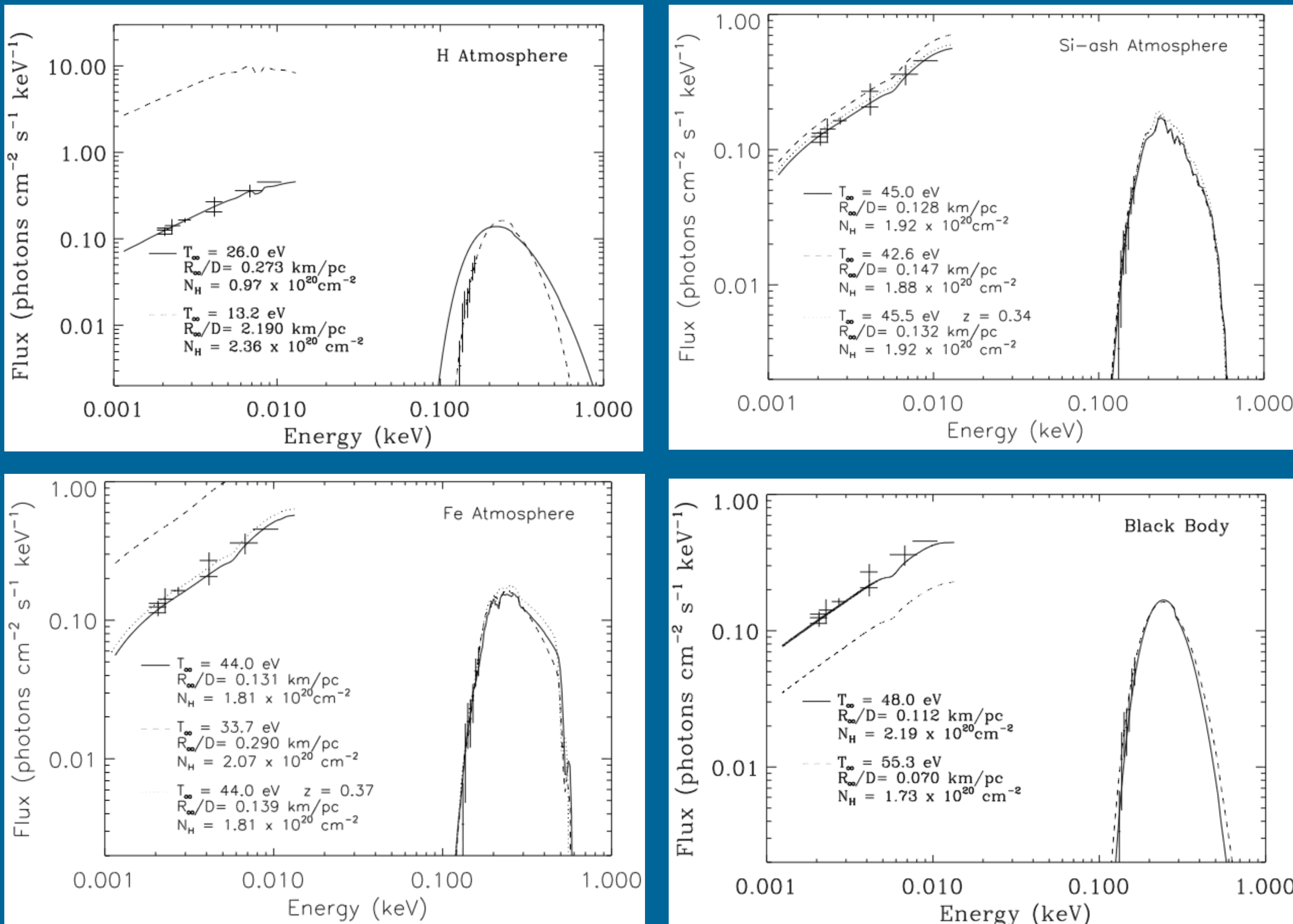
[a] 3 σ ranges, assuming $z = 0.305$. Weighting of the data is discussed in the text.
[b] Uncertainty does not include uncertainty in distance.
[c] The likelihood that the X-ray and optical parameters are the same.

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

$T_{BB} \sim 2T_H$

Pons et al. 2002

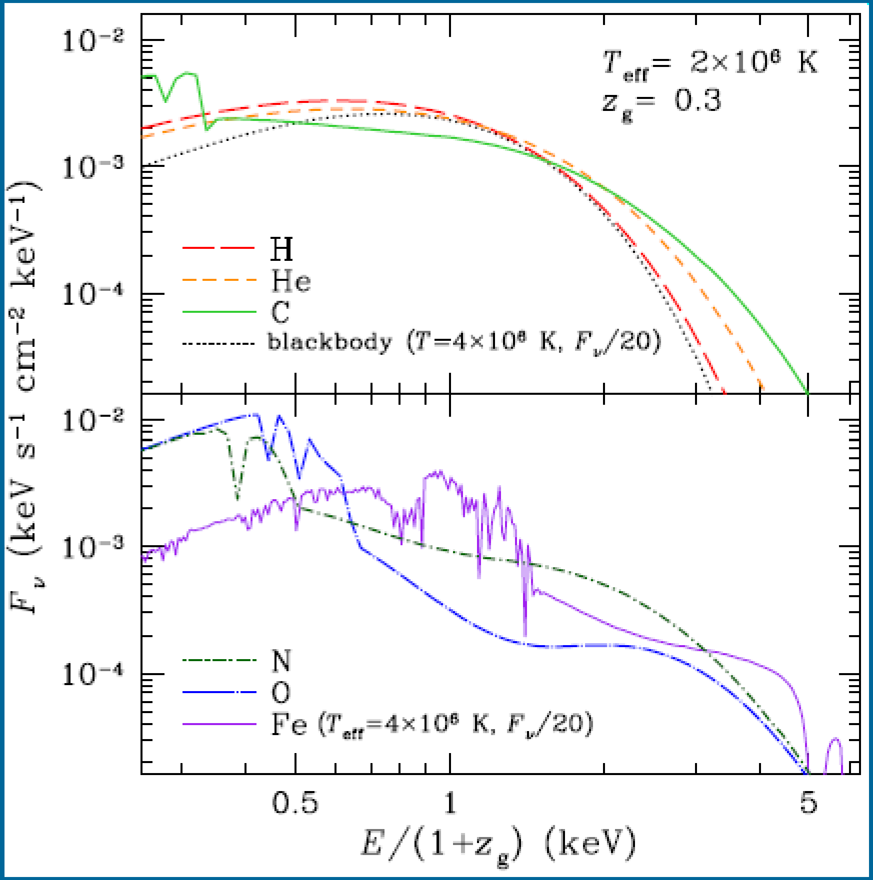
Different fits

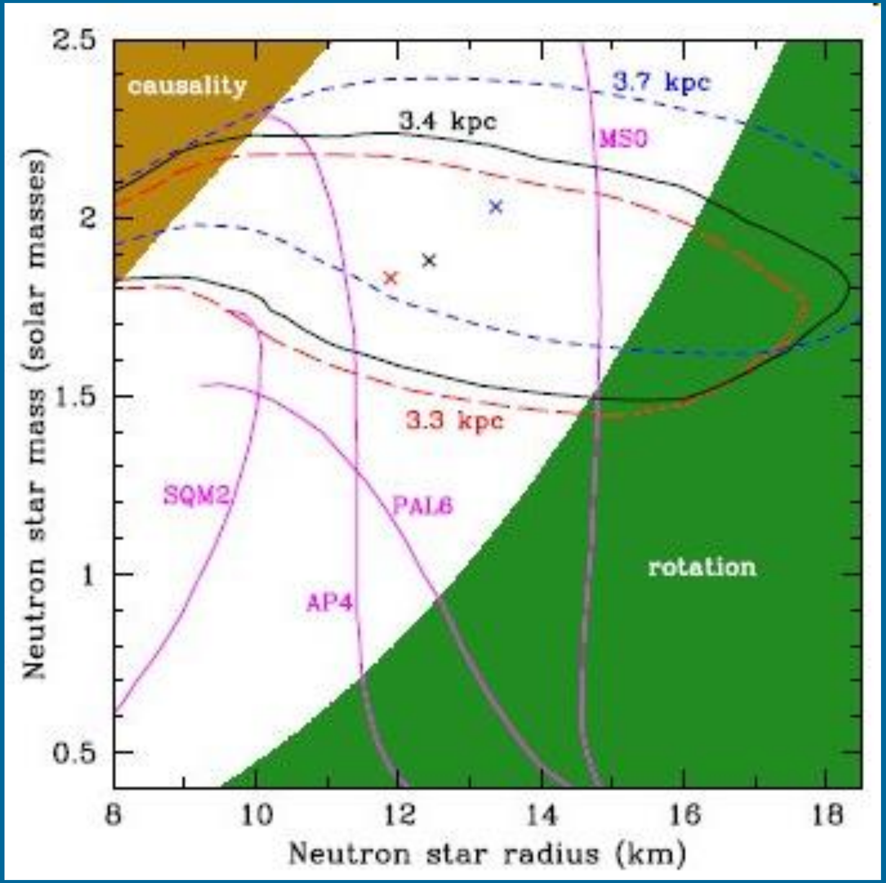


$T_{bb} \sim T_{Fe} > T_H$

Pons et al. 2002. See more fits in Ho et al. astro-ph/0612145

Cas A carbon atmosphere





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

0911.0672

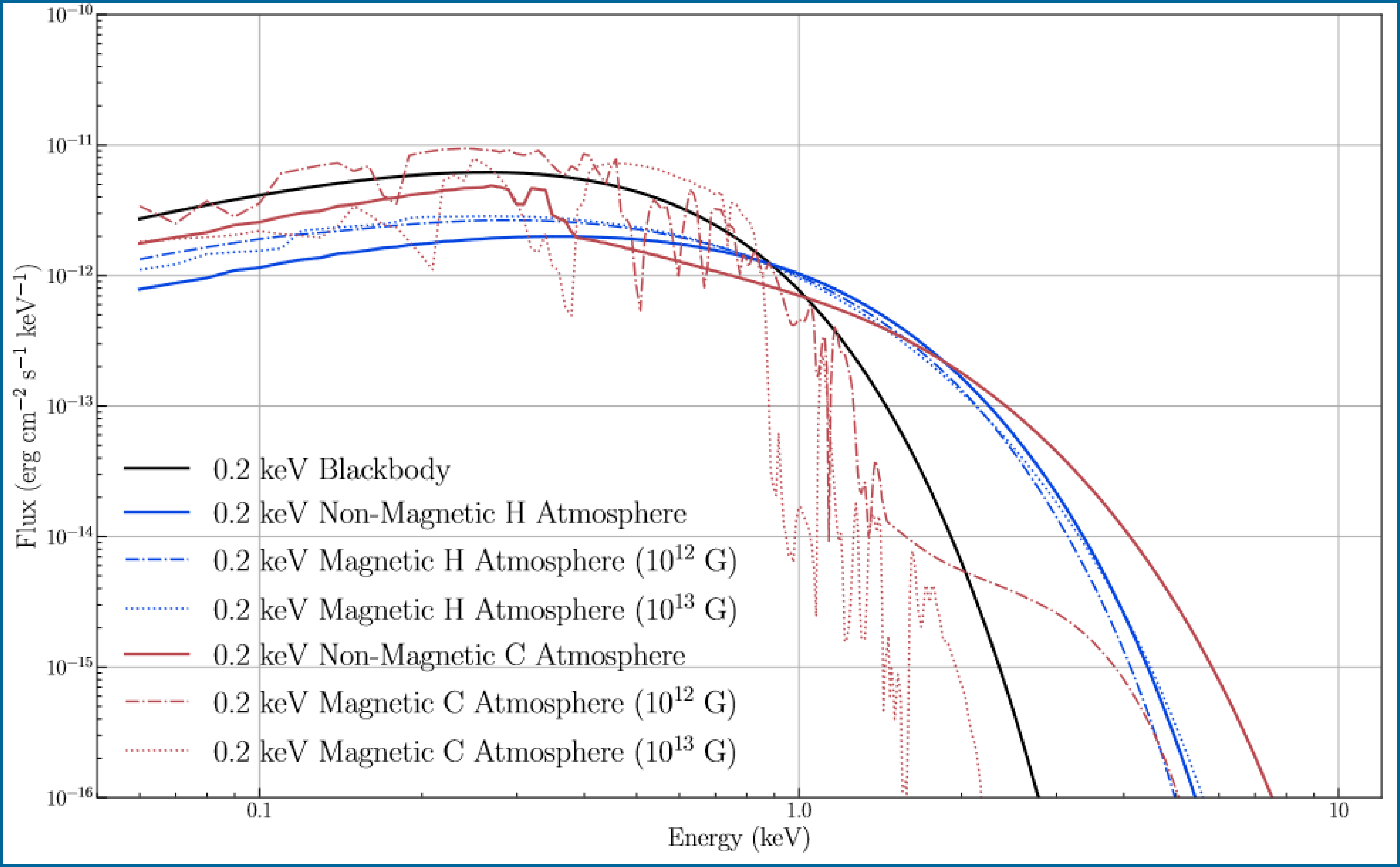
More carbon atmospheres

Table 5: Results of the best-fit carbon atmosphere model

CCO	χ^2_ν	NHP %	n_H 10^{22}cm^{-2}	T MK	A	Flux
J0852	0.86	79	$0.70^{+0.02}_{-0.02}$	$1.68^{+0.03}_{-0.03}$	0.13	1.34(1)
J1601	0.98	51	$4.71^{+0.25}_{-0.26}$	$1.84^{+0.13}_{-0.12}$	0.59	0.124(3)
J1713	0.98	55	$0.71^{+0.01}_{-0.01}$	$1.97^{+0.01}_{-0.02}$	0.2	3.185(12)
J1720	0.89	80	$5.74^{+0.24}_{-0.23}$	$2.37^{+0.11}_{-0.10}$	0.9	0.50(1)
J1732	1.32	0.18	$2.57^{+0.03}_{-0.03}$	$2.32^{+0.03}_{-0.03}$	0.81	2.656(15)
J2323	0.95	66	$2.06^{+0.09}_{-0.08}$	$1.97^{+0.07}_{-0.07}$	0.92	0.63(1)

Large emitting areas can be obtained for a carbon atmosphere.
Thus, absence of pulsations is naturally explained.
Explanation with the effects of orientation is statistically improbable.

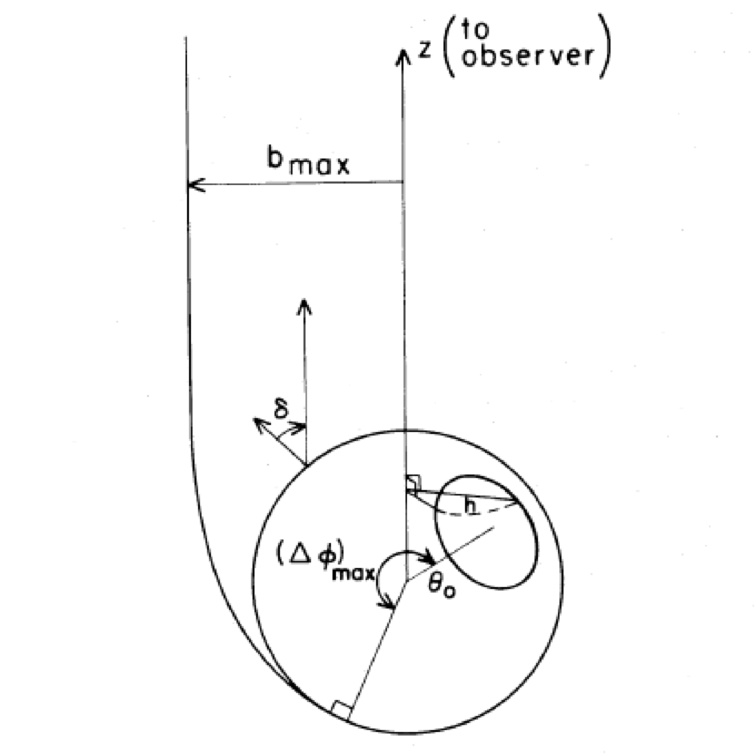
2109.06036



2302.05893. This paper contains critics of the carbon atmosphere approach to explain properties of CCOs.

Gravity Effects

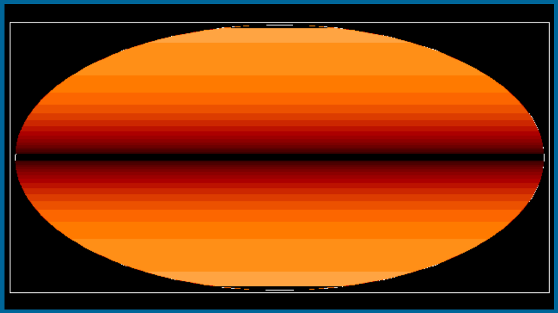
- Redshift
- Ray bending



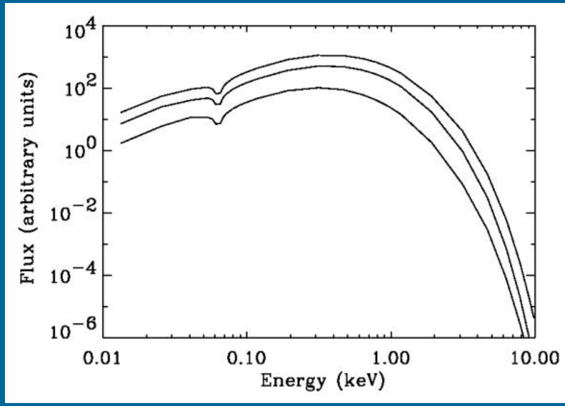
$$L_\infty = 4\pi R_\infty^2 \sigma T_\infty^4$$

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

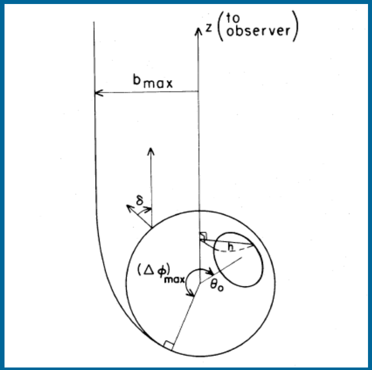
STEP 1
Specify viewing geometry and B-field topology; compute the surface temperature distribution

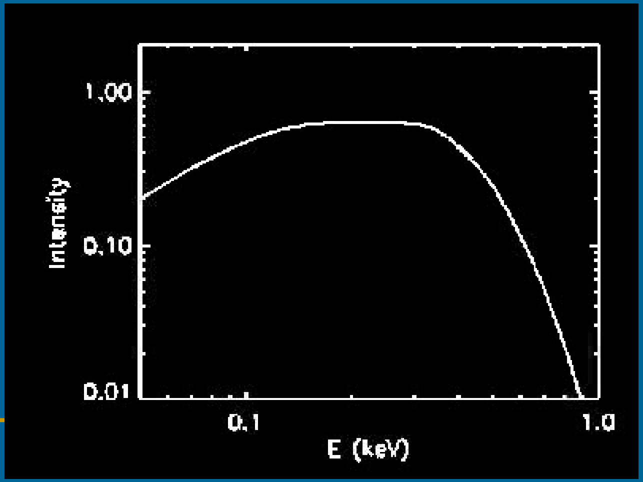


STEP 2
Compute emission from every surface patch



STEP 3
GR ray-tracing to obtain the spectrum at infinity

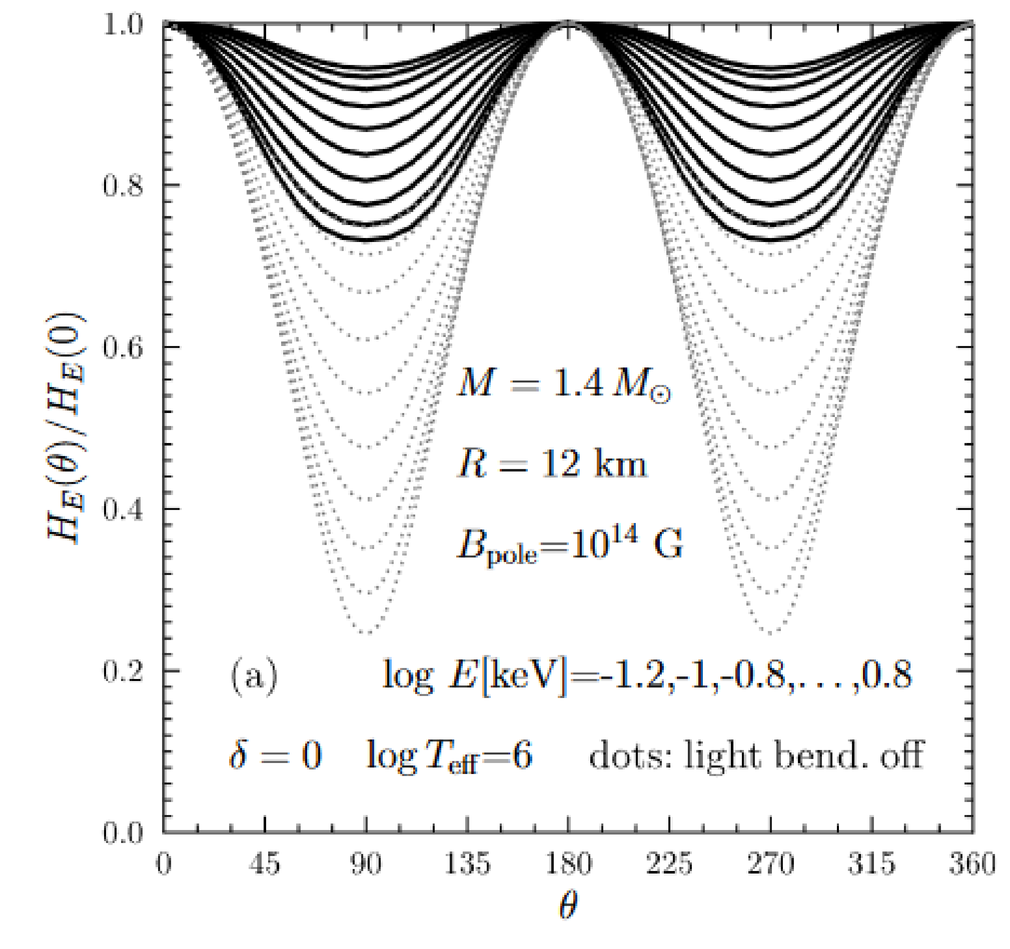




STEP 4
Predict lightcurve and phase-resolved spectrum
Compare with observations

Examples of light curves

Non-uniform temperature distribution due to dipolar magnetic field.



$B=10^{14}$ G

Top curves for smaller energies.

Dotted curves for
no gravitational light bending.

Orthogonal rotator,
spin axis perpendicular
to the line of sight.

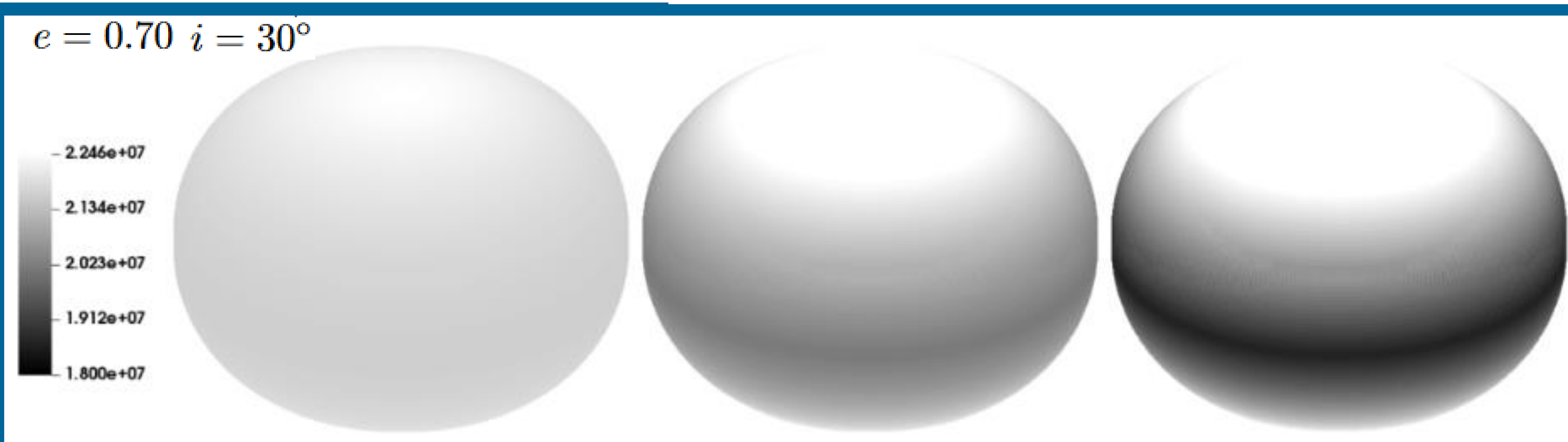
Composition of a heat blanket
does not influence significantly
the spectrum.

Gravitational darkening

Hydrogene+helium (0.7+0.3) atmosphere.
Fast rotation -> distortion of the stellar shape.
von Zeipel law: $T_{eff} \sim g^{1/4}$

$$\bar{\Omega} = \Omega \left(\frac{R_{eq}^3}{GM} \right)^{1/2}$$

$$g(\theta)/g_0 = 1 + (c_e\bar{\Omega}^2 + d_e\bar{\Omega}^4 + f_e\bar{\Omega}^6)\sin^2(90^\circ - \theta) + (c_p\bar{\Omega}^2 + d_p\bar{\Omega}^4 + f_p\bar{\Omega}^6 - d_{60}\bar{\Omega}^4)\cos^2(90^\circ - \theta) + d_{60}\bar{\Omega}^4\cos(90^\circ - \theta)$$

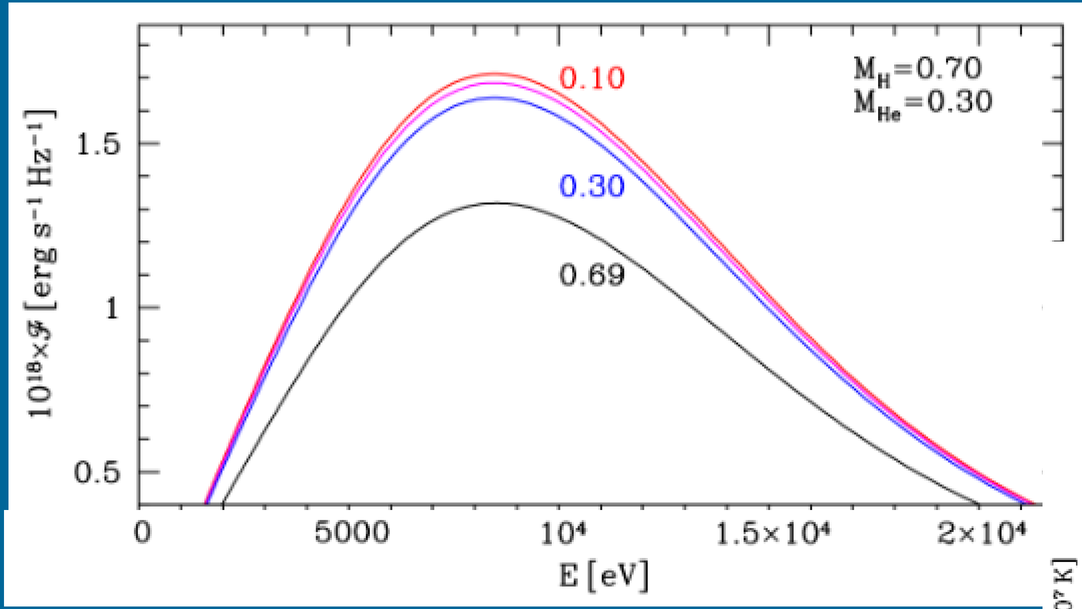


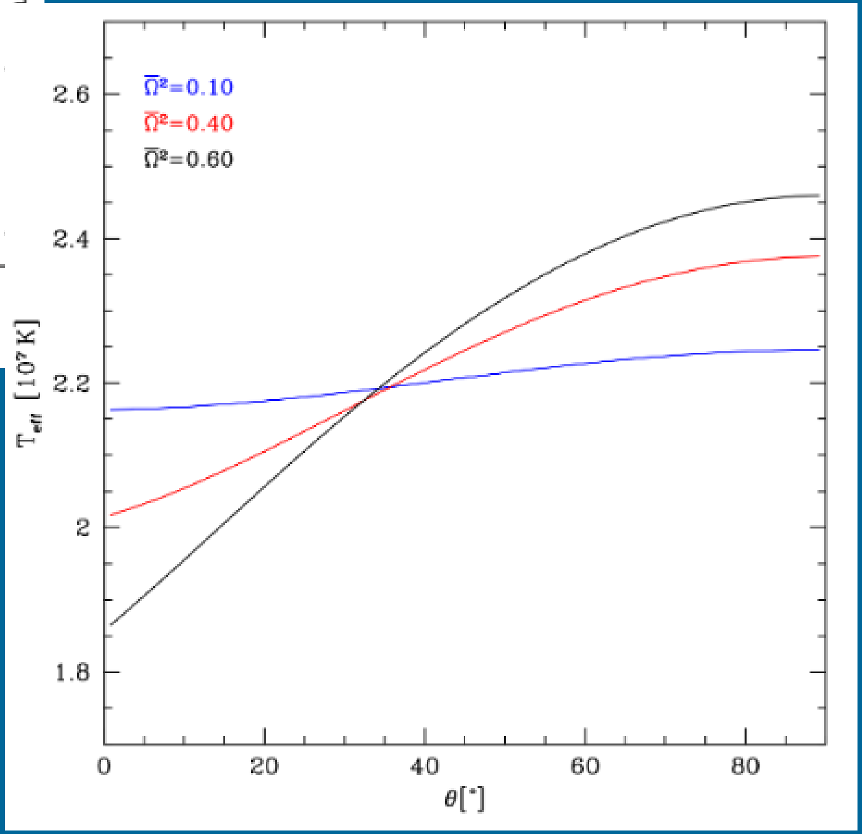
$\bar{\Omega}^2 = 0.10$ $\bar{\Omega}^2 = 0.40$ $\bar{\Omega}^2 = 0.60$

For undisturbed star: $T_{eff} = 2.20 \times 10^7$ K and $\log(g) = 14.40$ (cgs)

2201.05428

Gravitational darkening - 2





2201.05428

The Seven X-ray dim Isolated NSs

- Soft thermal spectrum (kT $\approx$ 50-100 eV)
- No hard, non-thermal tail
- Radio-quiet, no association with SNRs
- Low column density ($N_H \approx 10^{20}$ cm^{-2})
- X-ray pulsations in all (but one?) sources ($P \approx 3$-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?
  $\dot{M}_{Bondi} \sim n_{ISM}/v^3$ 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

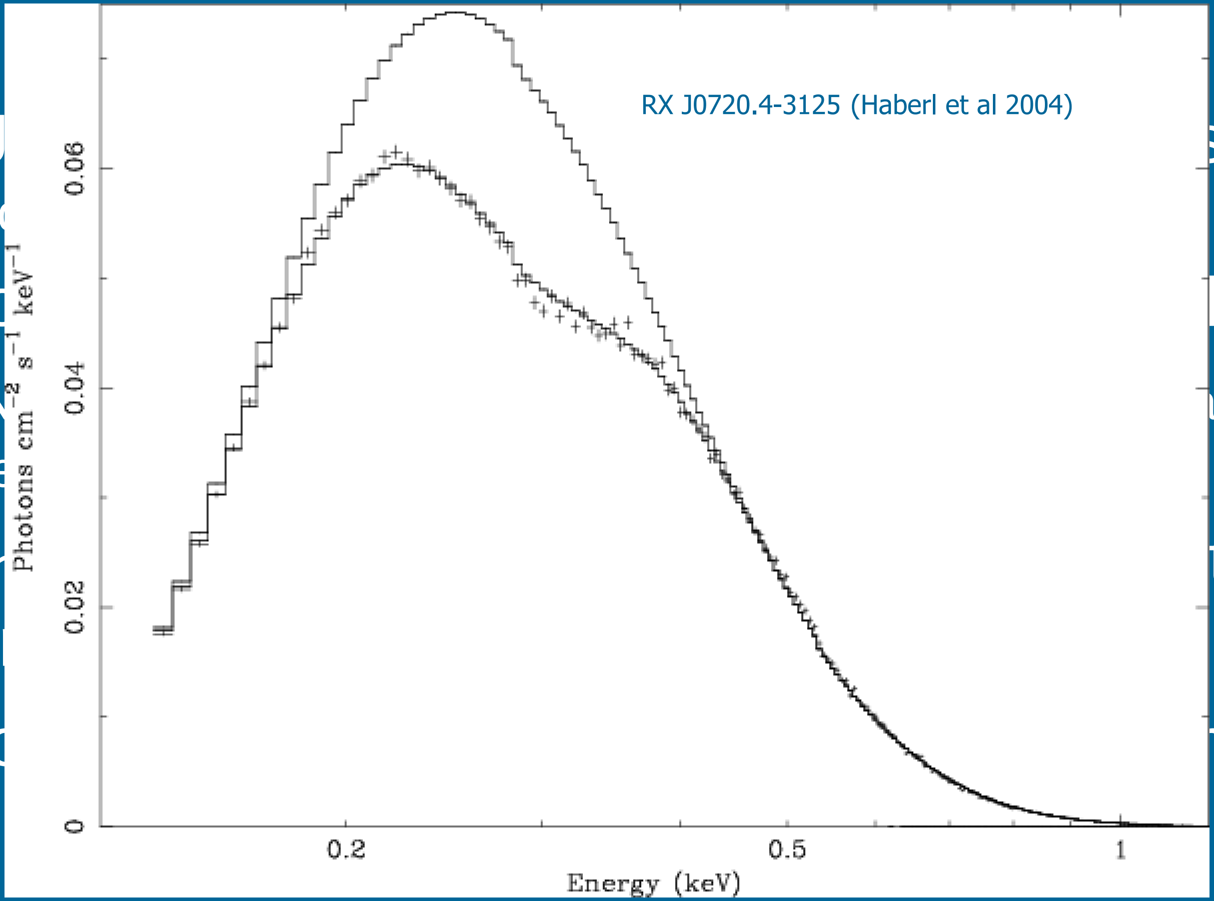
Note a claim for an excess at harder (keV) X-rays: 1703.05995

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_{50CCD} = 28.6
RX J1605.3+3249 (RBS 1556)	96	-----	??	m_{50CCD} = 26.8
1RXS J214303.7+065419 (RBS 1774)	104	9.43	4%	B=27.4

(*) variable source

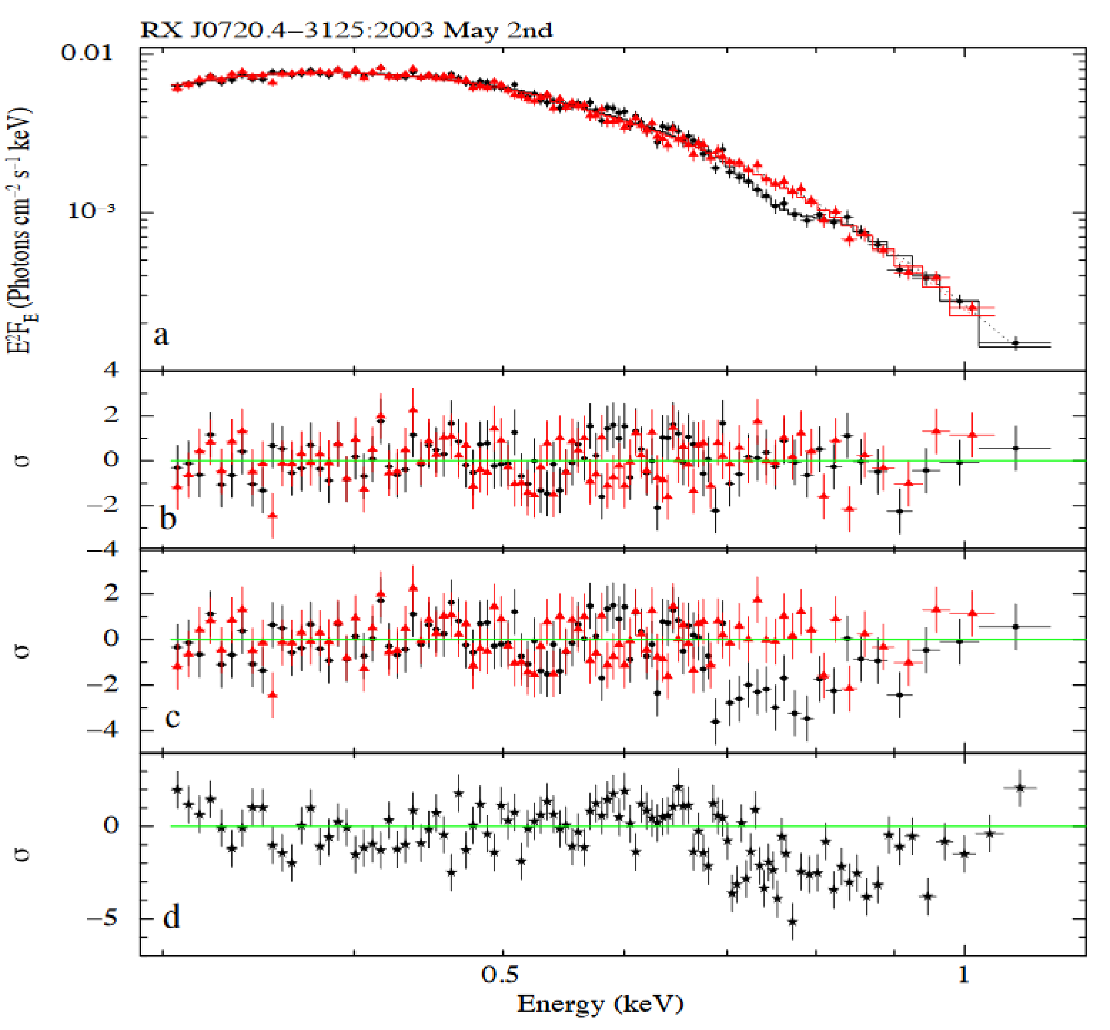
Featureless ? No Thanks !



- RX J … s
  (Chan…
- A bro… her
  ICoN… al 2004;
  Zane e…
- E_{line} … th E_1 ~
  $2E_2$ i…
- Proto… high B
  ?

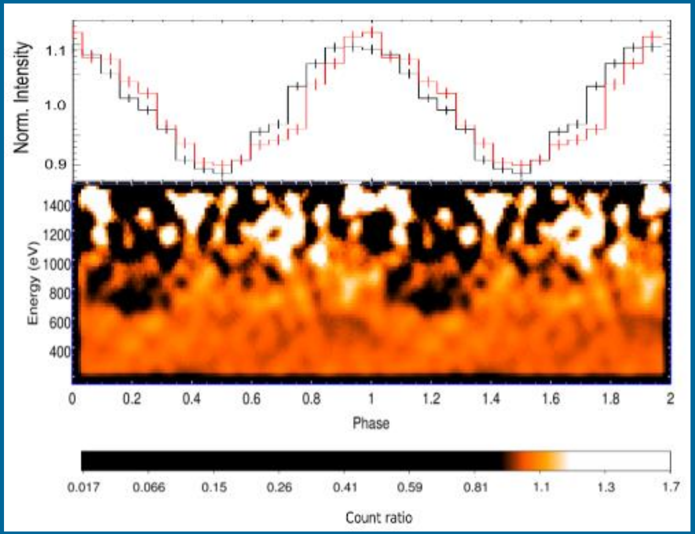
Source	Energy (eV)	EW (eV)	B_{line} (B_{sd}) (10^{13} G)	Notes
RX J1856.5-3754	no	no	?	-
RX J0720.4-3125	270	40	5 (2)	Variable line
RX J0806.4-4123	460	33	9	-
RX J0420.0-5022	330	43	7	-
RX J1308.6+2127	300	150	6 (3)	-
RX J1605.3+3249	450	36	9	-
1RXS J214303.7+065419	700	50	14	-

Phase variable spectral feature



RX J0720.4−3125

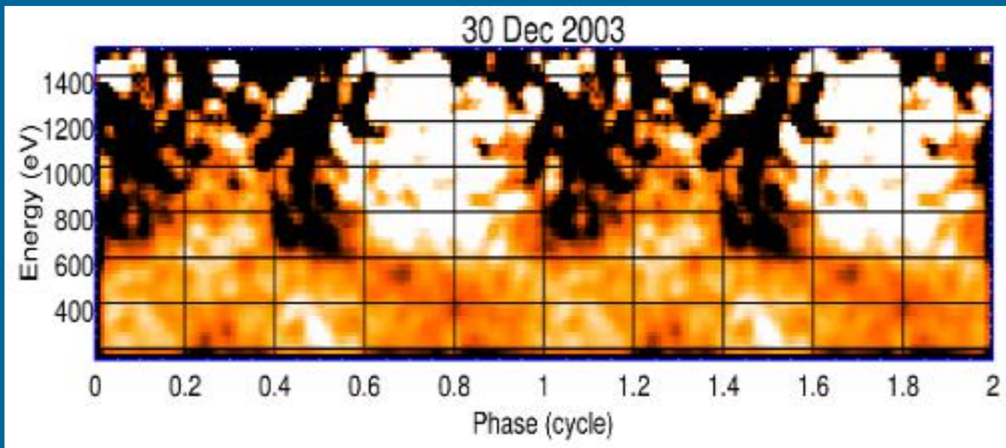
Black: phase 0.1-0.3
red: phase 0.5-0.7



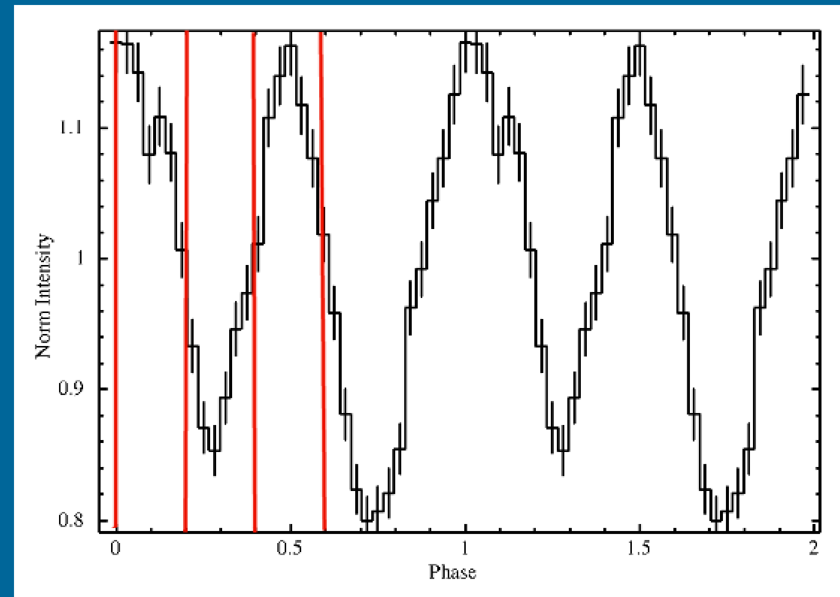
1506.04206

More phase-dependent features in M7

RX J1308.6+2127



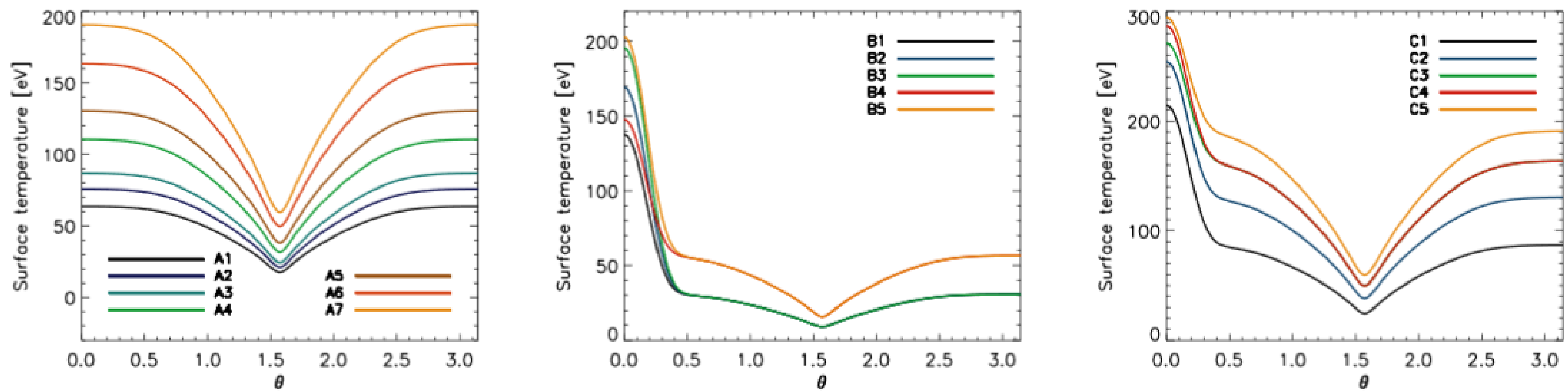
Parameter[a]	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1
			BB+GAUSS		
kT_{BB} (eV)	$77.7^{+1.8}_{-2.0}$	$75.4^{+2.2}_{-2.5}$	$84.9^{+1.3}_{-1.4}$	$75.6^{+2.1}_{-2.7}$	$84.9^{+1.8}_{-2.0}$
R_{BB} (km)	4.3±0.5	5.6±1.0	2.6±0.1	5.8±1.1	3.4±0.3
Flux[b]	$3.34^{+0.04}_{-0.09}$	$3.67^{+0.15}_{-0.09}$	$3.10^{+0.05}_{-0.07}$	$3.68^{+0.07}_{-0.06}$	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^{+13}_{-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^2_ν	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]

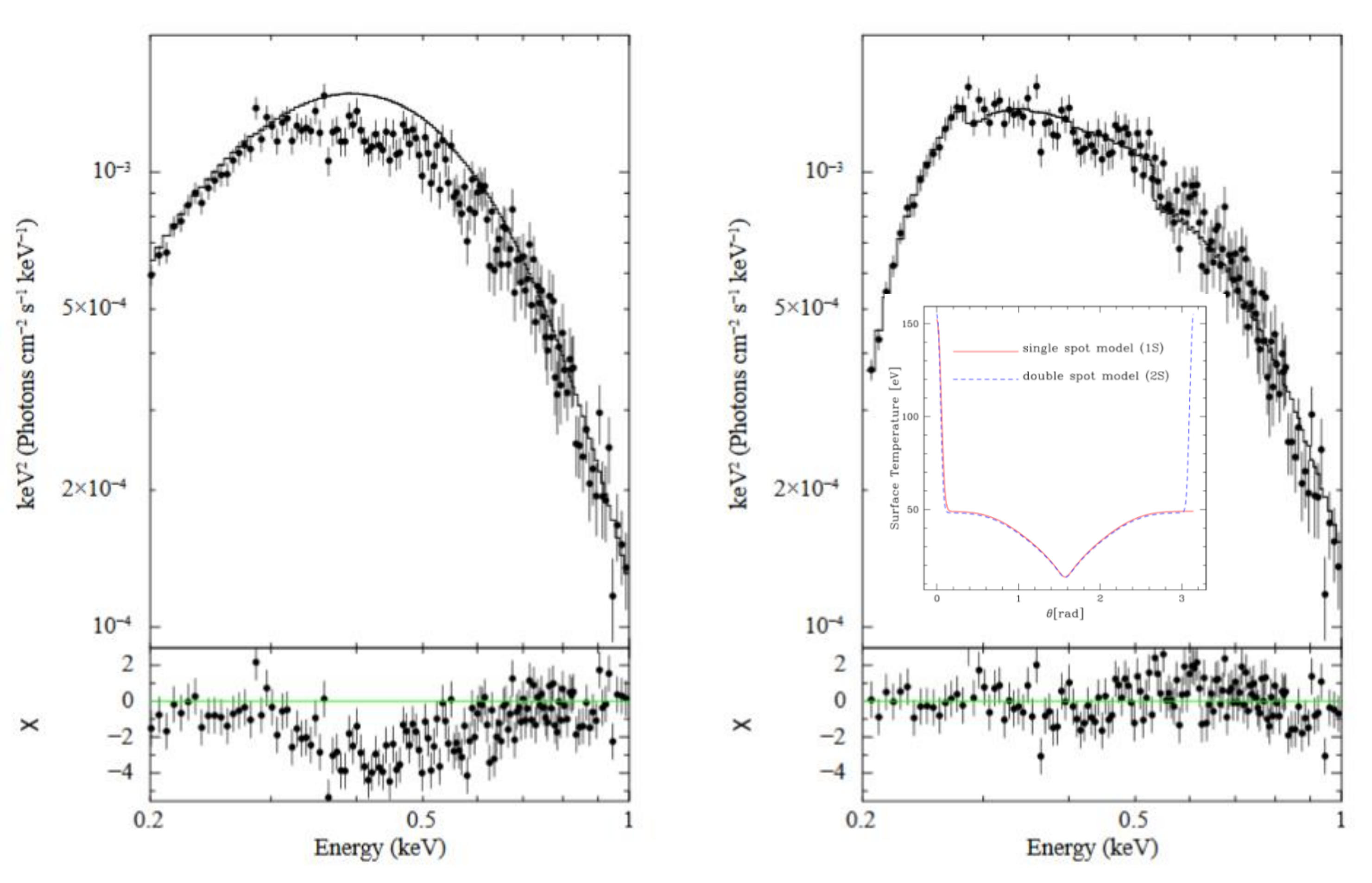


1406.0874

RX J0806.4-4123

BB+line

Non-uniform distrubution

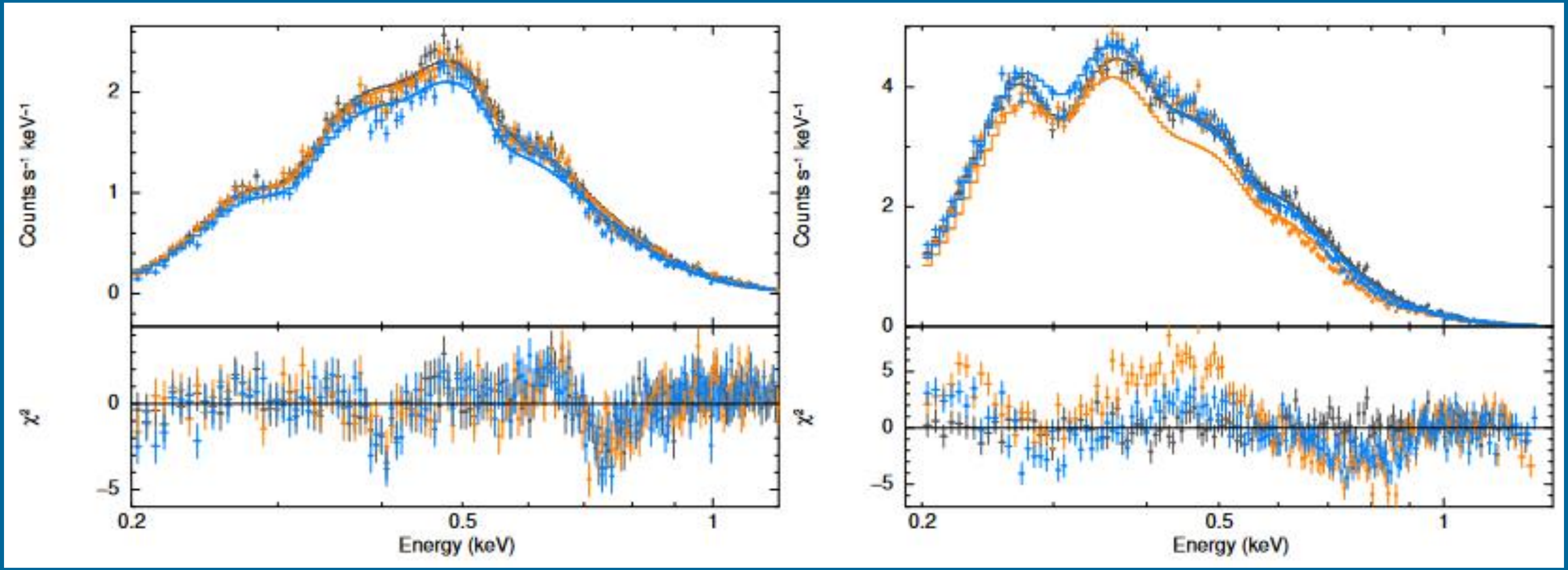


1406.0874

eROSITA data

RX J2143.0+0654

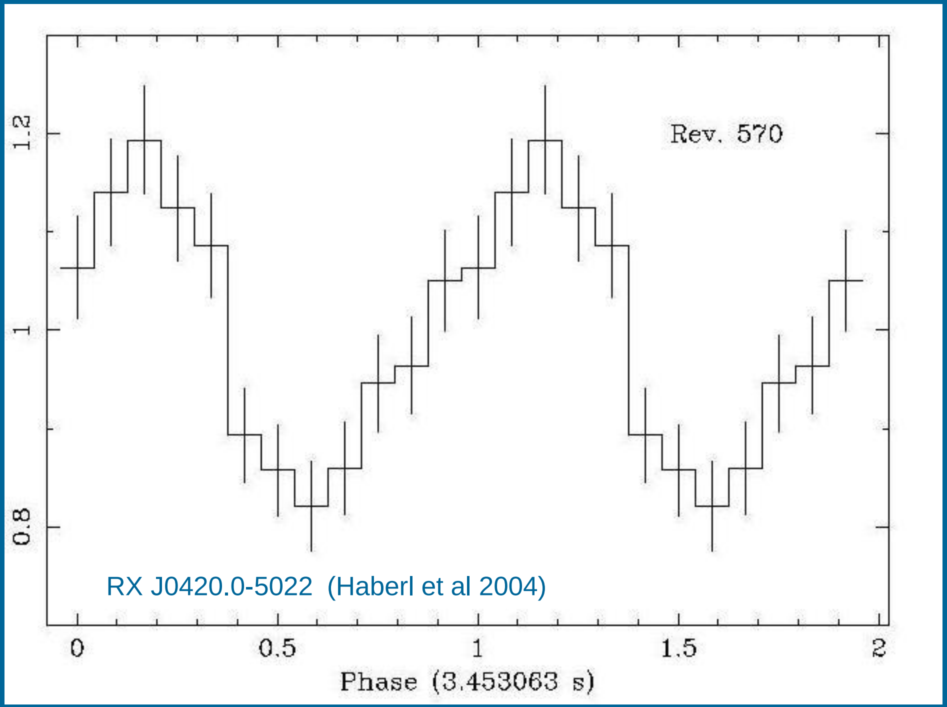
RX J1605.3+3249



Different curves correspond to different epochs of observation

2202.06793

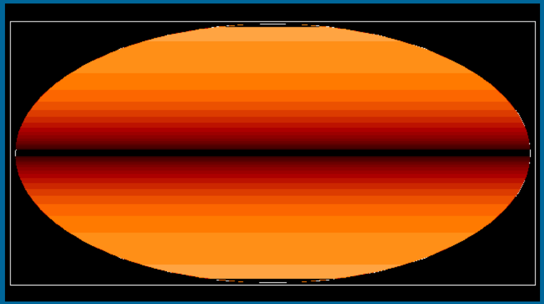
Pulsating ICoNS - I



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

Pulsating ICoNS - II

Core-centred dipole field + Atmosphere emission = Too small pulsed fractions Symmetrical pulse profiles (Zane & Turolla 2006)



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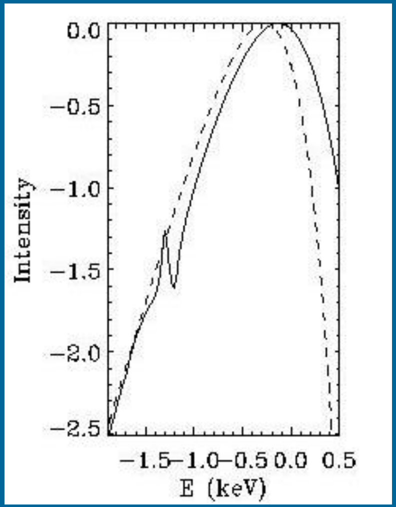

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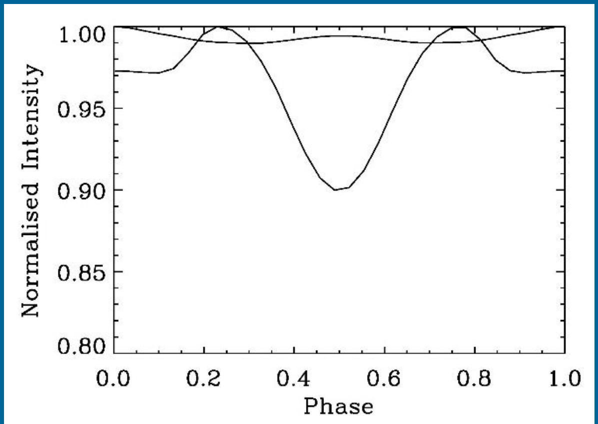
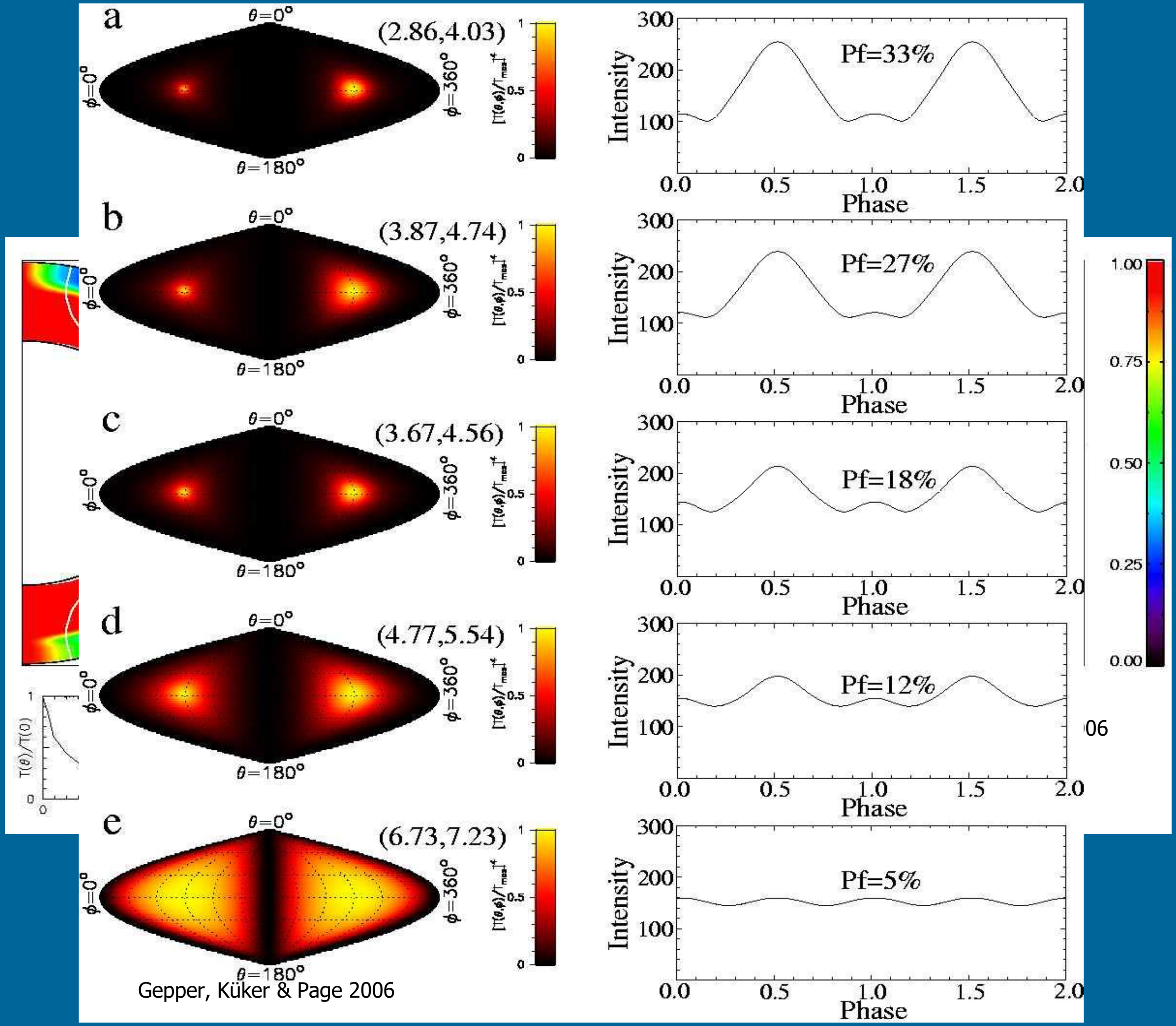
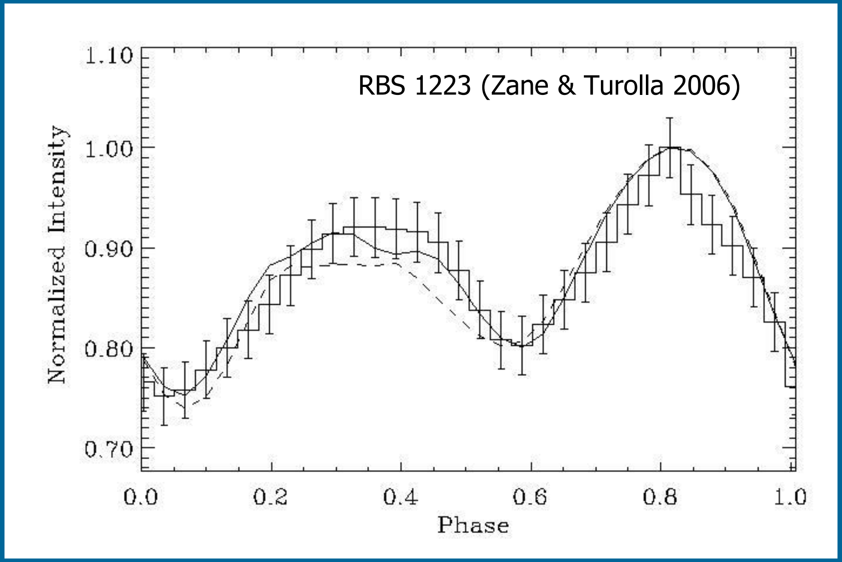


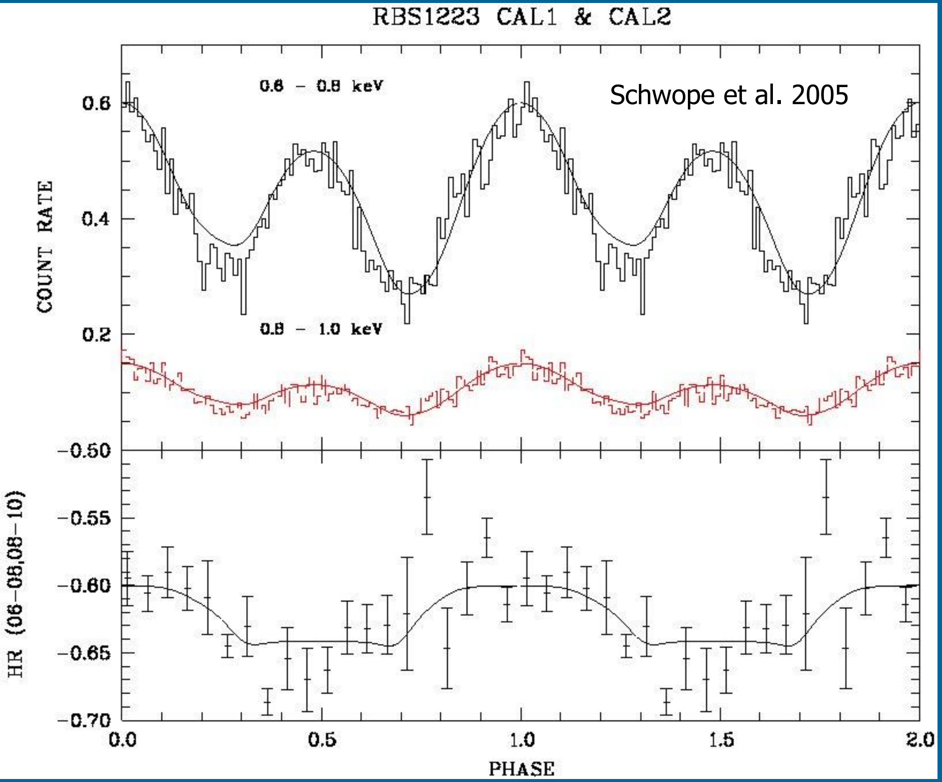
Crustal Magnetic Fields

- 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



Gepper, Küker & Page 2006



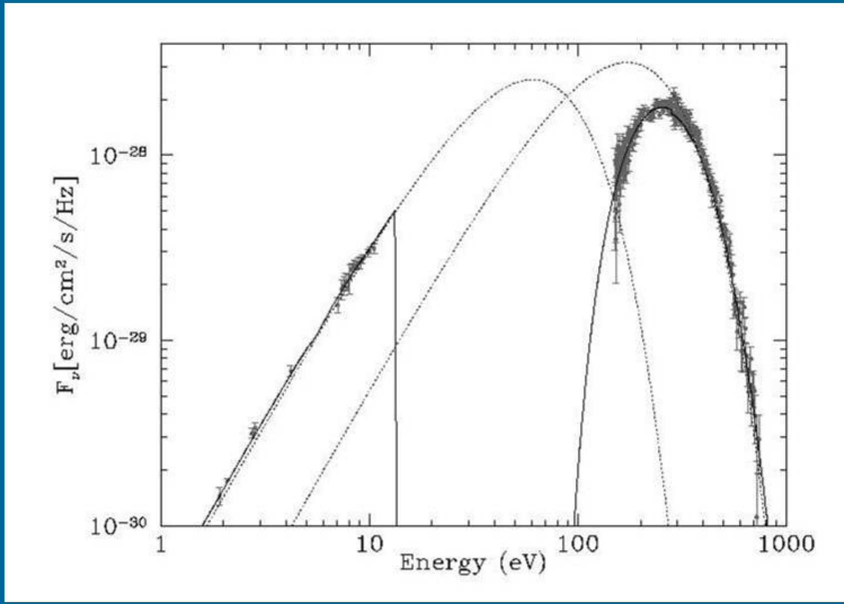


Indications for non-antipodal caps (Schwope et al 2005)

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

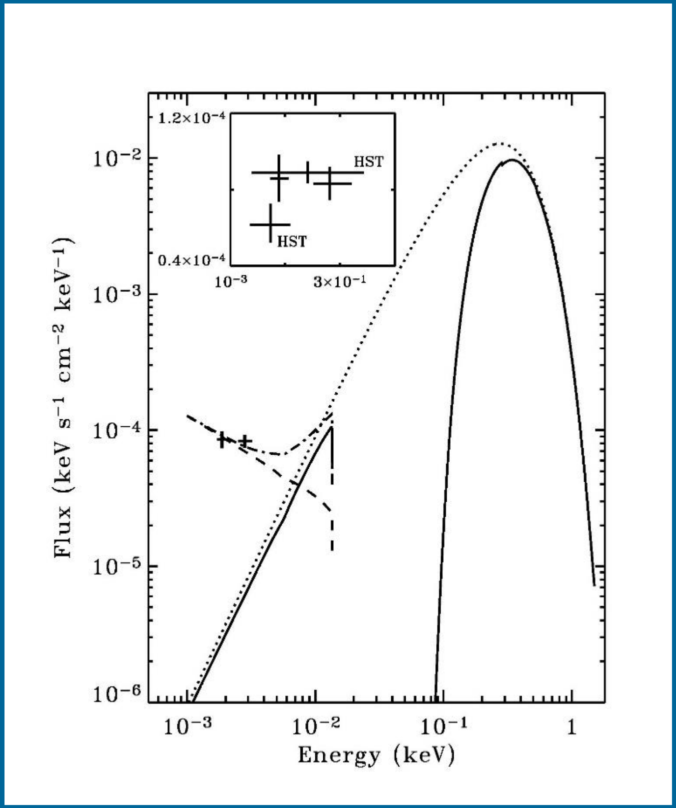
RX J1856.5-3754 - II

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; Trűmper 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

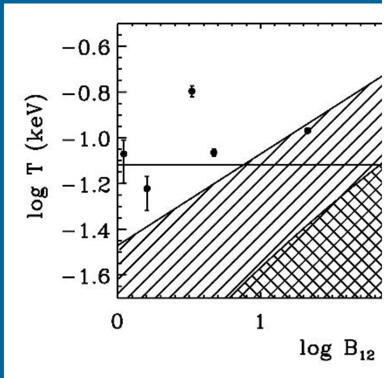


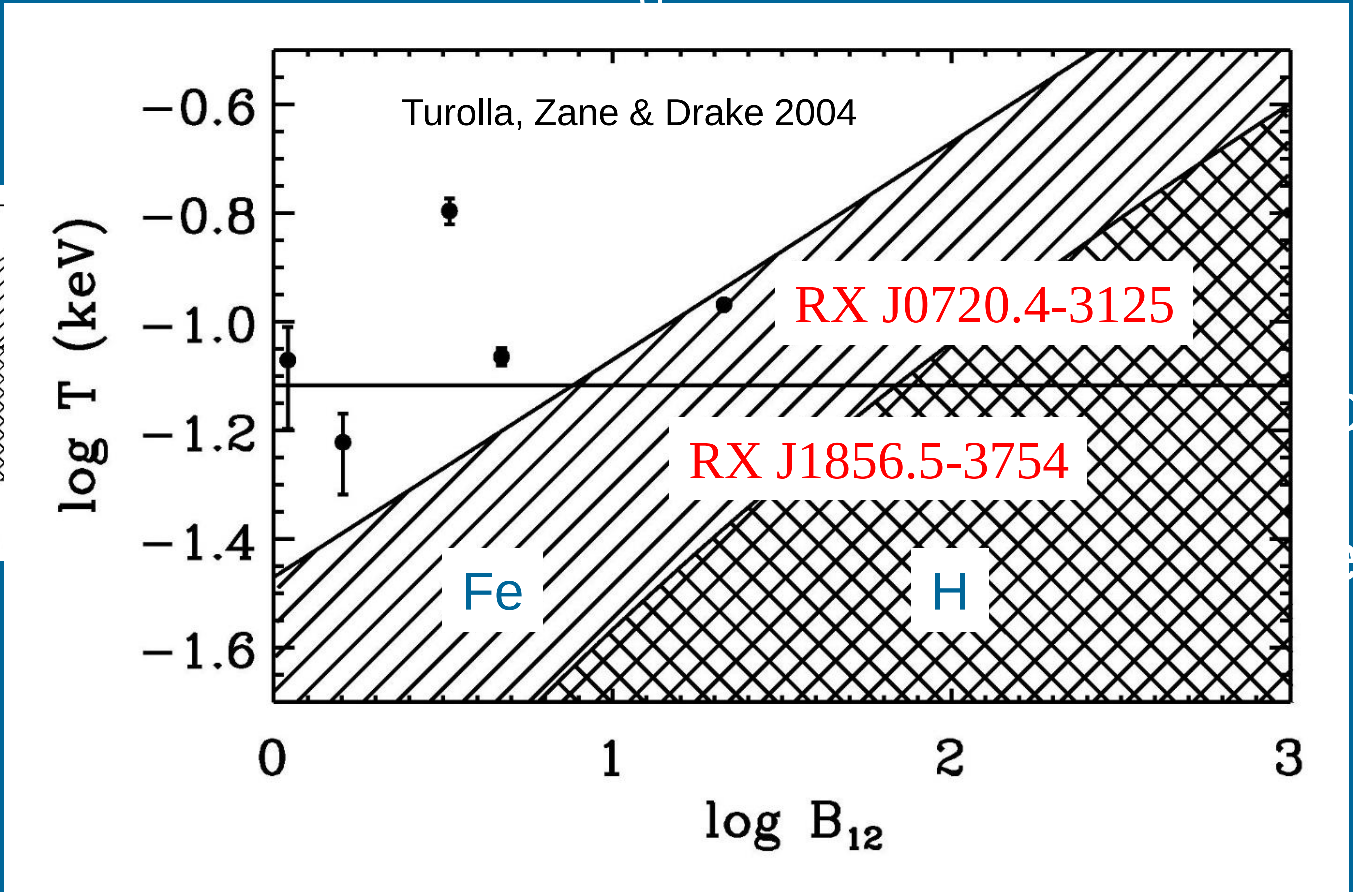
RX J1605 multiwavelength SED (Motch et al 2005)

- In the most of the sources with a confirmed optical counterpart $F_{opt} \approx$ 5-10 x $B_\nu(T_{BB,X})$
- $F_{opt} \approx \nu^2$?
- 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 >> B_0 ~ 2.35 x 10^9 G atoms





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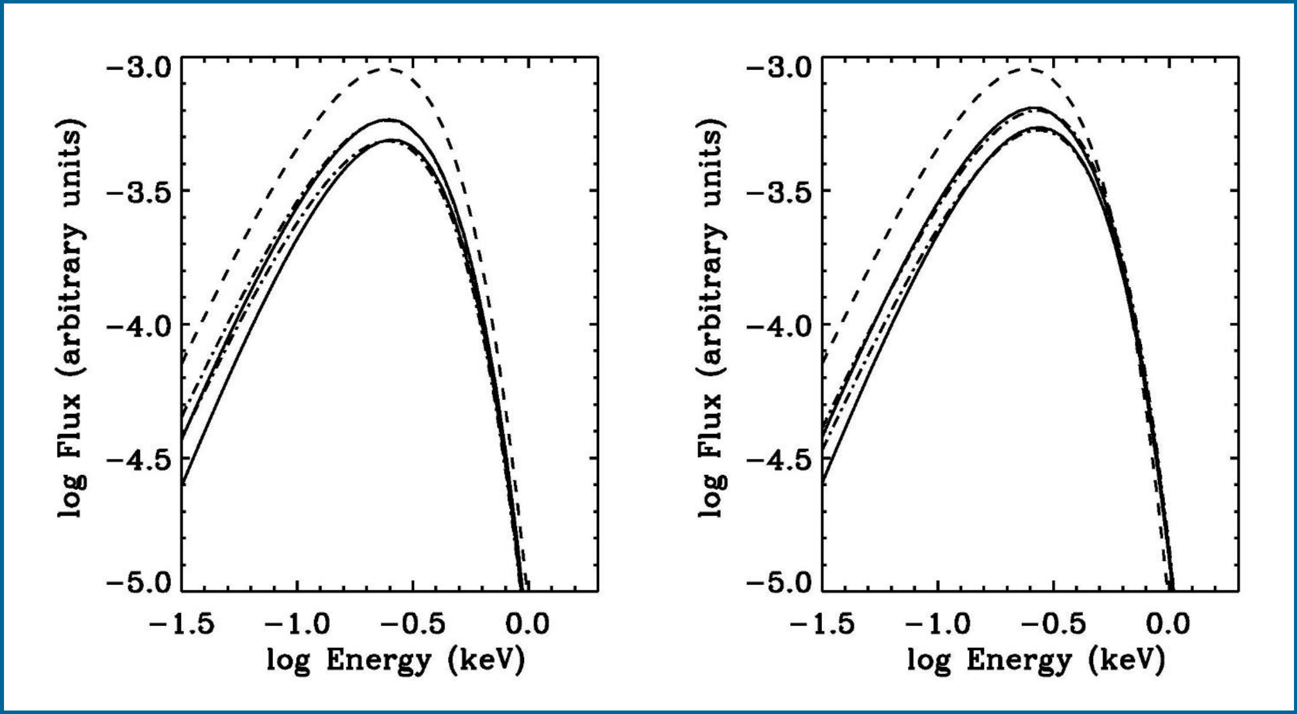
e

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 ~ 2 - 3.

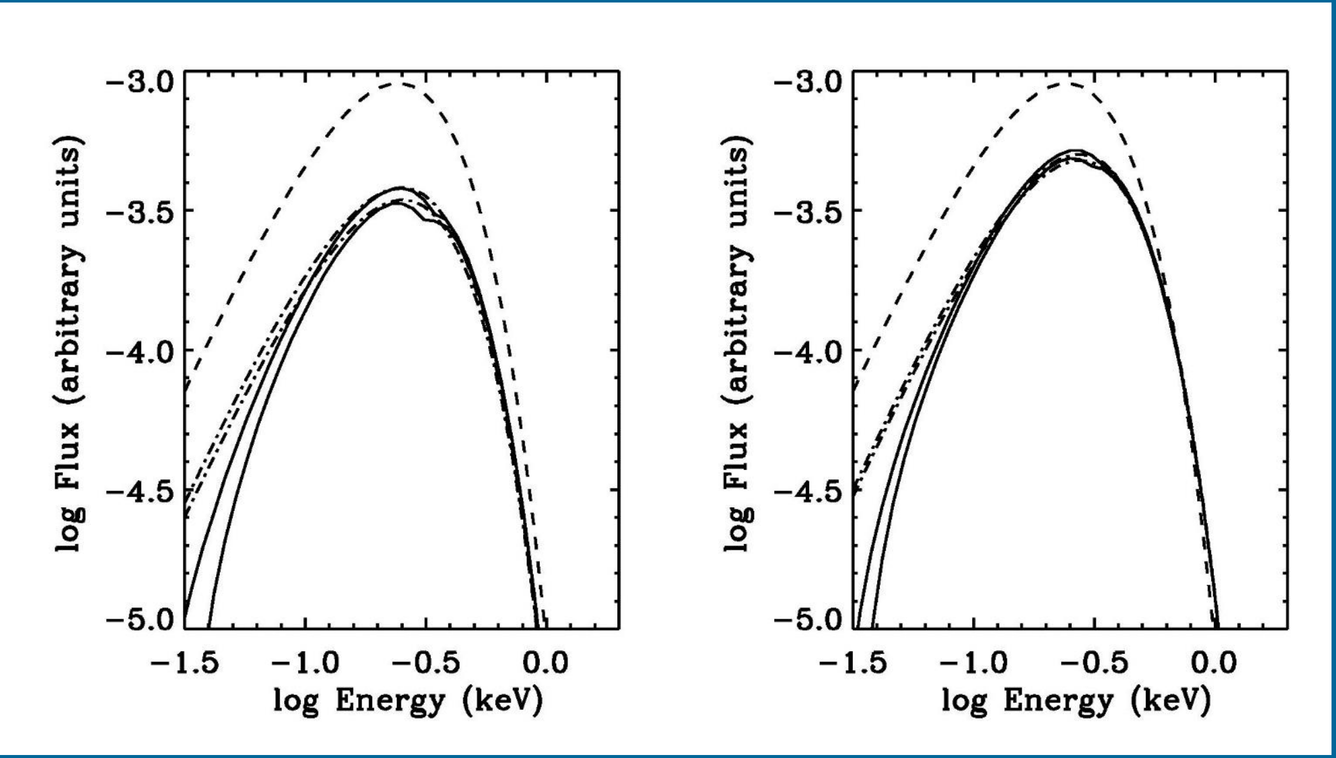


Turolla, Zane & Drake (2004)

Spectra from Bare NS - II

Proper account for damping
of free electrons by lattice interactions
(e-phonon scattering; Yakovlev & Urpin 1980; Potekhin1999)

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



Turolla, Zane & Drake (2004)

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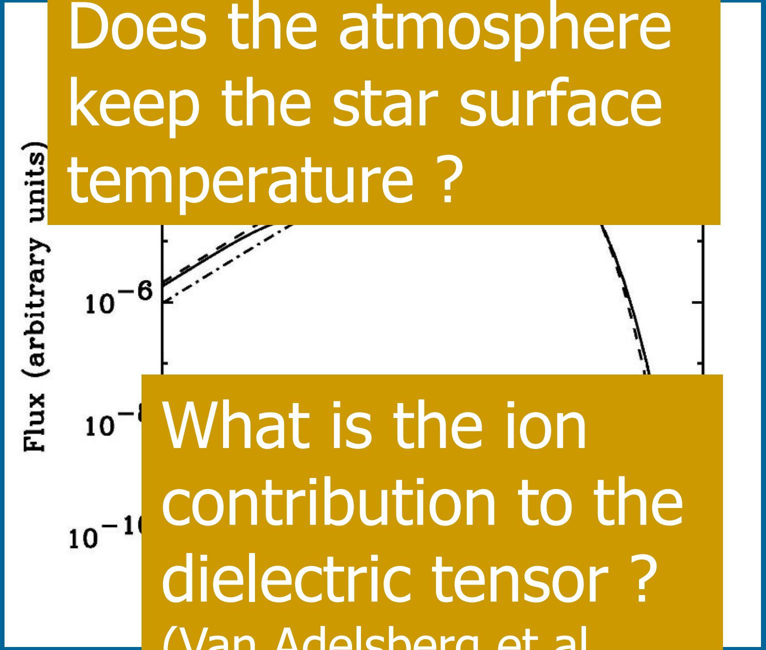
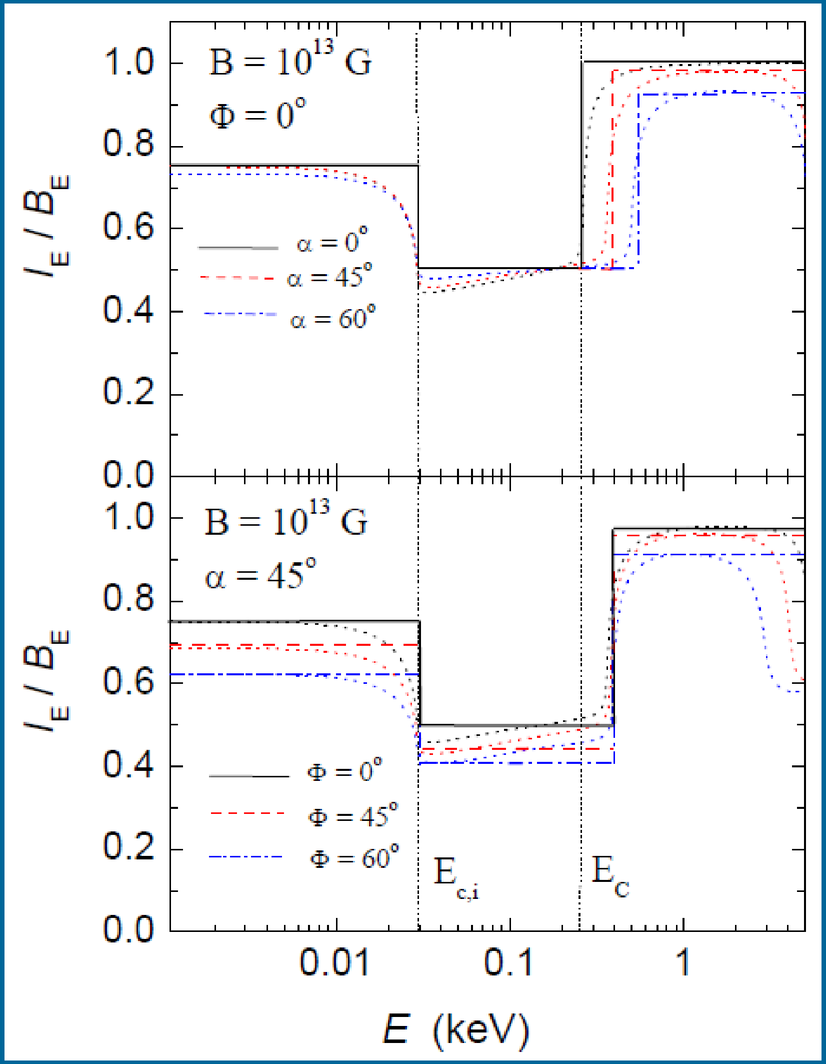
$$R_\infty = 4.25\, f_E^{-1/2} \left(\frac{D}{100\ \mathrm{pc}} \right) \left(\frac{T_{BB}}{60\ \mathrm{keV}} \right)^{-2} \mathrm{km}$$

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)

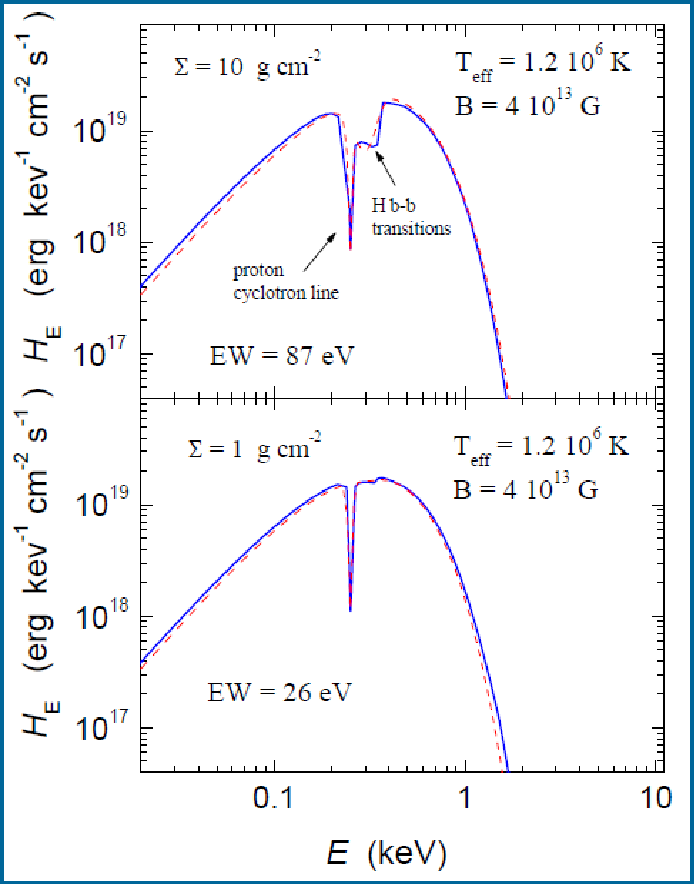
Condensed iron surface emissivity

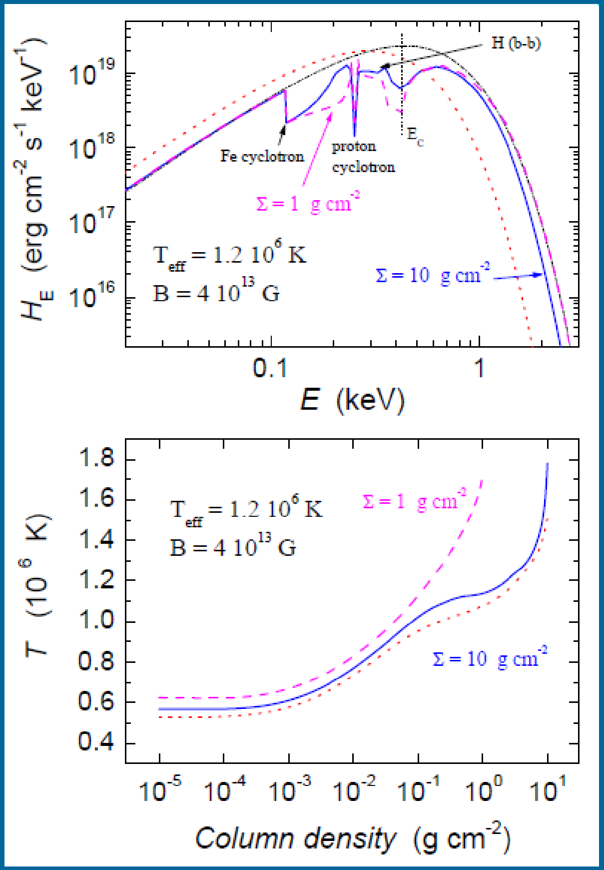


Free ions approximation.

1006.3292

Thin hydrogen magnetized atmosphere above blackbody and iron condensed surface



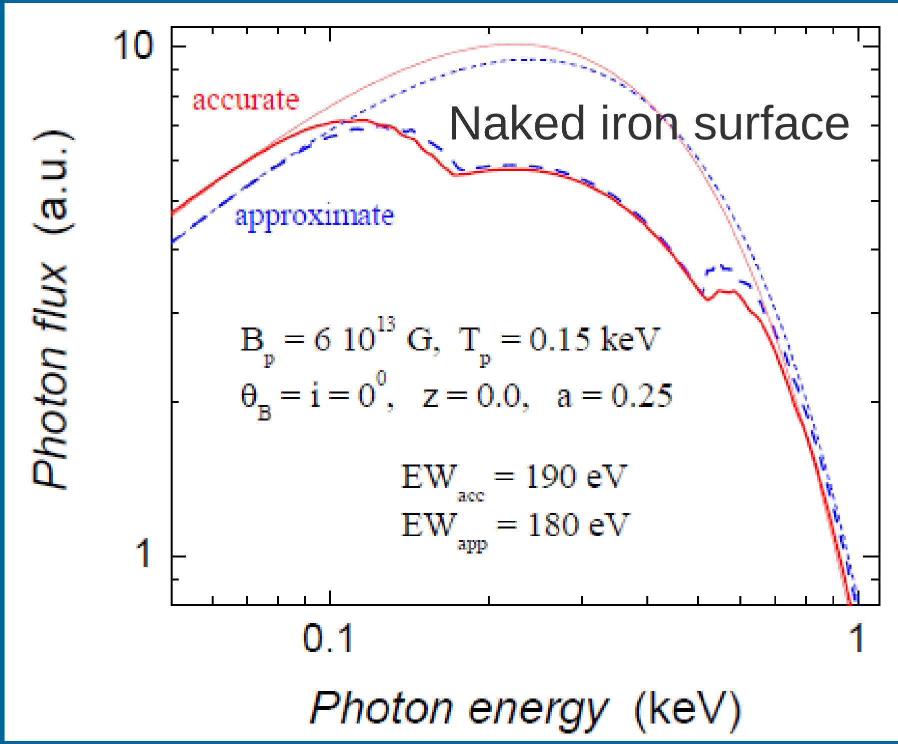


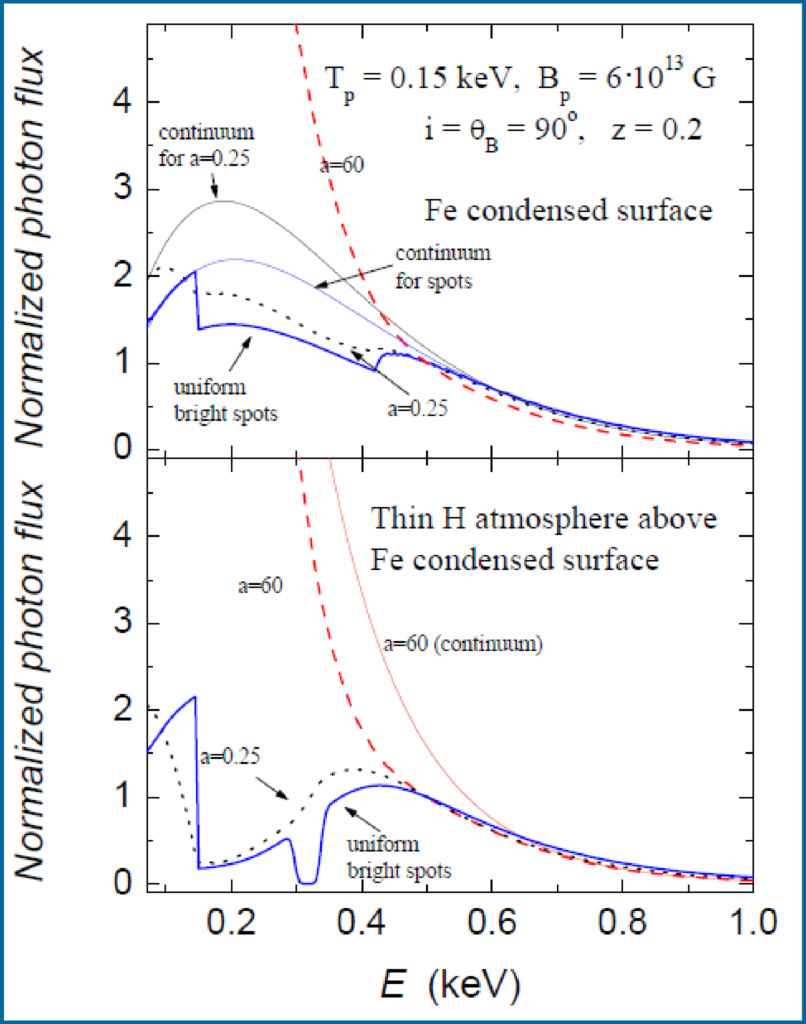
Below atmosphere was a blackbody spectrum

Below – iron condensed surface

1006.3292

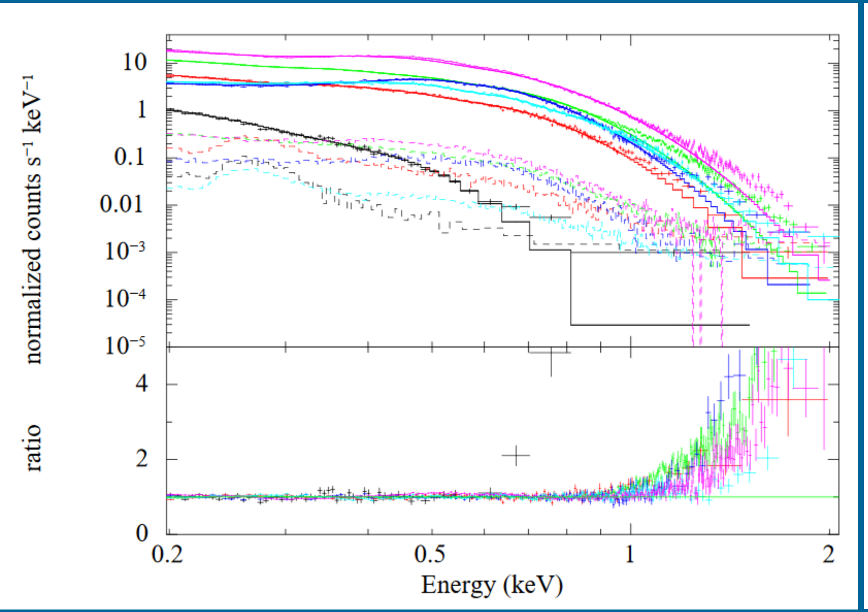
Let us make it realistic

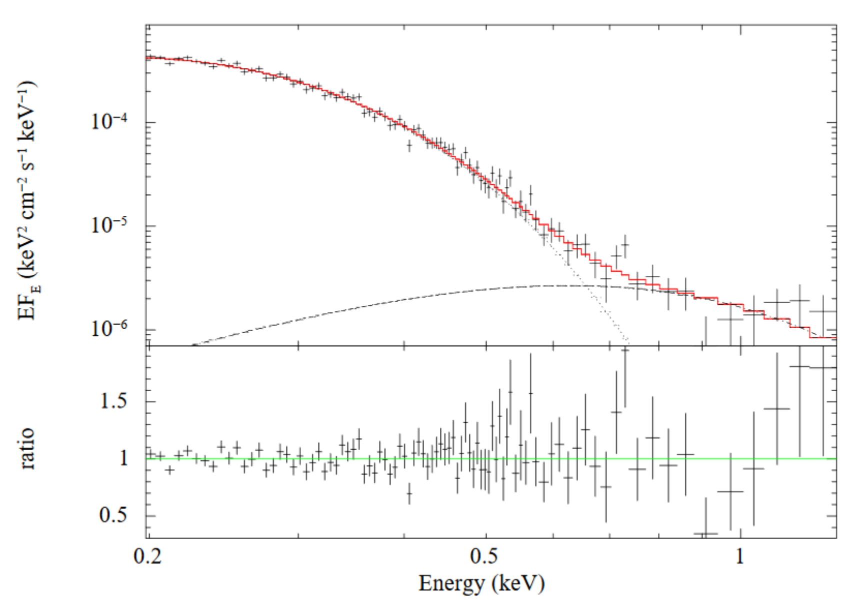




Excess at >1 keV?

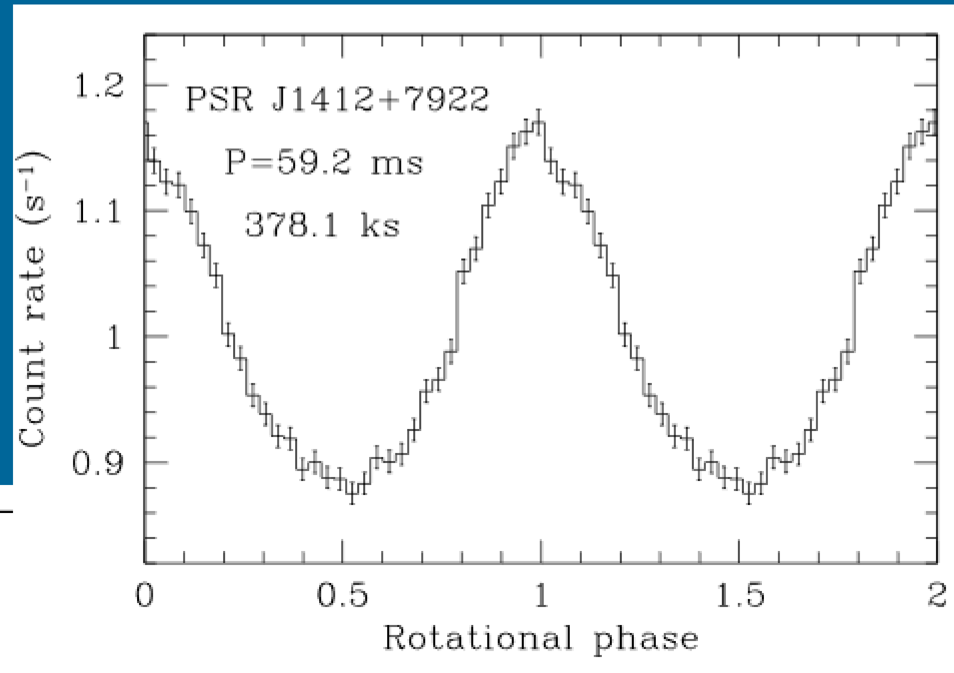
Analysis of spectra of M7 demonstrated a strange excess at energies > 1 keV. This is somehow similar to what magnetars demonstrate.

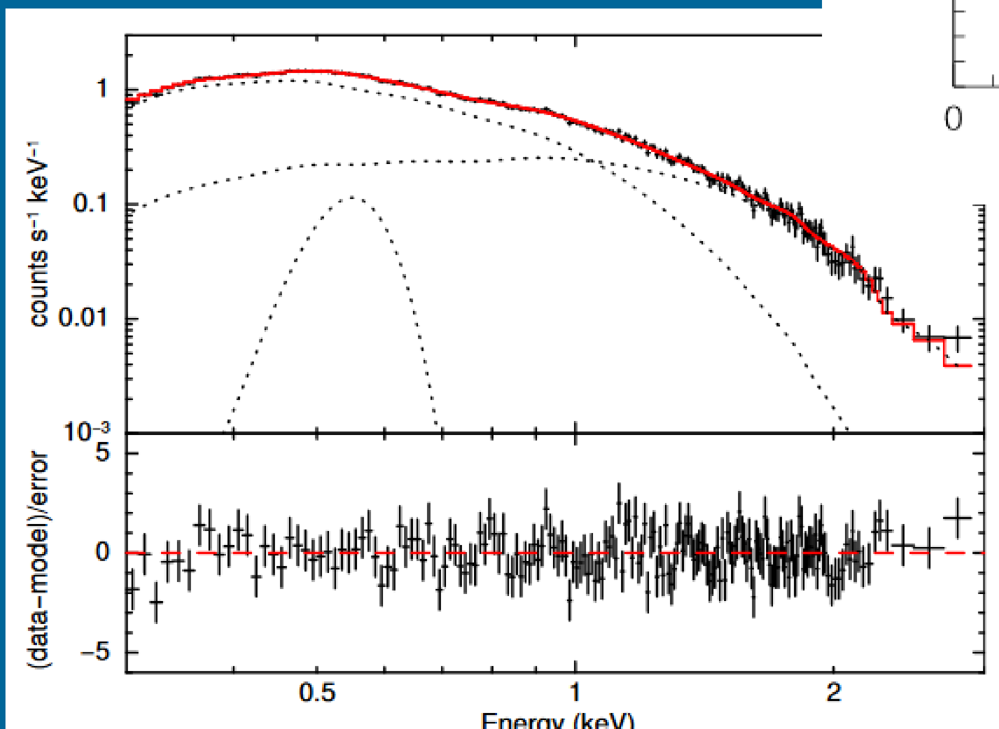




1811.11982

Calvera spectrum

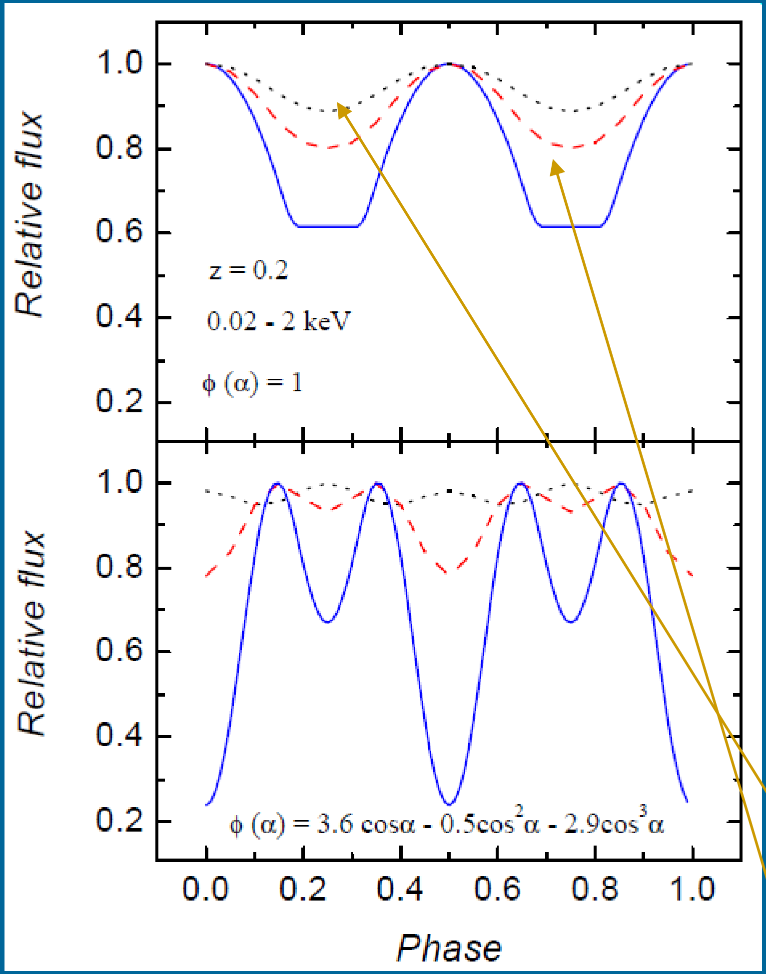


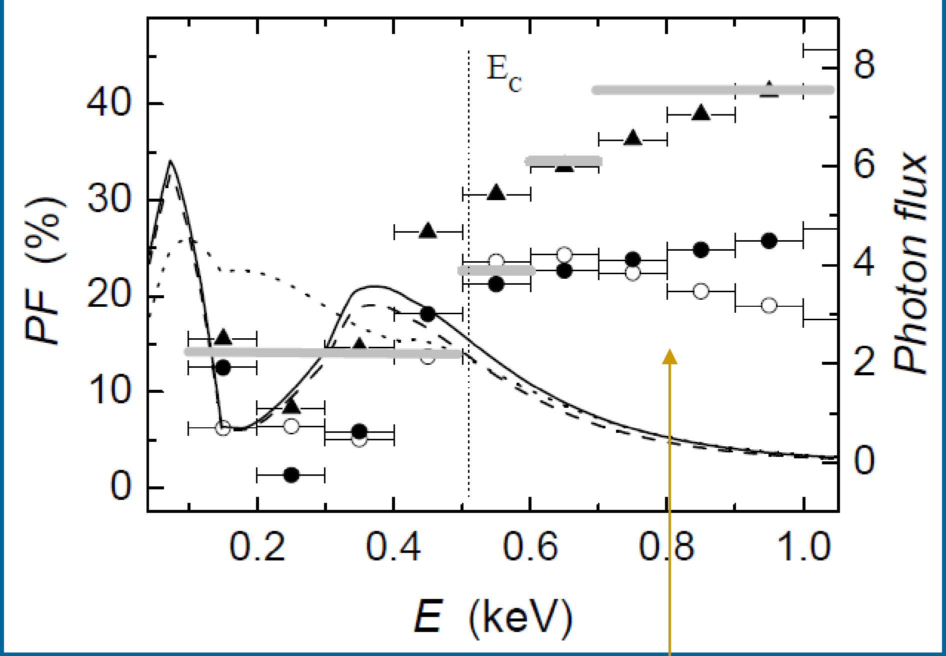


kT_1 (keV)	0.154 ± 0.004
R_1 (km) [b]	$2.21^{+0.08}_{-0.07}$
kT_2 (keV)	$0.319^{+0.013}_{-0.012}$
R_2 (km) [b]	0.37 ± 0.04

1902.00144

Light curves and pulsed fraction





1010.0125

$$a_{1,2} = (1 + \mu_{1,2}^2 R^2)/4$$

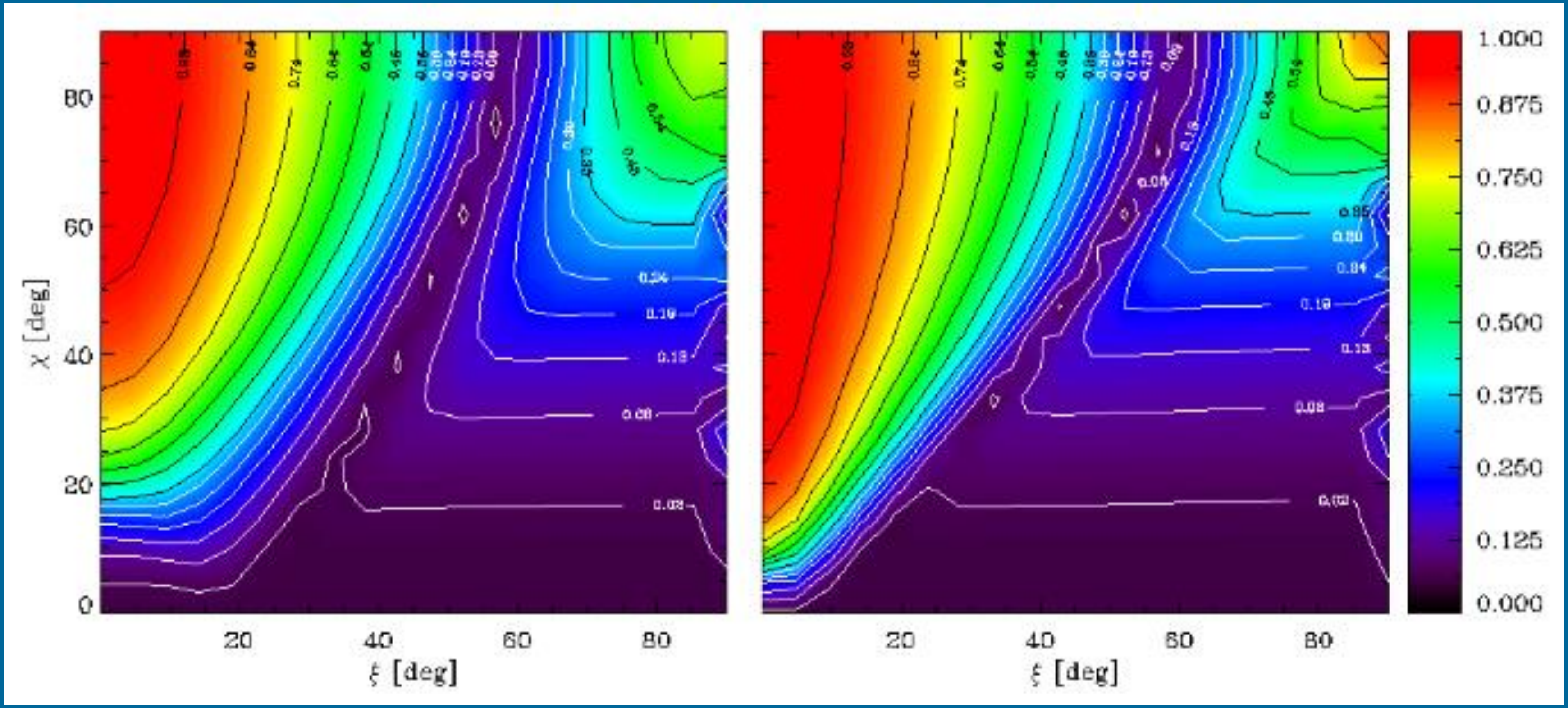
$$a_1 = a_2 = 0.25 \text{ (dotted curves)}$$

$$a_1 = a_2 = 60 \text{ (dashed curves)}$$

1006.3292

Polarization

Contour plots for the phase-averaged polarization fraction at optical (2 eV, left panel) and X-ray (0.3 keV, right panel)

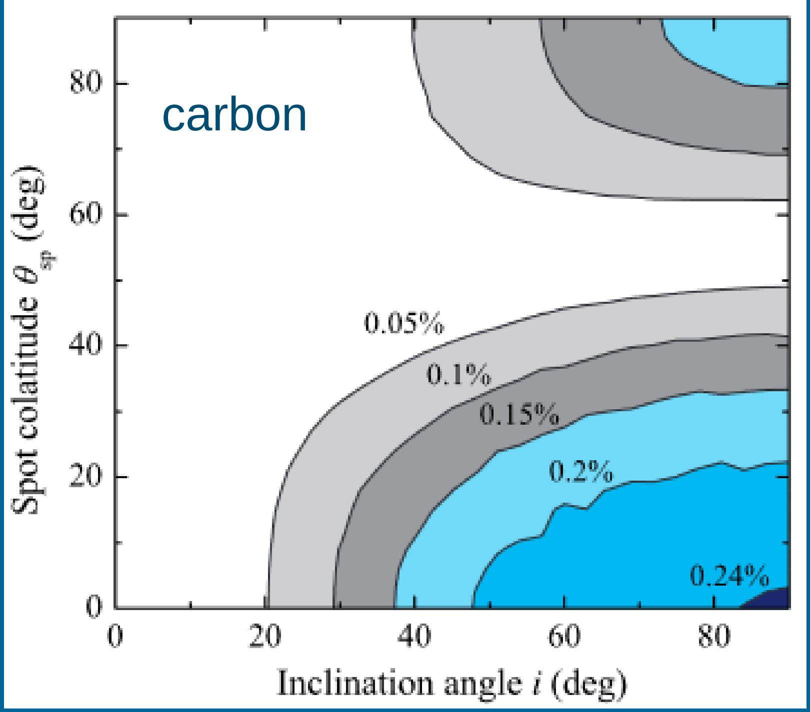


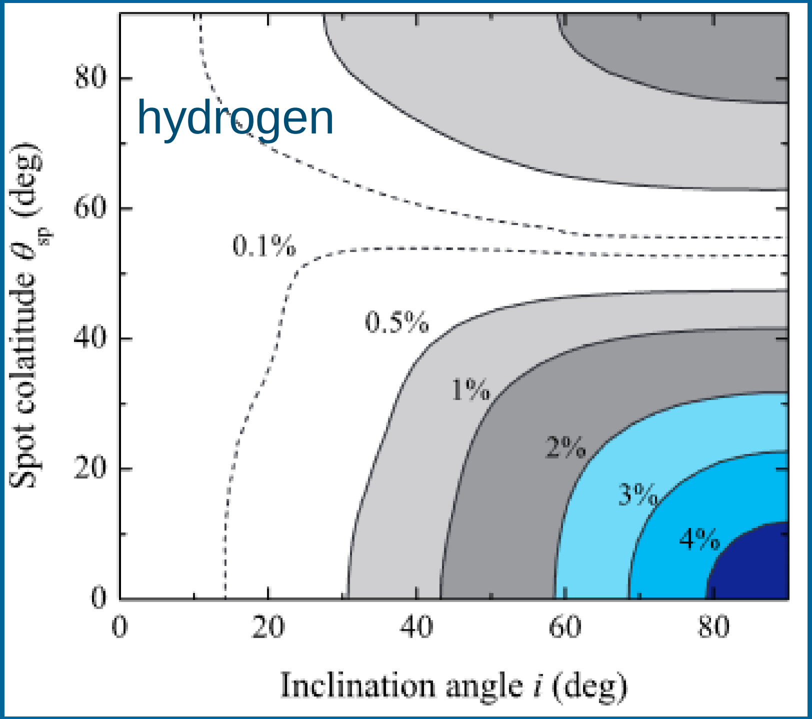
For RX J1856 polarization was detected in optics: 1610.08323.

1509.05023, see 2001.07663 about polarization in magnetars

Distinguishing between carbon and hydrogen with polarization

Polarization measurements potentially can distinguish
between different compositions but not with the present-day instruments (IXPE).



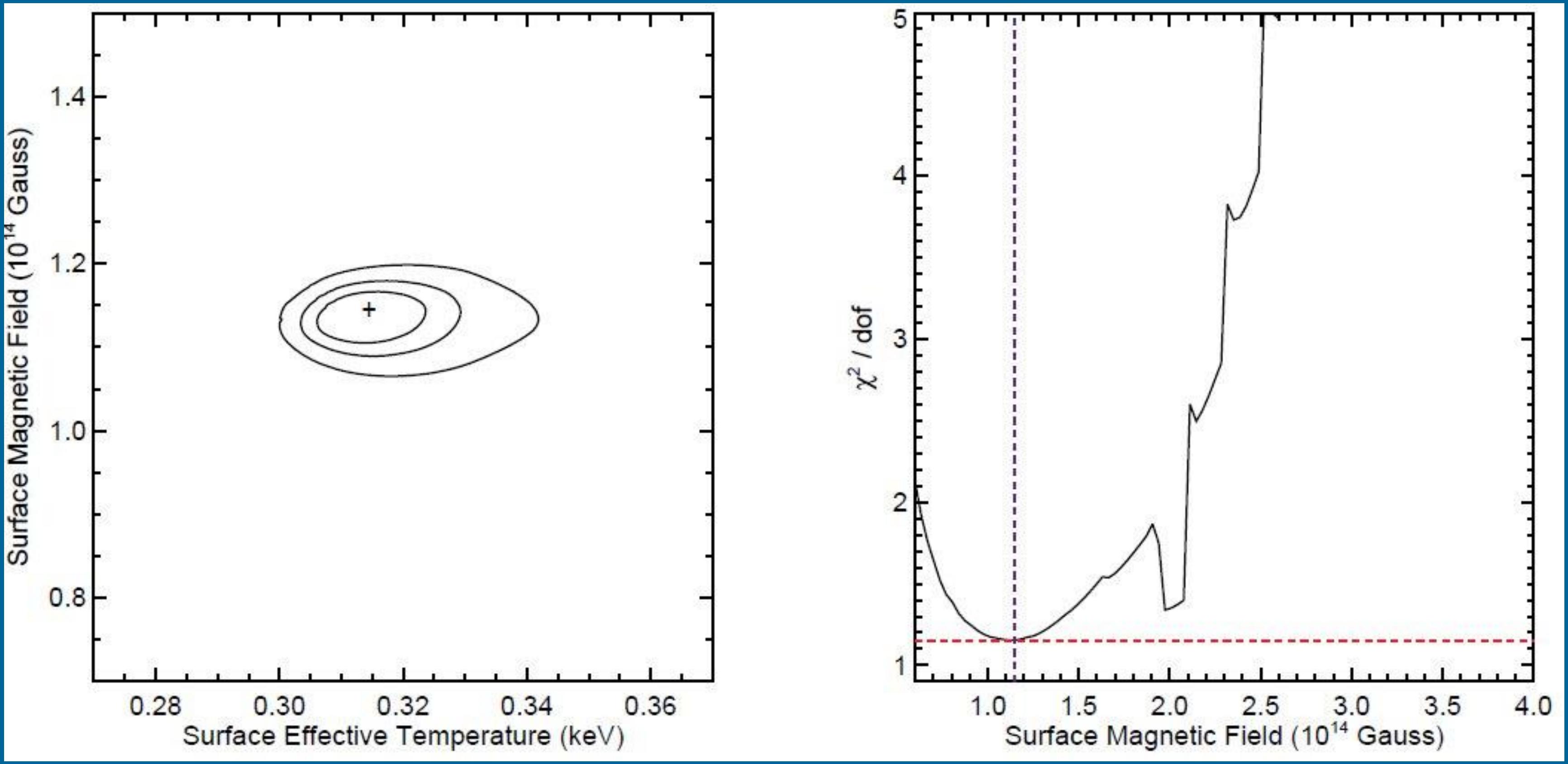


Map of the phase-averaged PD in the 2–8 keV band

2303.01382

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.



1103.3024

New results in 1507.02689

Conclusions

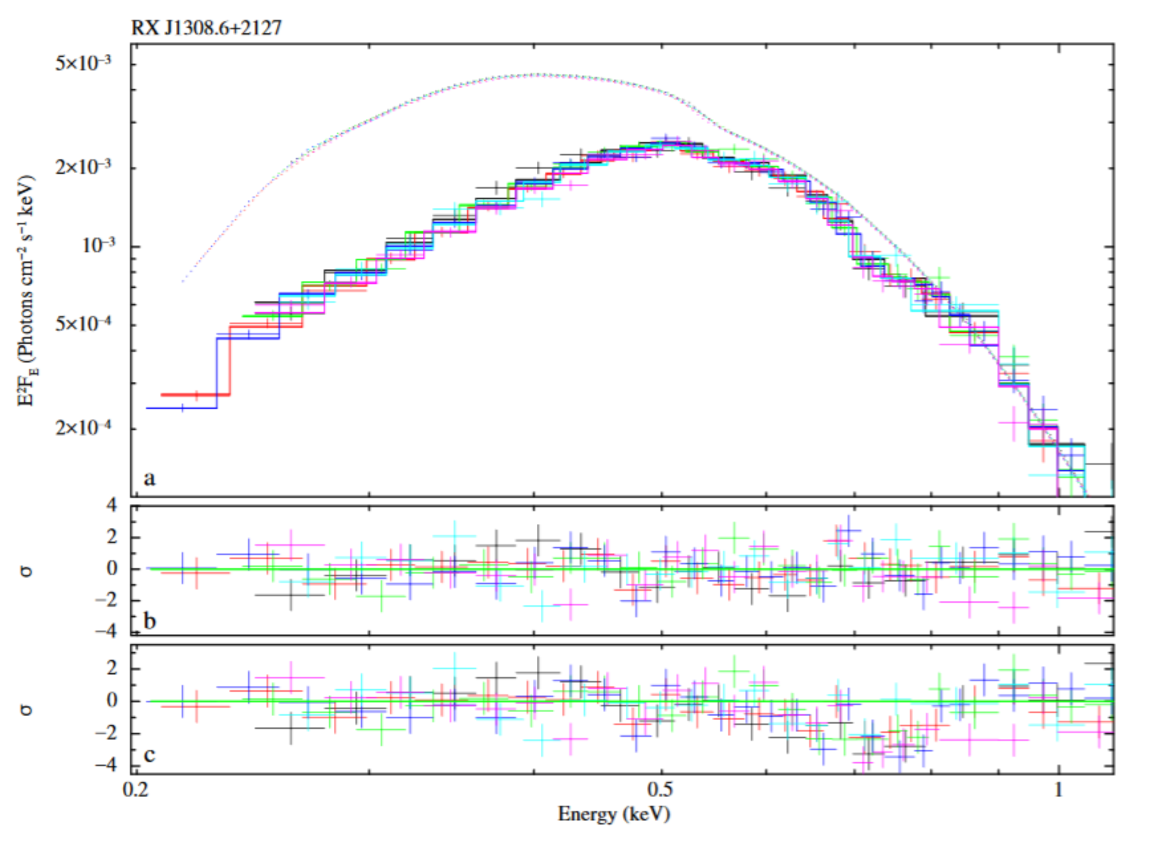
- Emission from cooling NSs is more complicated than a simple blackbody
- Light bending (gravity)
- Atmospheres
- Magnetic field distribution - effects on properties of atmospheres and emission
- Magnetic field (including toroidal) in the crust – non-uniform temp.distr.
- Condensate
- Rotation at ~msec 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 } Calculations of spectra from magnetized atmos.
- arXiv: 1006.3292 }
- arXiv: 1210.0916 – review
- arXiv: 1409.7666 – review
- arXiv: 1403.0074 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

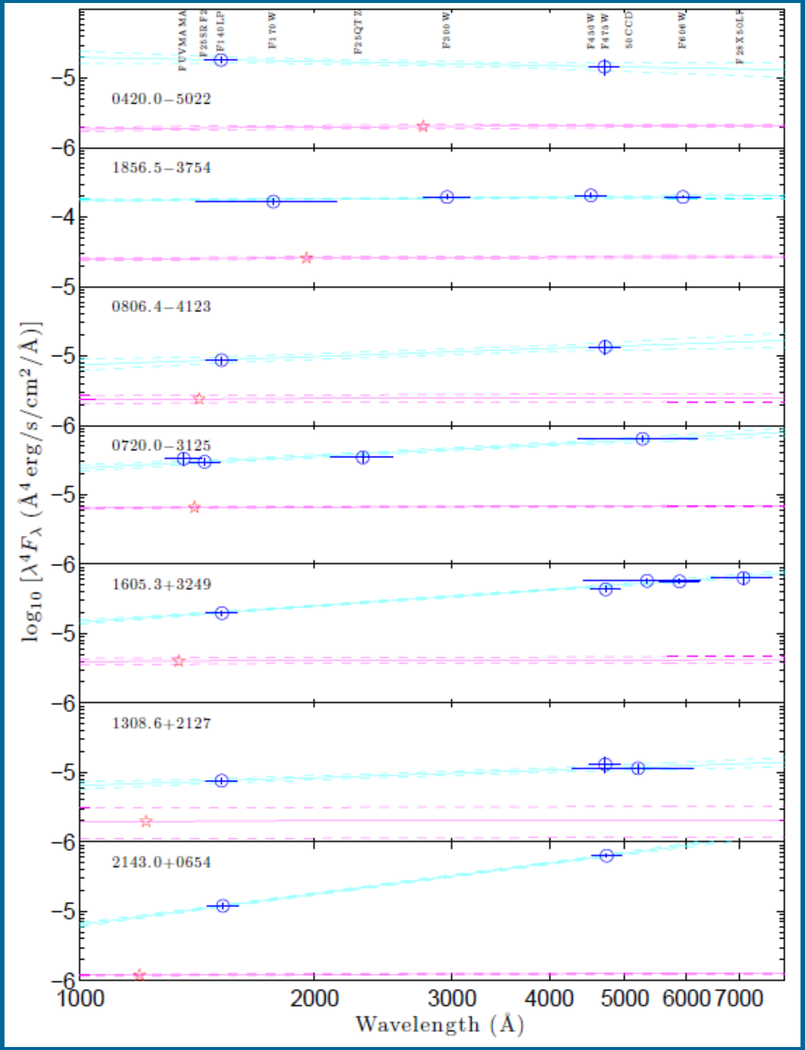


All in optics and UV

All seven objects have confirmed optical and ultraviolet counterparts.

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

kT



New data: Kaplan et al. 1105.4178

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