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

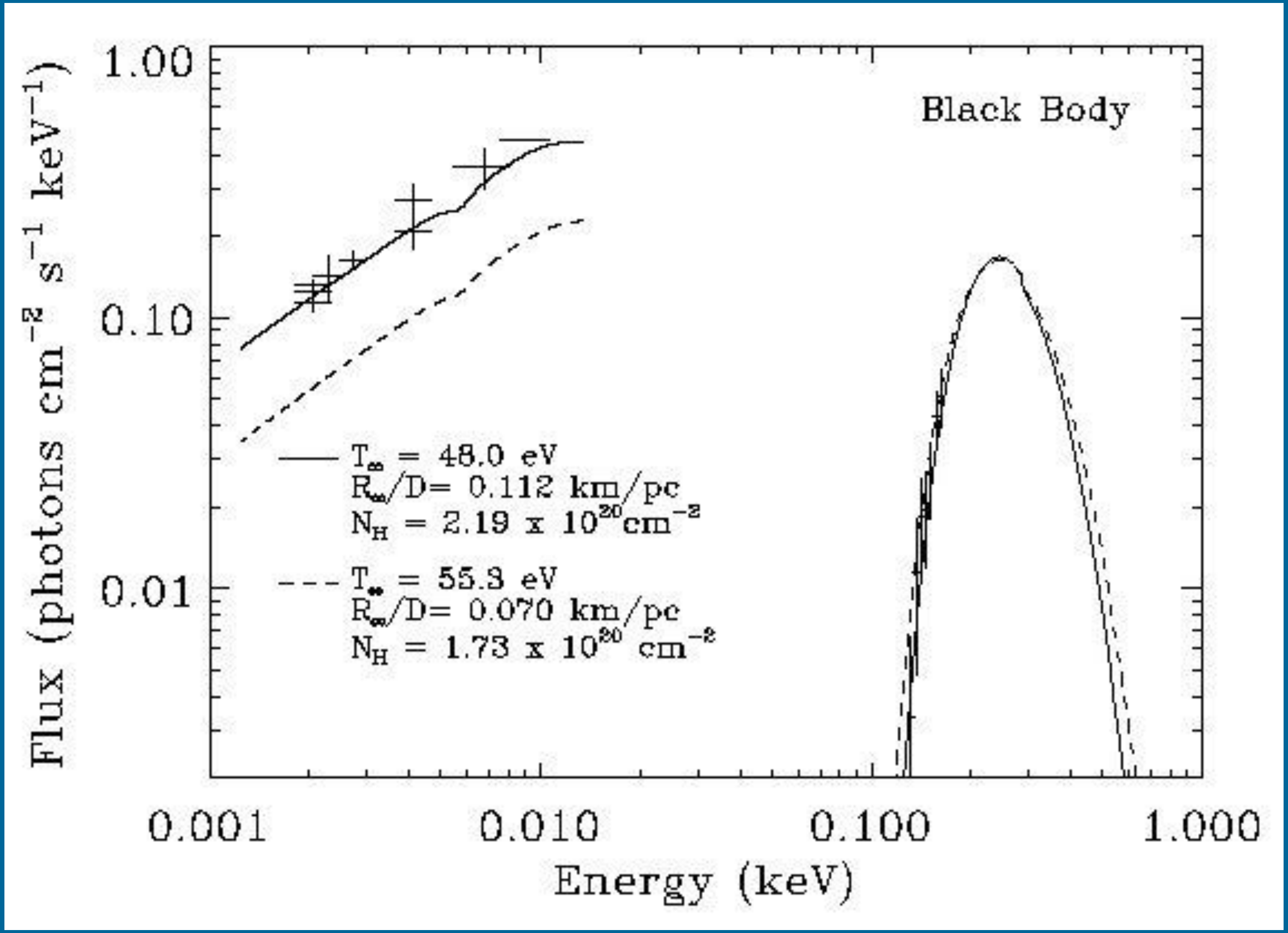
NS Radii - II

- 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

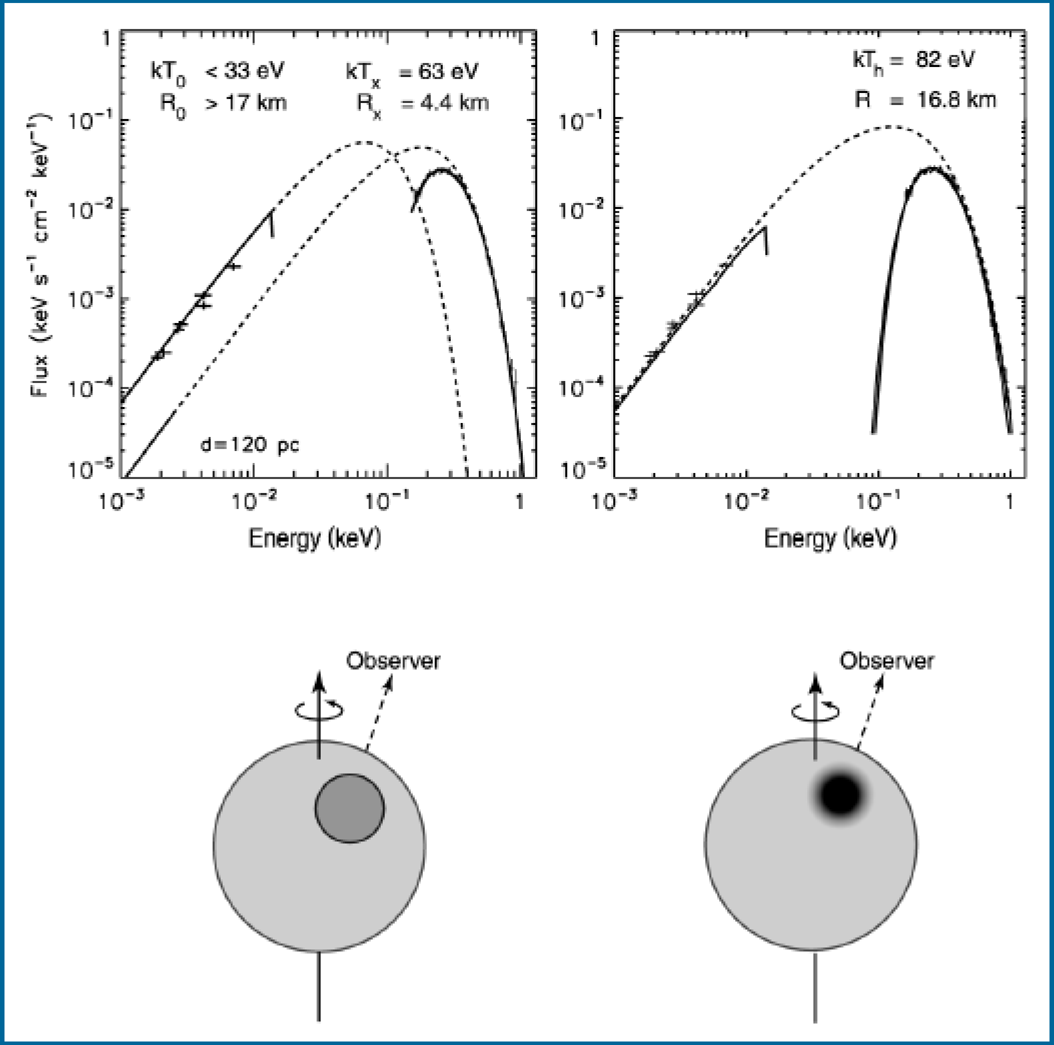
Uncertainties in temperature



- 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



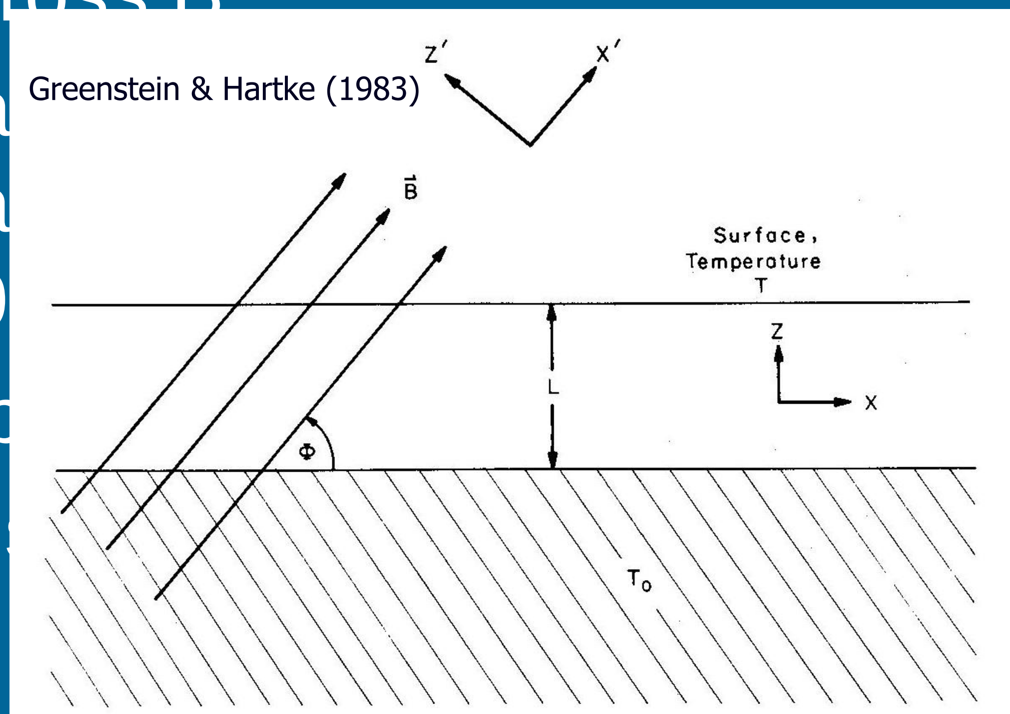
In the case of RX J1856 because of significant (~6) optical excess it was proposed that there is a spot, or there is a continuous temperature gradient.

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 $\rho \gg 10$ ...
- Envelop ... ,

  B ~ con ... 1D



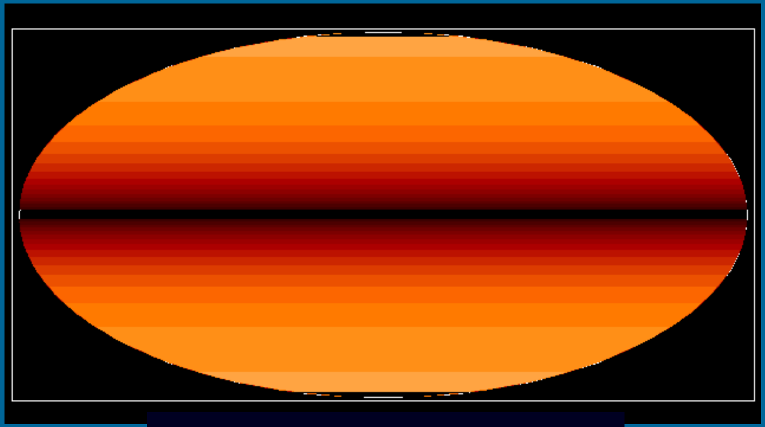
$$T_S = \left[\cos^2\Theta + \left(K_{perp}/K_{par}\right)\sin^2\Theta\right]^{1/4} T_{pole}$$

$$K_{perp}/K_{par} << 1$$

K - conductivity

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

Valid for strong fields: $K_{perp} << K_{par}$



Core centered dipole

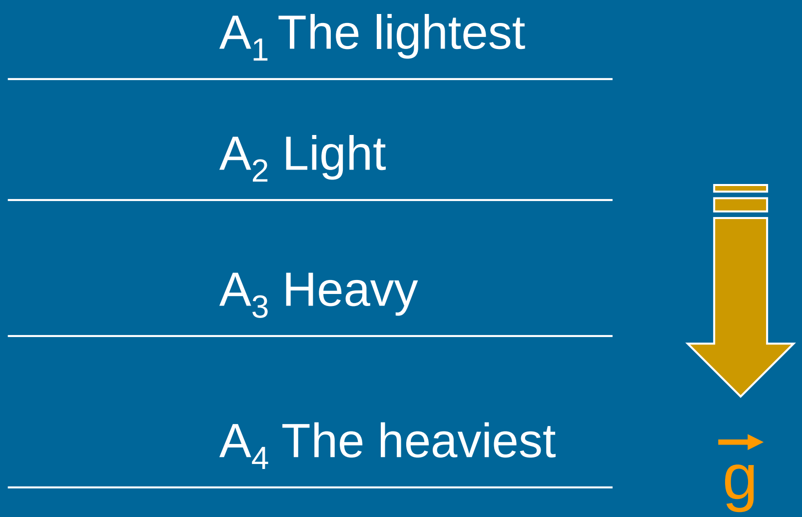
Core centered quadrupole

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, $h_{atm} \approx$ 1-10 cm ($h_{atm} \sim kT/mg$)
- Spectra depend on g, chemical composition and magnetic field
- Plane-parallel approximation (locally)

Atmospheric composition



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.

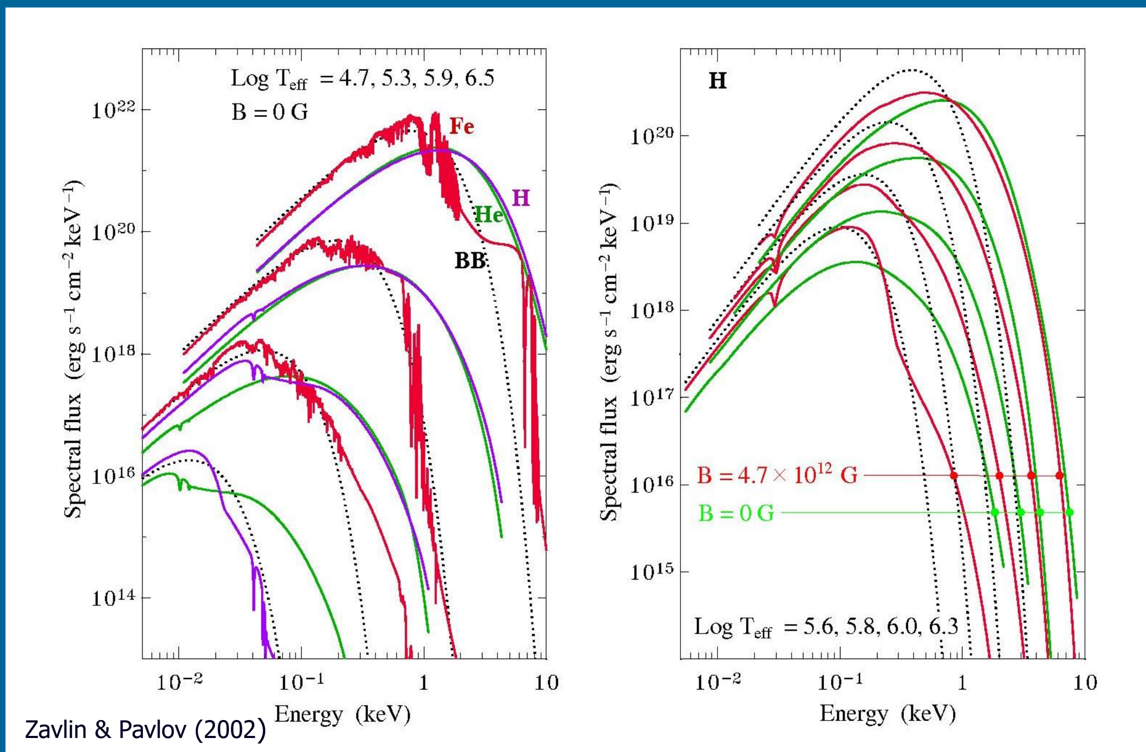
10^{-20} solar mass of hydrogen is enough to form a hydrogen atmosphere.

See astro-ph/ 0702426

- Free-free absorption dominates

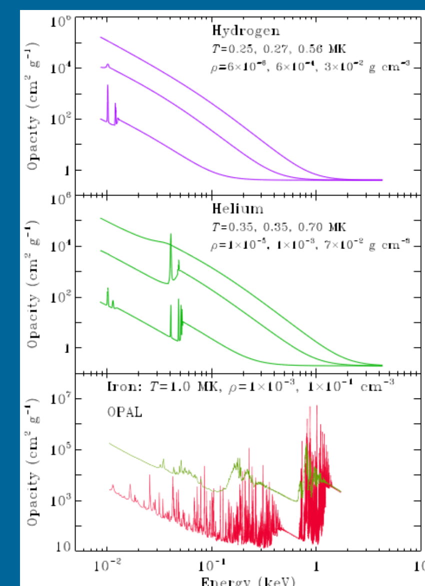
$$\kappa_\nu \propto \nu^{-3}, h\nu >> kT$$

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



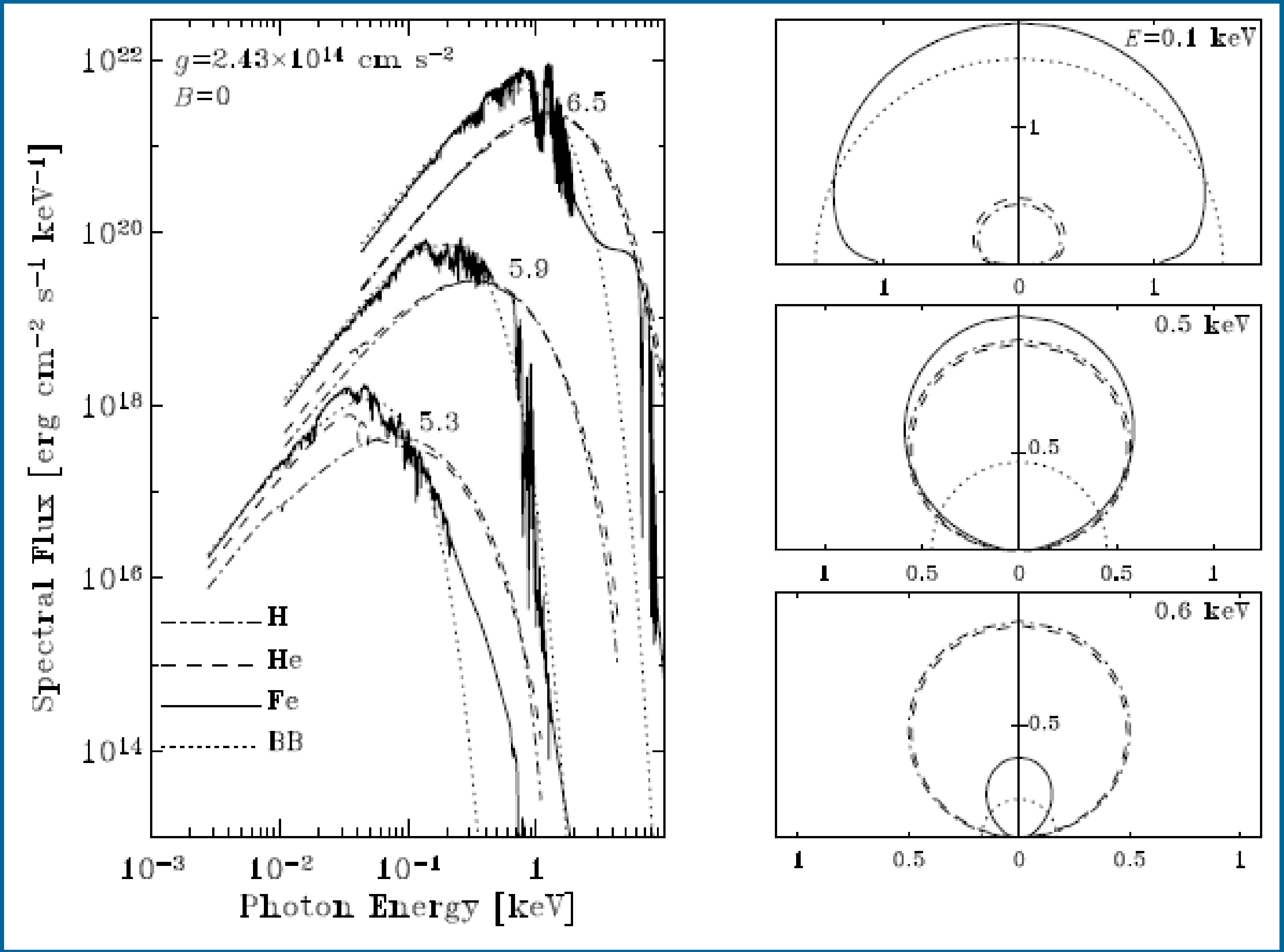
Zavlin & Pavlov (2002)

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



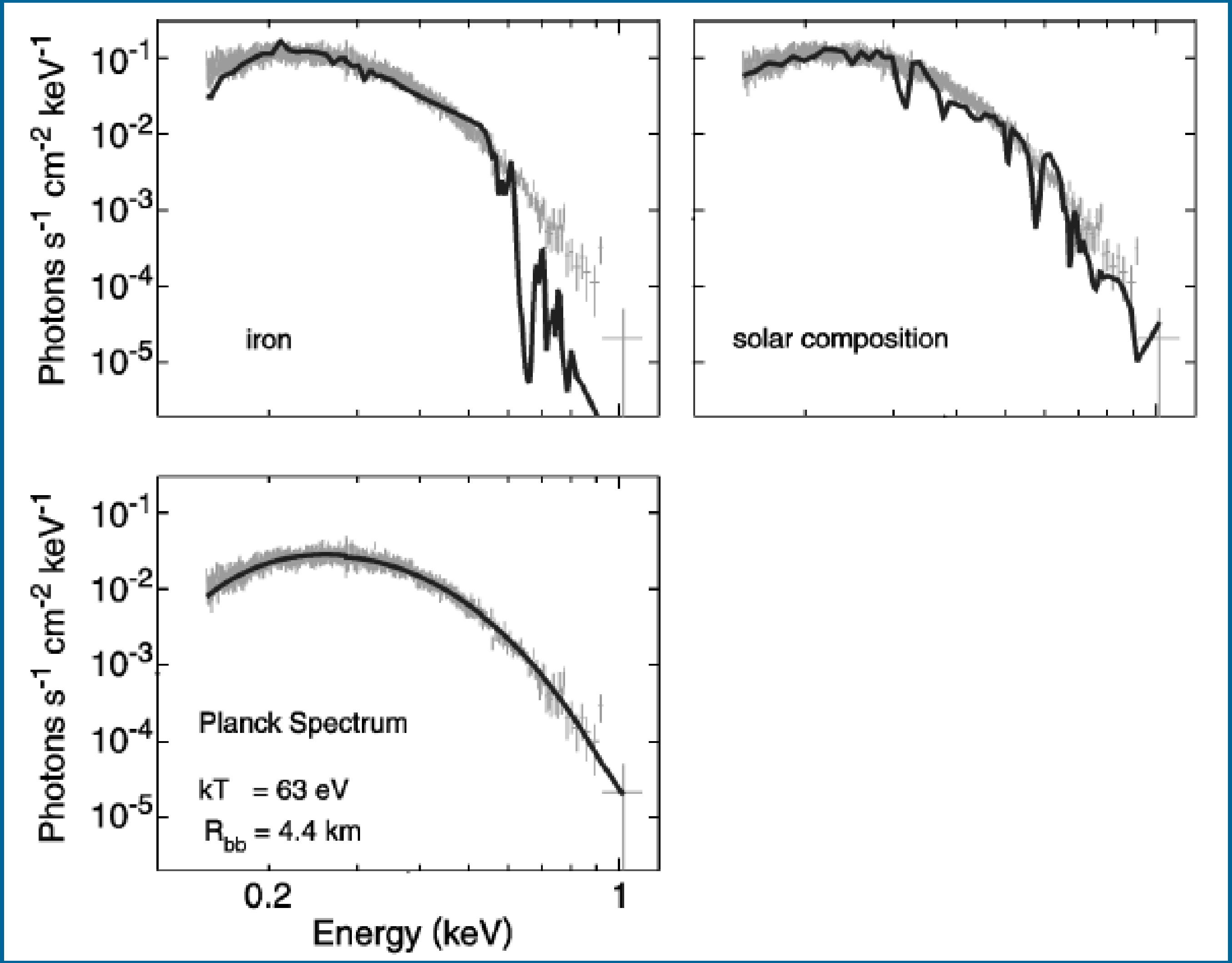
astro-ph/0206025

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

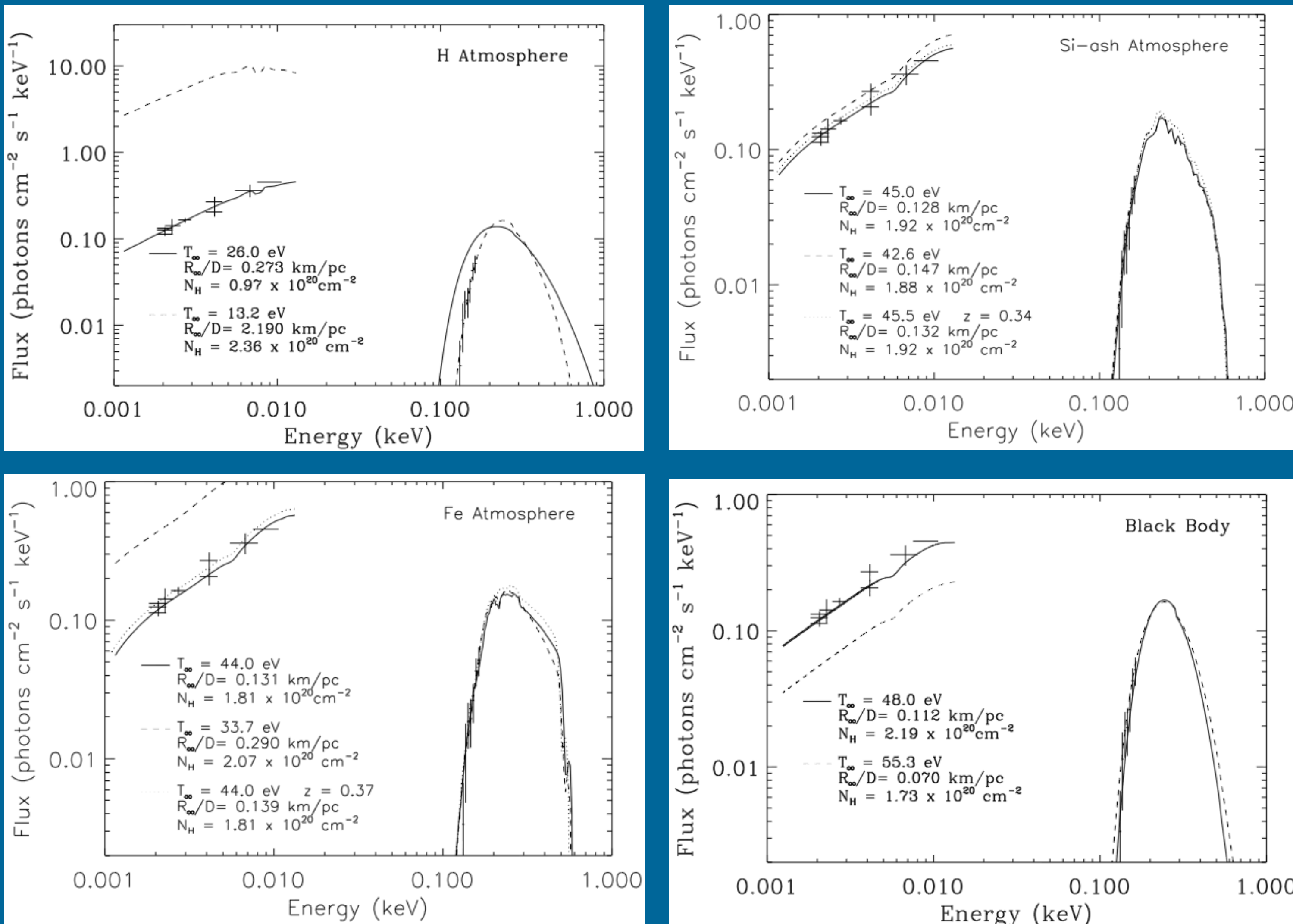
[a] 3 σ ranges, assuming $z = 0.305$. Weighting of the data is discussed in the text.
[b] Uncertainty does not include uncertainty in distance.
[c] The likelihood that the X-ray and optical parameters are the same.

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}~$2T_H$

Pons et al. 2002

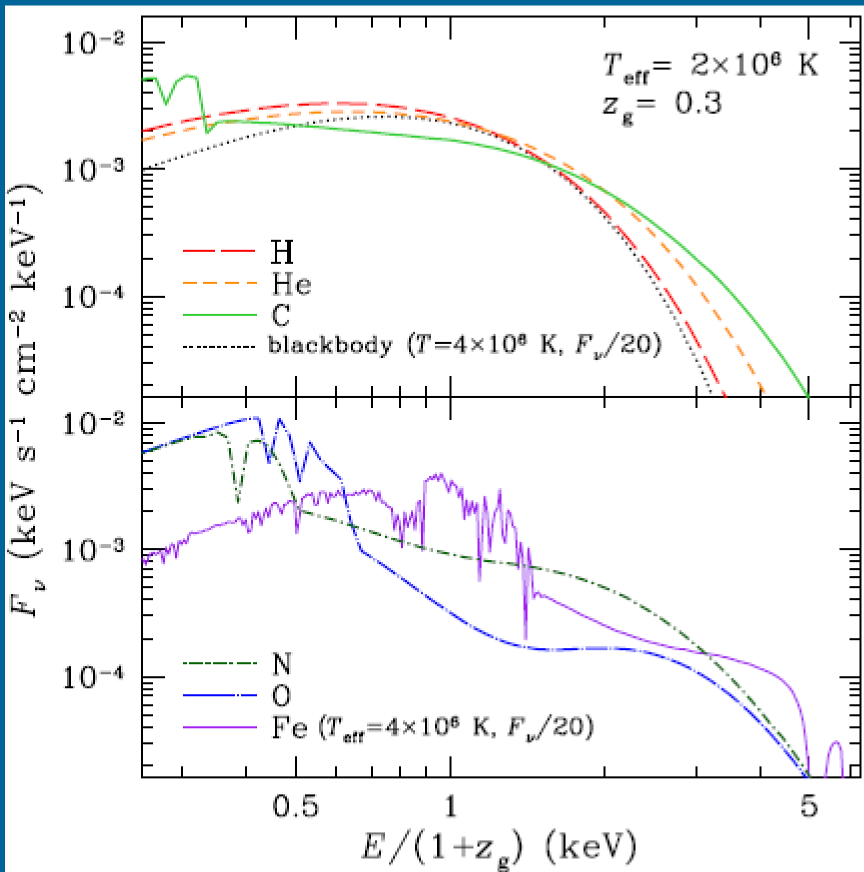
Different fits

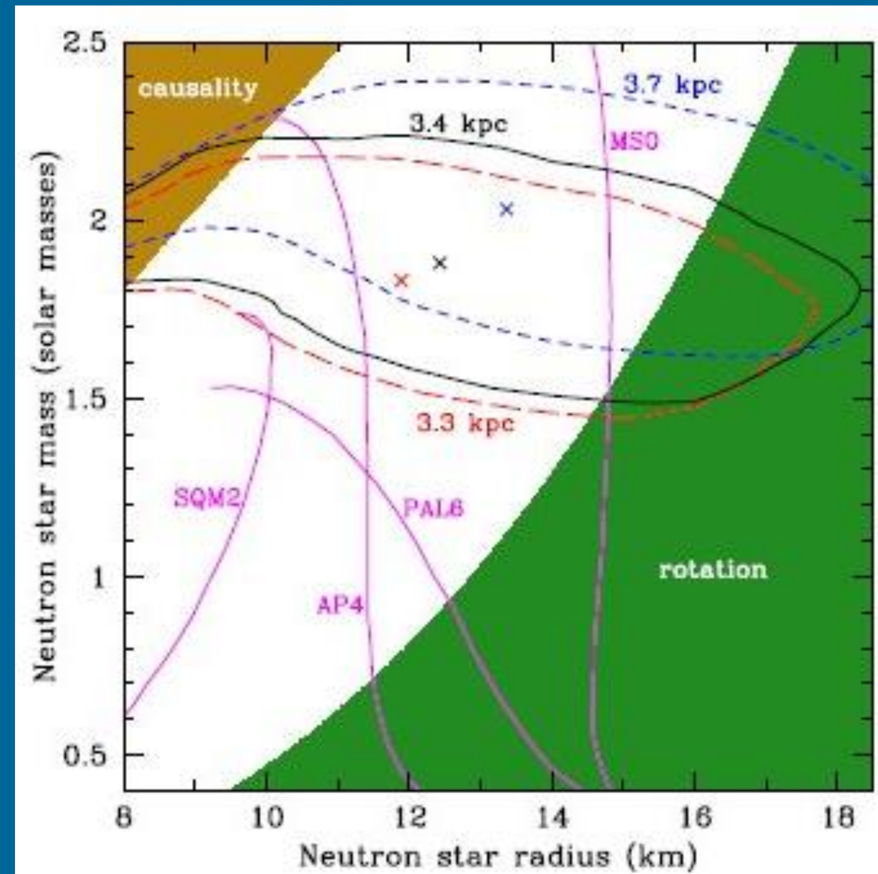


$T_{bb} \sim T_{Fe} > T_H$

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

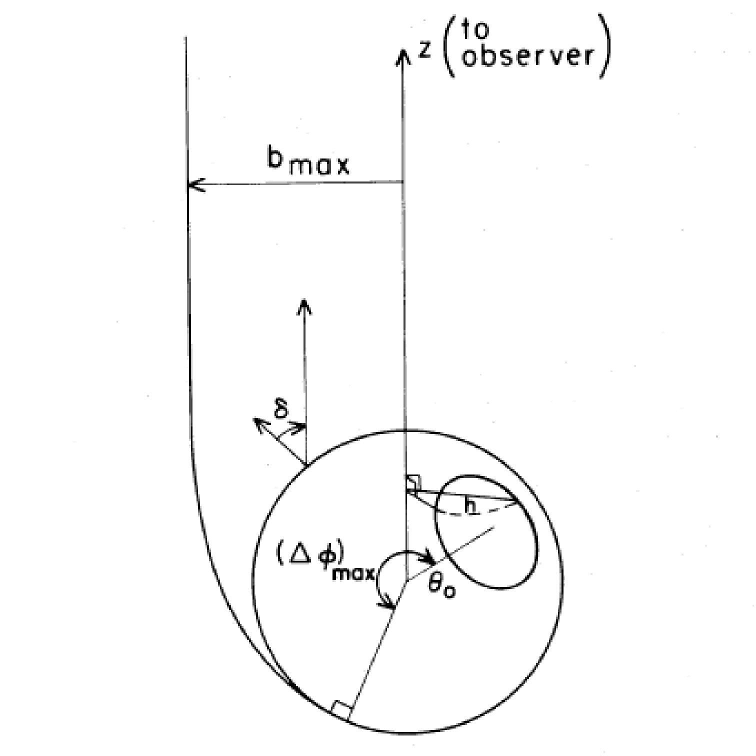
CCO	χ^2_ν	NHP %	n_{H} $10^{22}\mathrm{cm}^{-2}$	T MK	A	Flux
J0852	0.86	79	$0.70^{+0.02}_{-0.02}$	$1.68^{+0.03}_{-0.03}$	0.13	1.34(1)
J1601	0.98	51	$4.71^{+0.25}_{-0.26}$	$1.84^{+0.13}_{-0.12}$	0.59	0.124(3)
J1713	0.98	55	$0.71^{+0.01}_{-0.01}$	$1.97^{+0.01}_{-0.02}$	0.2	3.185(12)
J1720	0.89	80	$5.74^{+0.24}_{-0.23}$	$2.37^{+0.11}_{-0.10}$	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

Gravity Effects

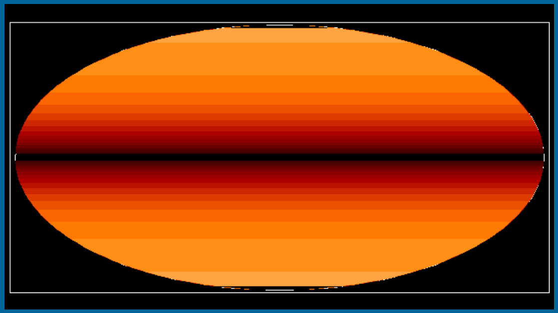
- Redshift
- Ray bending



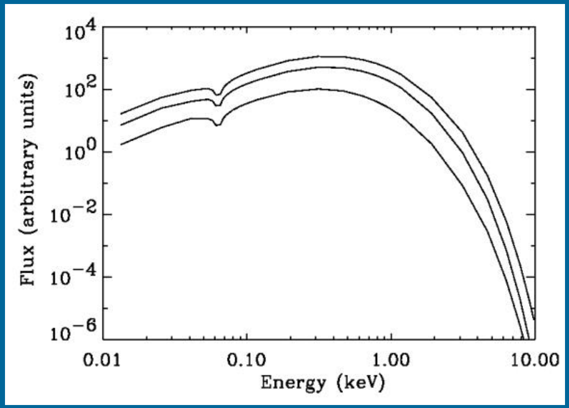
$$L_\infty = 4\pi \, R_\infty^2 \, \sigma \, T_\infty^4$$

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

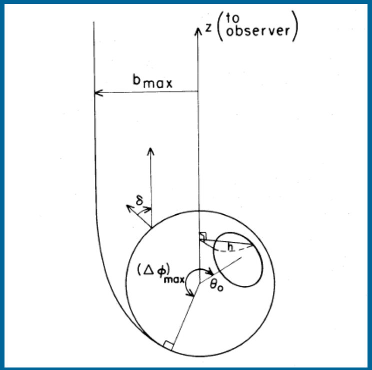
STEP 1
Specify viewing geometry and B-field topology; compute the surface temperature distribution



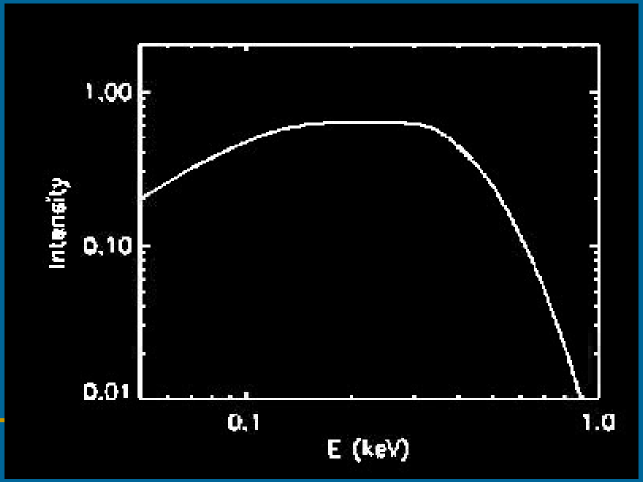
STEP 2
Compute emission from every surface patch



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

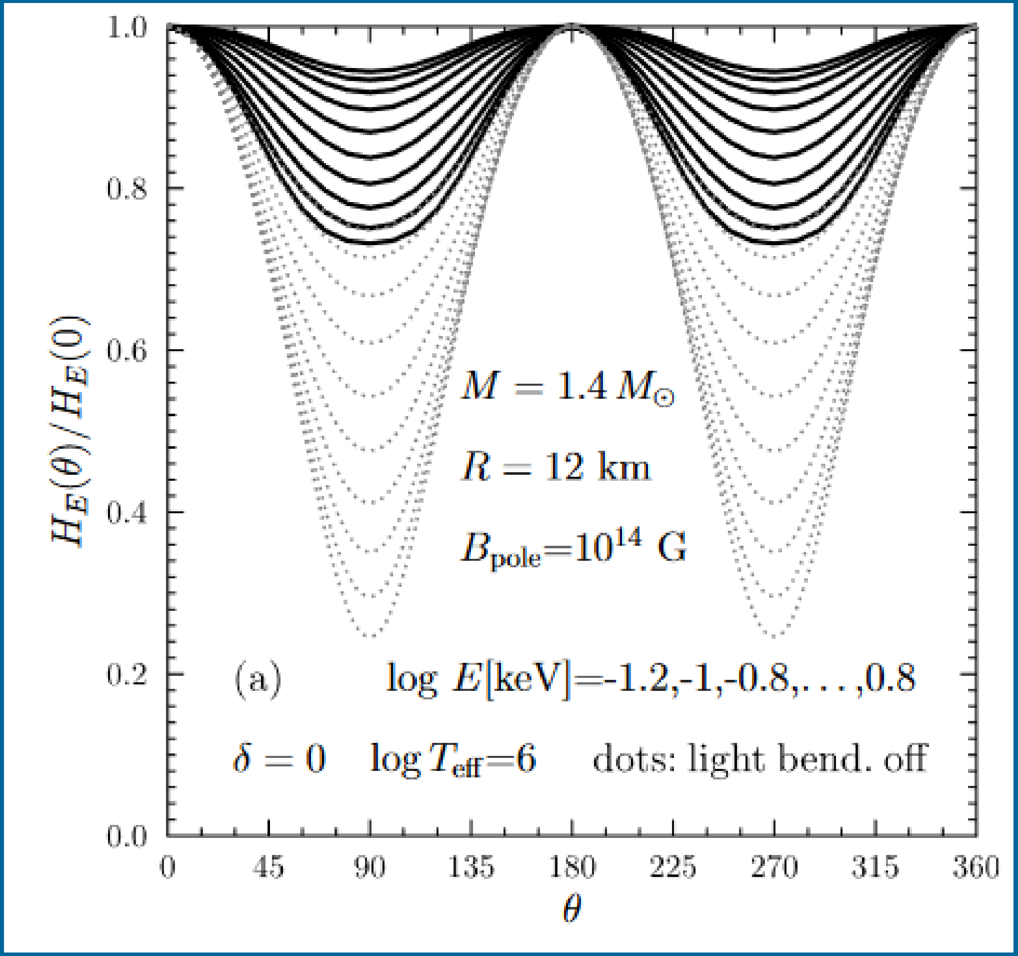


STEP 4
Predict lightcurve and phase-resolved spectrum
Compare with observations



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.

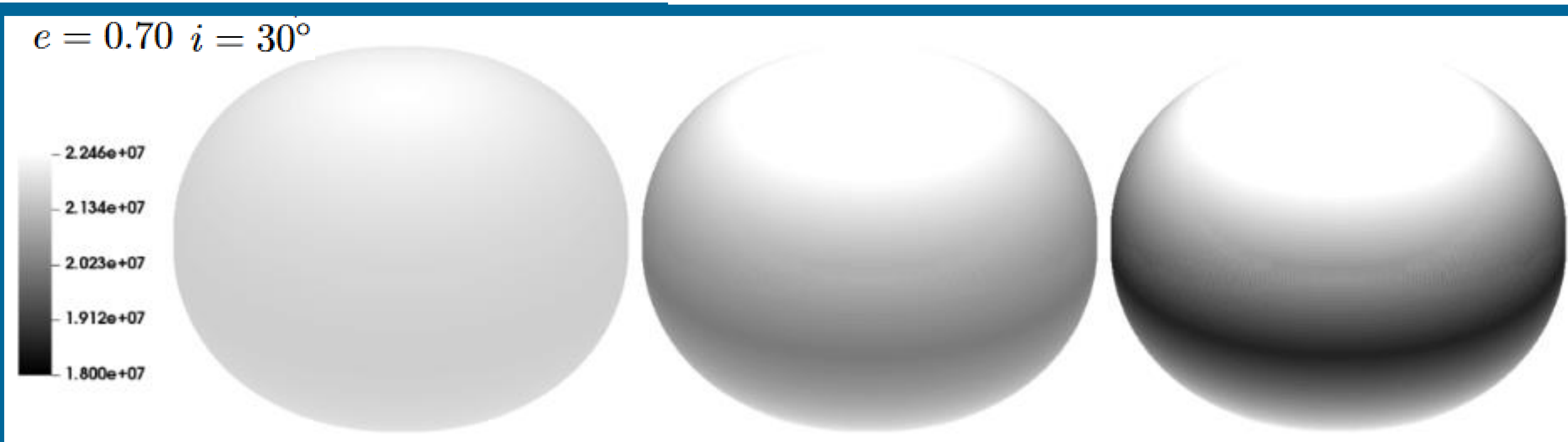
Composition of a heat blanket
does not influence significantly
the spectrum.

Gravitational darkening

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

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

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

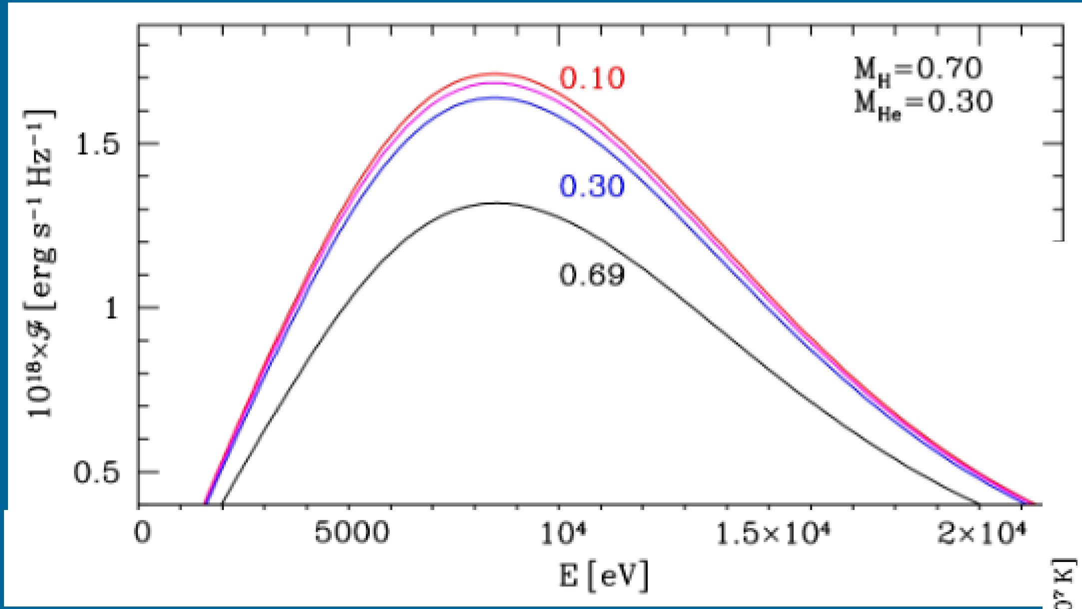


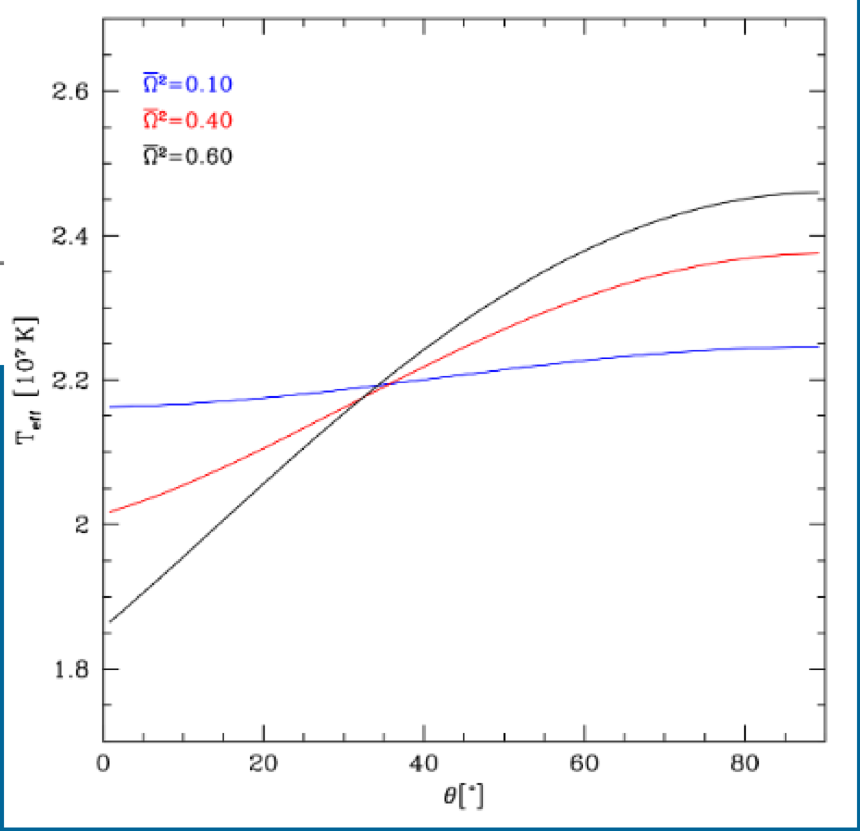
$\bar{\Omega}^2 = 0.10$ $\bar{\Omega}^2 = 0.40$ $\bar{\Omega}^2 = 0.60$

For undisturbed star: $T_{\rm eff} = 2.20 \times 10^7\,{\rm K}$ 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

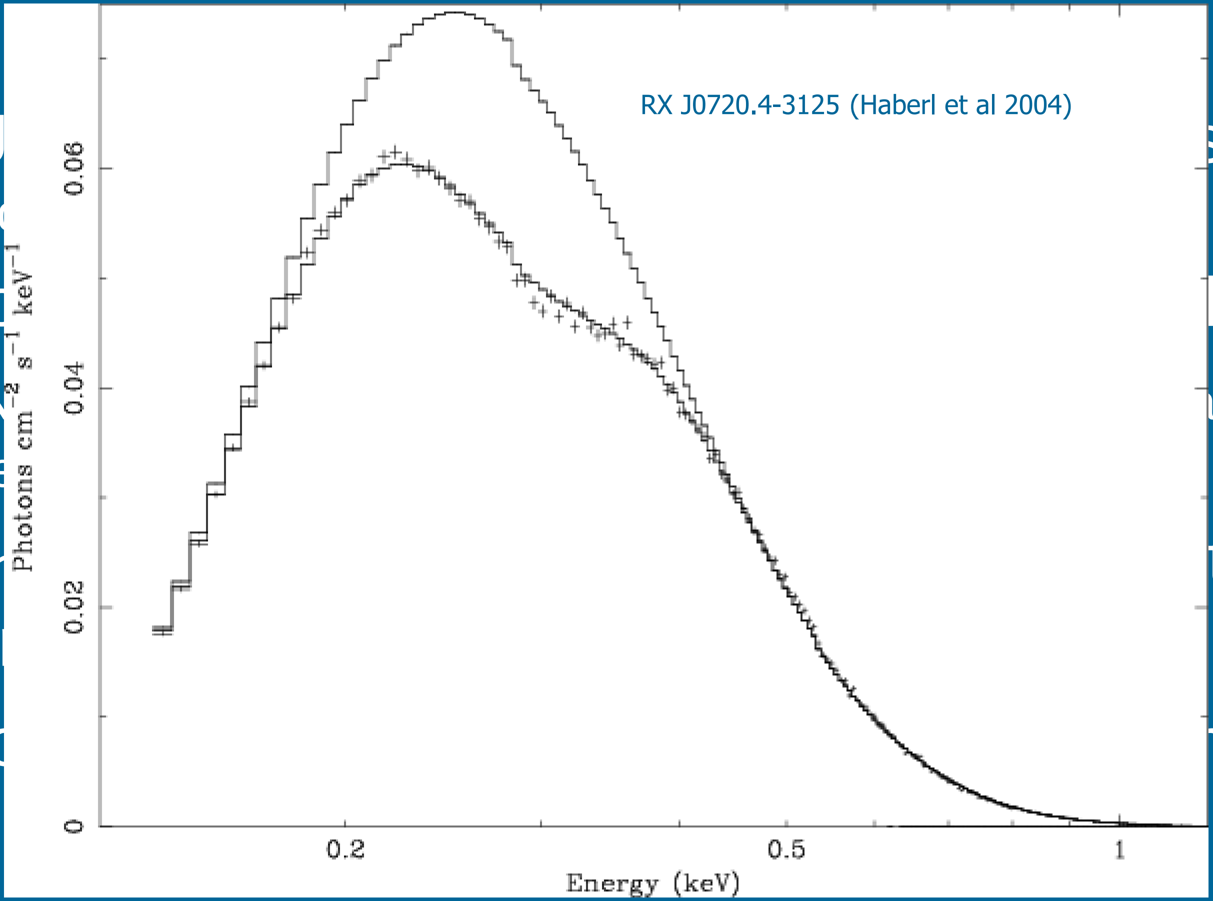
The Magnificent Seven

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

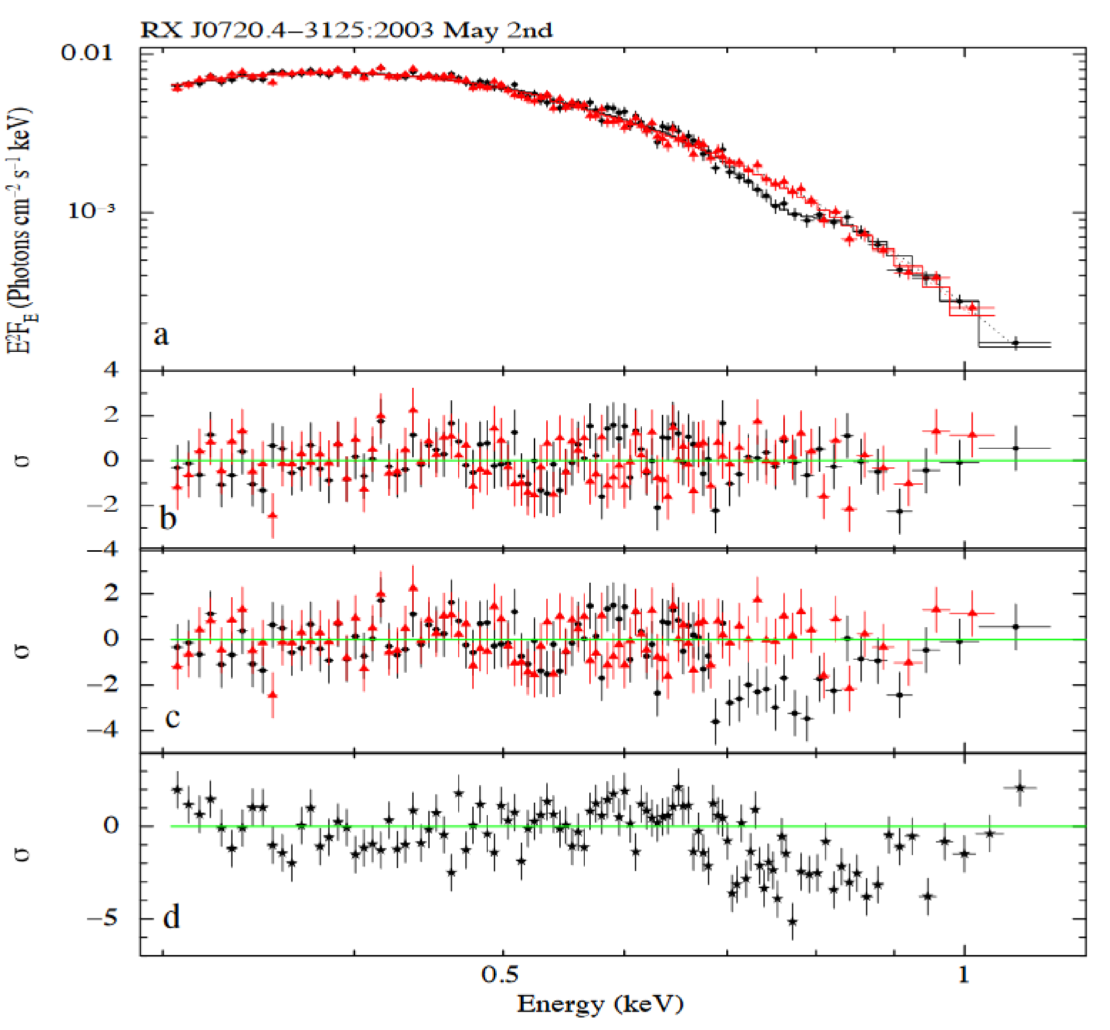
Featureless ? No Thanks !

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



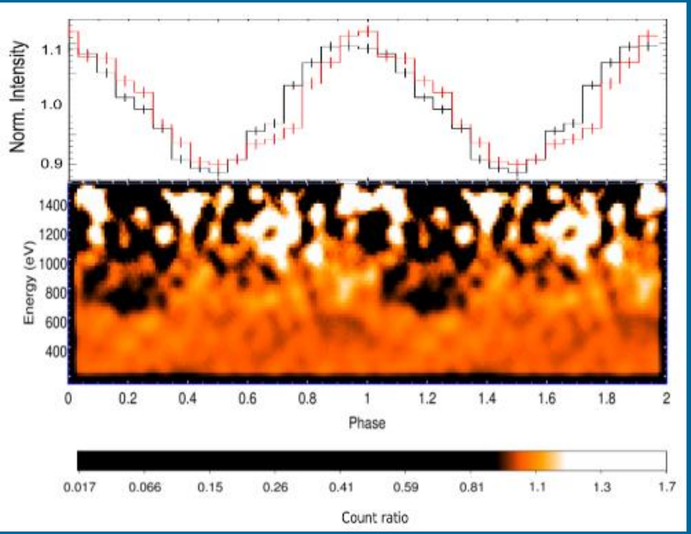
Source	Energy (eV)	EW (eV)	B_{line} (B_{sd}) (10^{13} G)	Notes
RX J1856.5-3754	no	no	?	-
RX J0720.4-3125	270	40	5 (2)	Variable line
RX J0806.4-4123	460	33	9	-
RX J0420.0-5022	330	43	7	-
RX J1308.6+2127	300	150	6 (3)	-
RX J1605.3+3249	450	36	9	-
1RXS J214303.7+065419	700	50	14	-

Phase variable spectral feature



RX J0720.4−3125

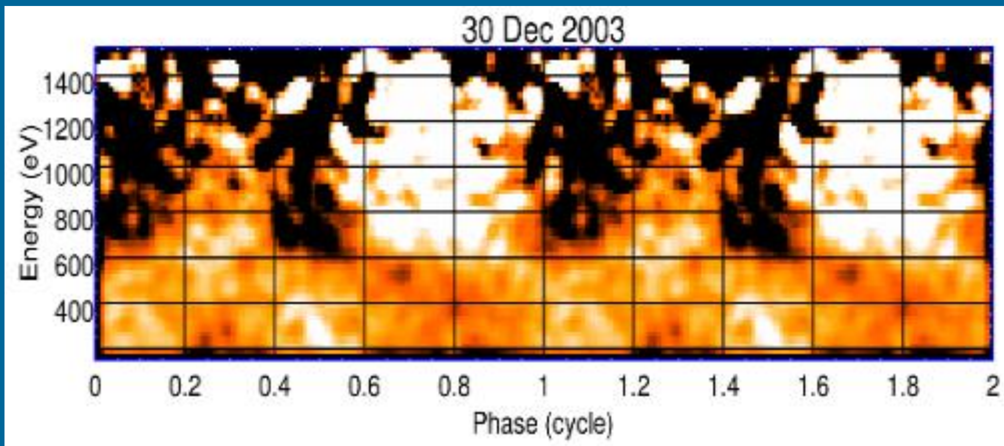
Black: phase 0.1-0.3
red: phase 0.5-0.7

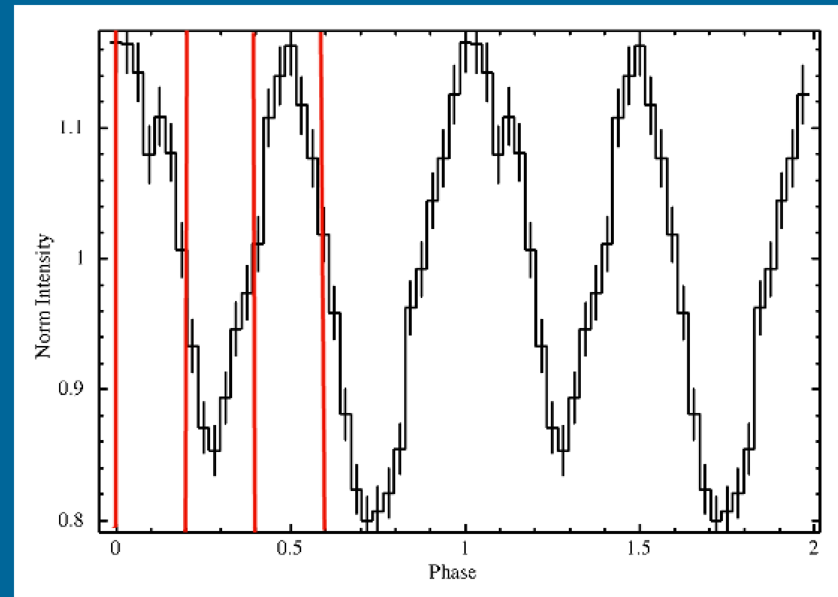


1506.04206

More phase-dependent features in M7

RX J1308.6+2127



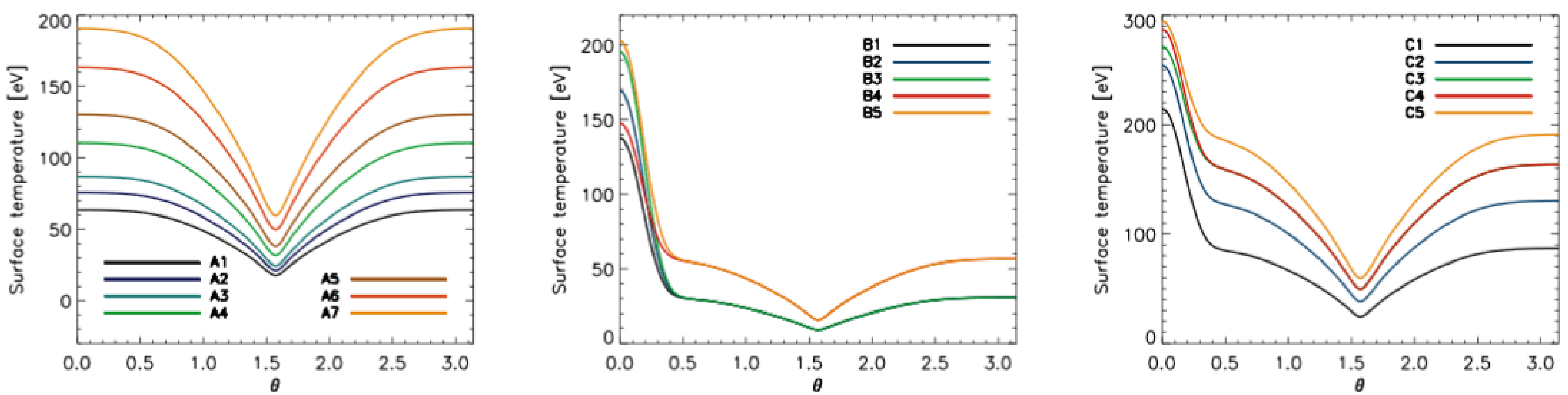


Parameter[a]	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1
			BB+GAUSS		
kT_{BB} (eV)	$77.7^{+1.8}_{-2.0}$	$75.4^{+2.2}_{-2.5}$	$84.9^{+1.3}_{-1.4}$	$75.6^{+2.1}_{-2.7}$	$84.9^{+1.8}_{-2.0}$
R_{BB} (km)	4.3±0.5	5.6±1.0	2.6±0.1	5.8±1.1	3.4±0.3
Flux[b]	$3.34^{+0.04}_{-0.09}$	$3.67^{+0.15}_{-0.09}$	$3.10^{+0.05}_{-0.07}$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

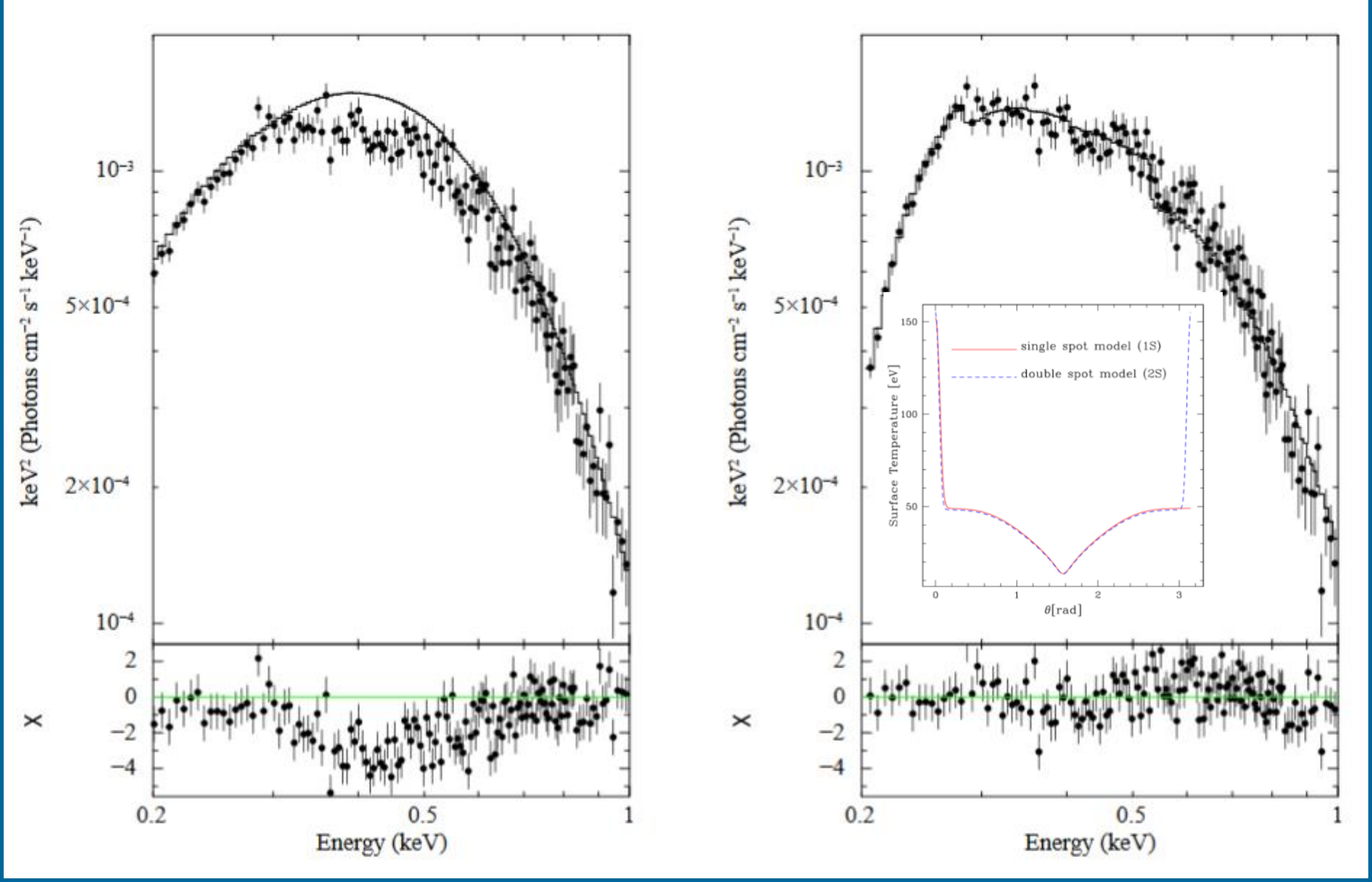


1406.0874

RX J0806.4-4123

BB+line

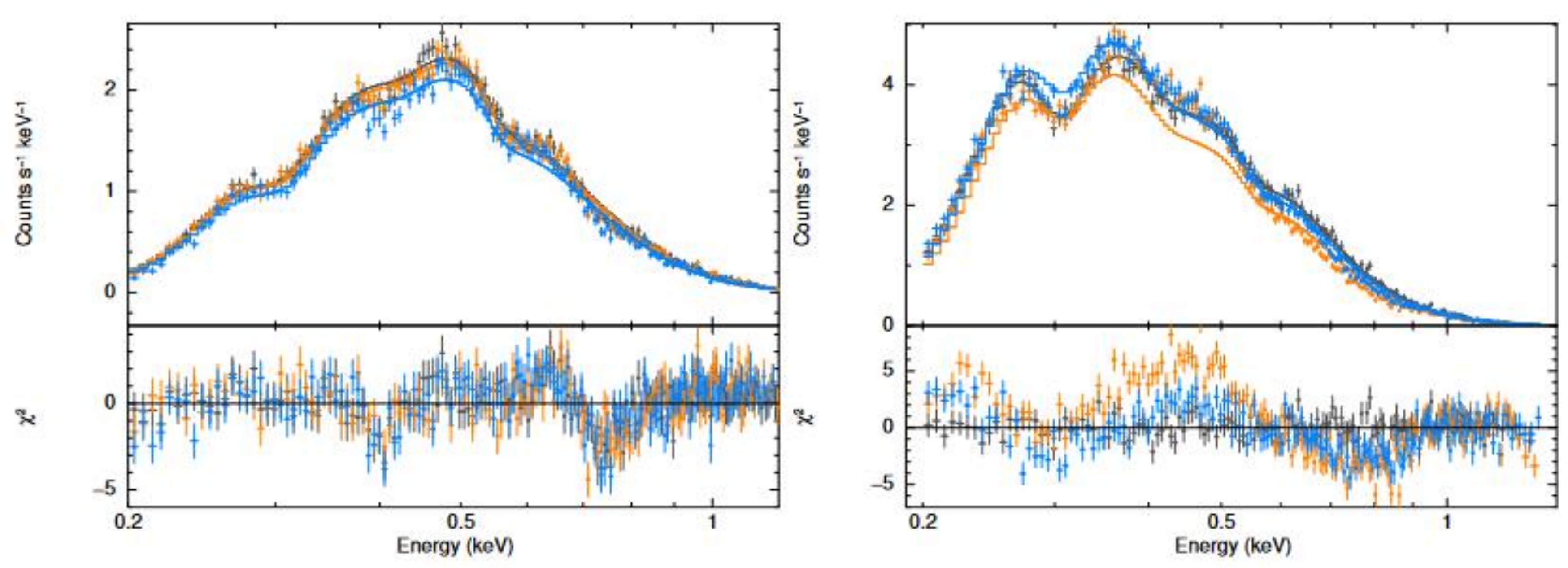
Non-uniform distrubution



1406.0874

eROSITA data

RX J2143.0+0654 RX J1605.3+3249



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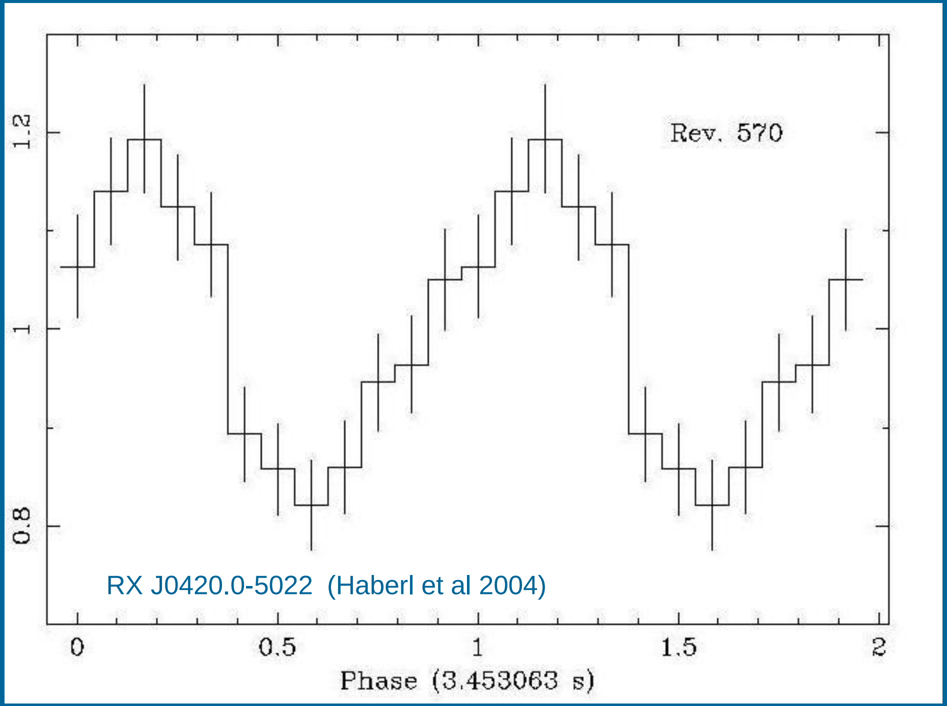
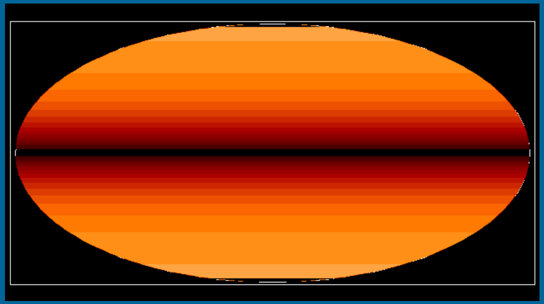
Pulsating ICoNS - I



- 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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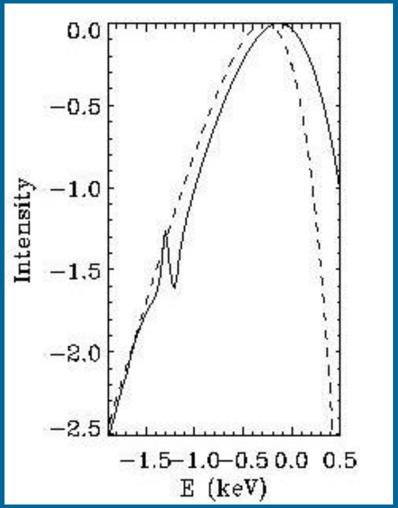

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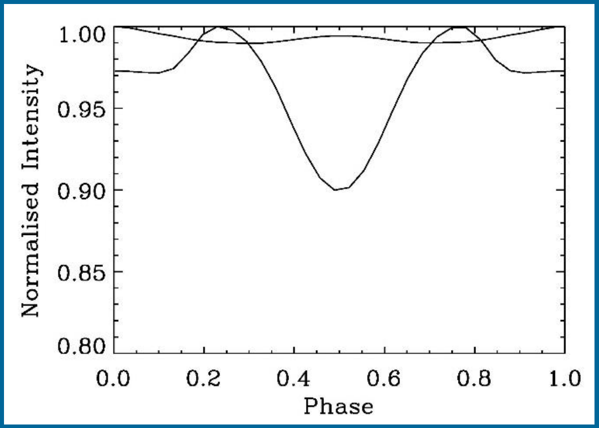
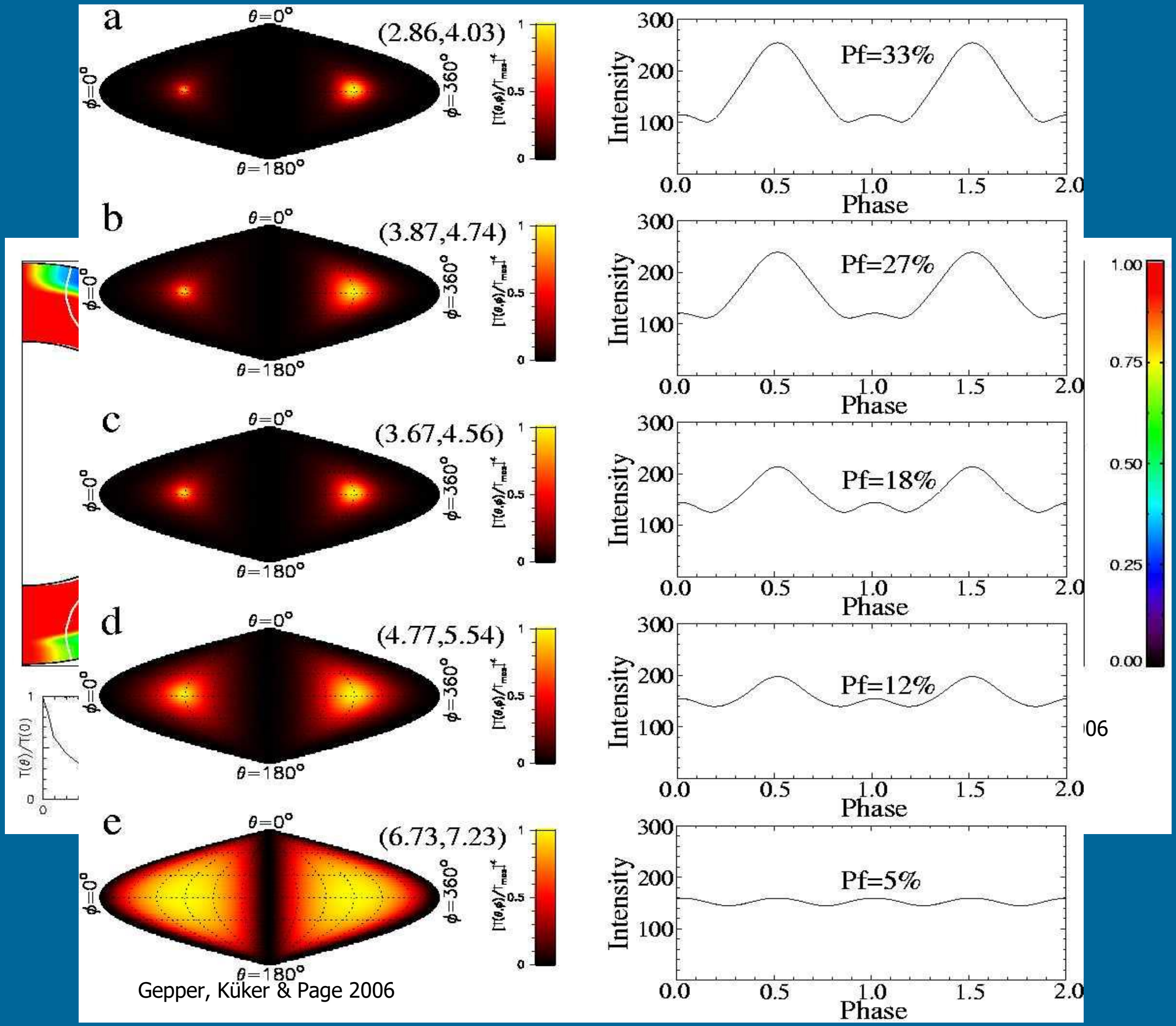
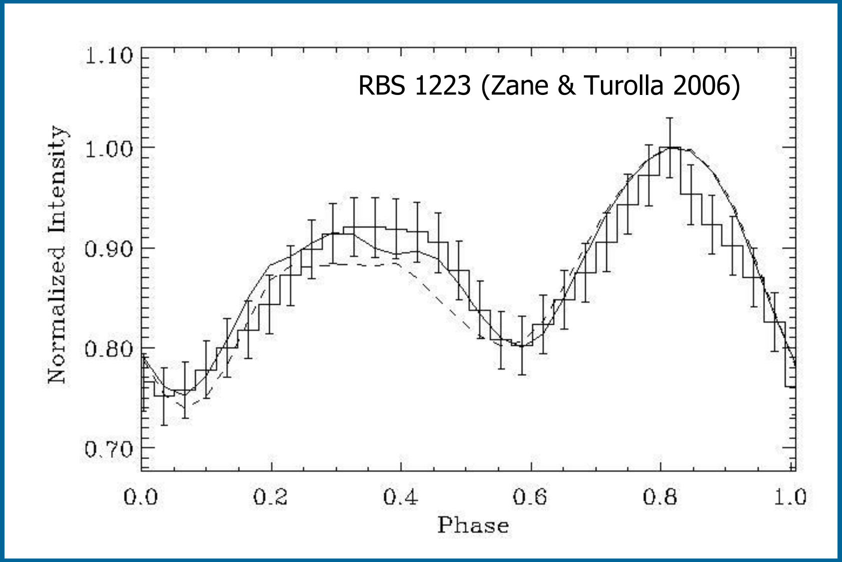


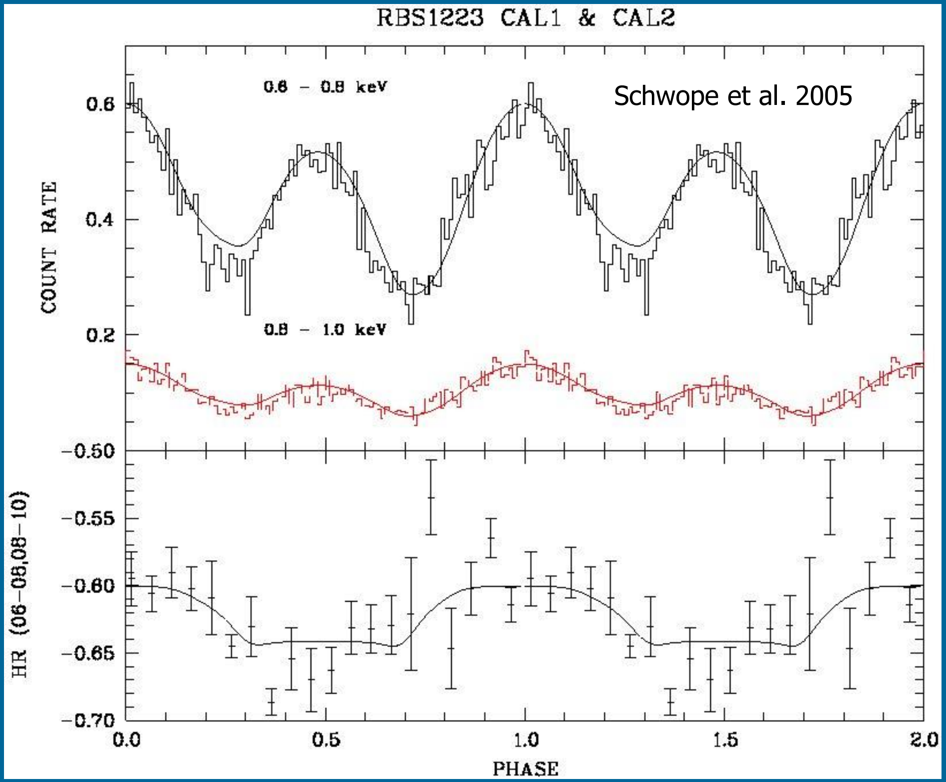
Crustal Magnetic Fields

- 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



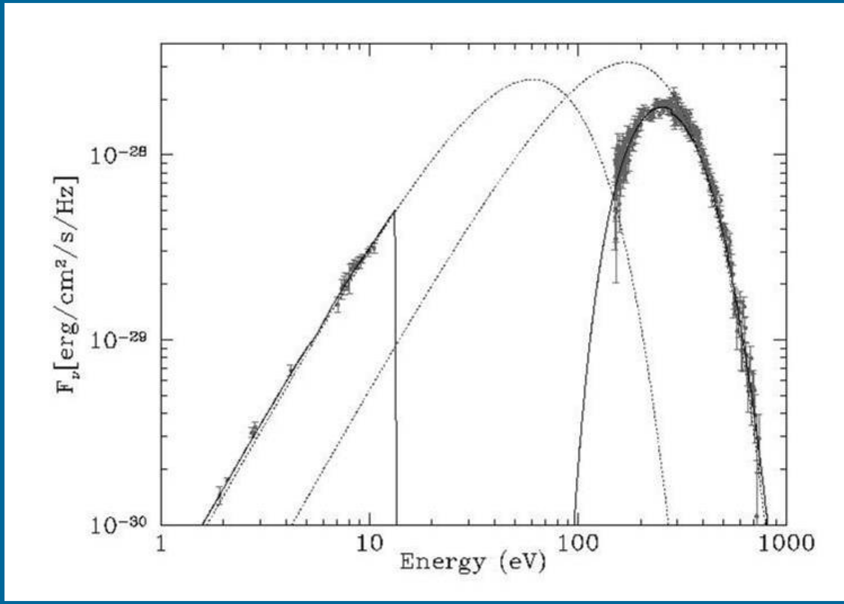


Indications for non-antipodal caps (Schwope et al 2005)

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

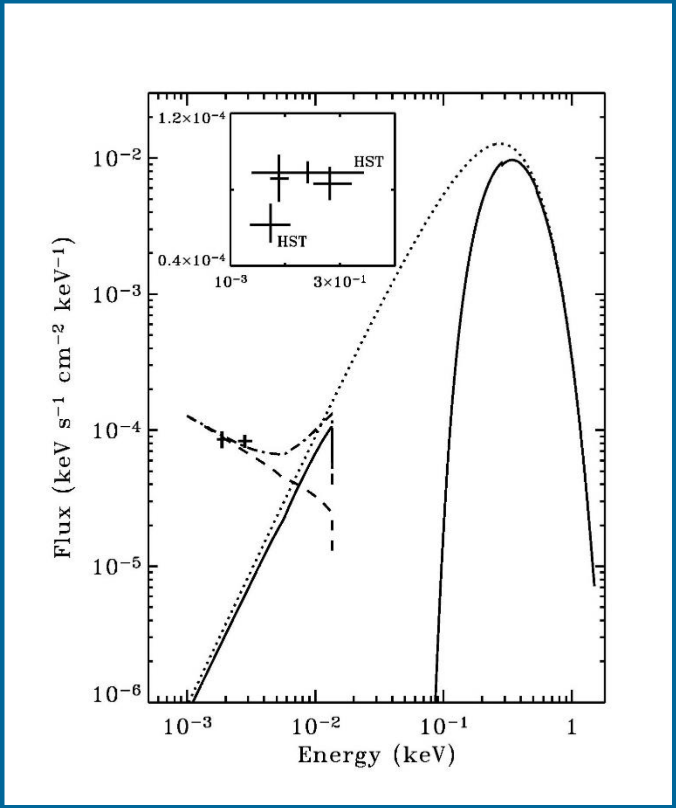
RX J1856.5-3754 - II

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

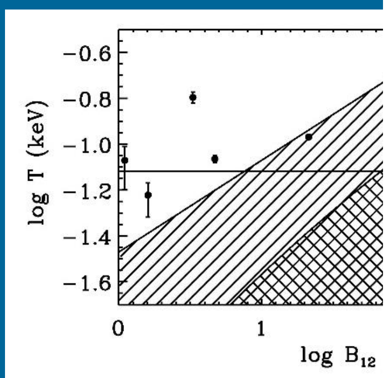


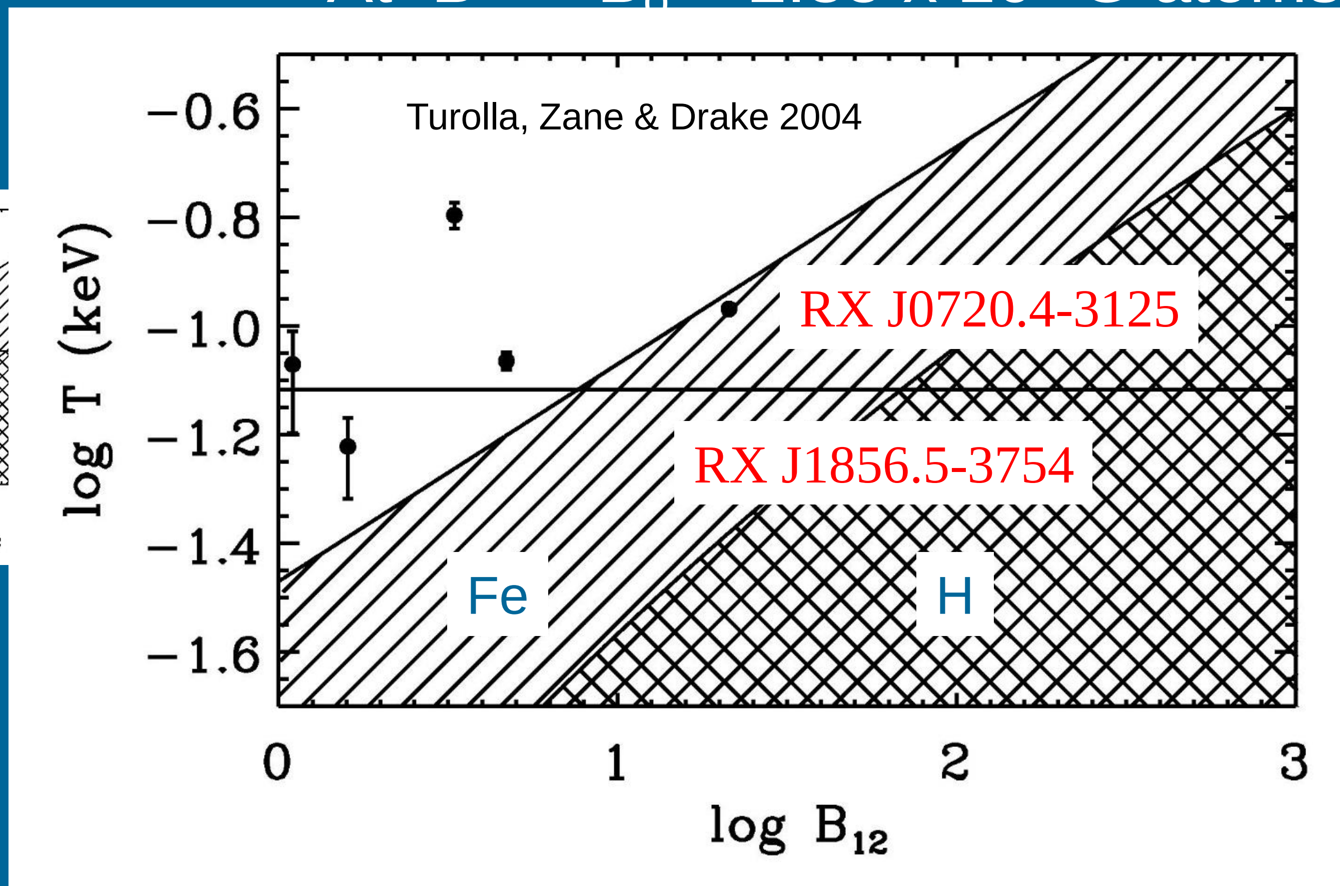
RX J1605 multiwavelength SED (Motch et al 2005)

- 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





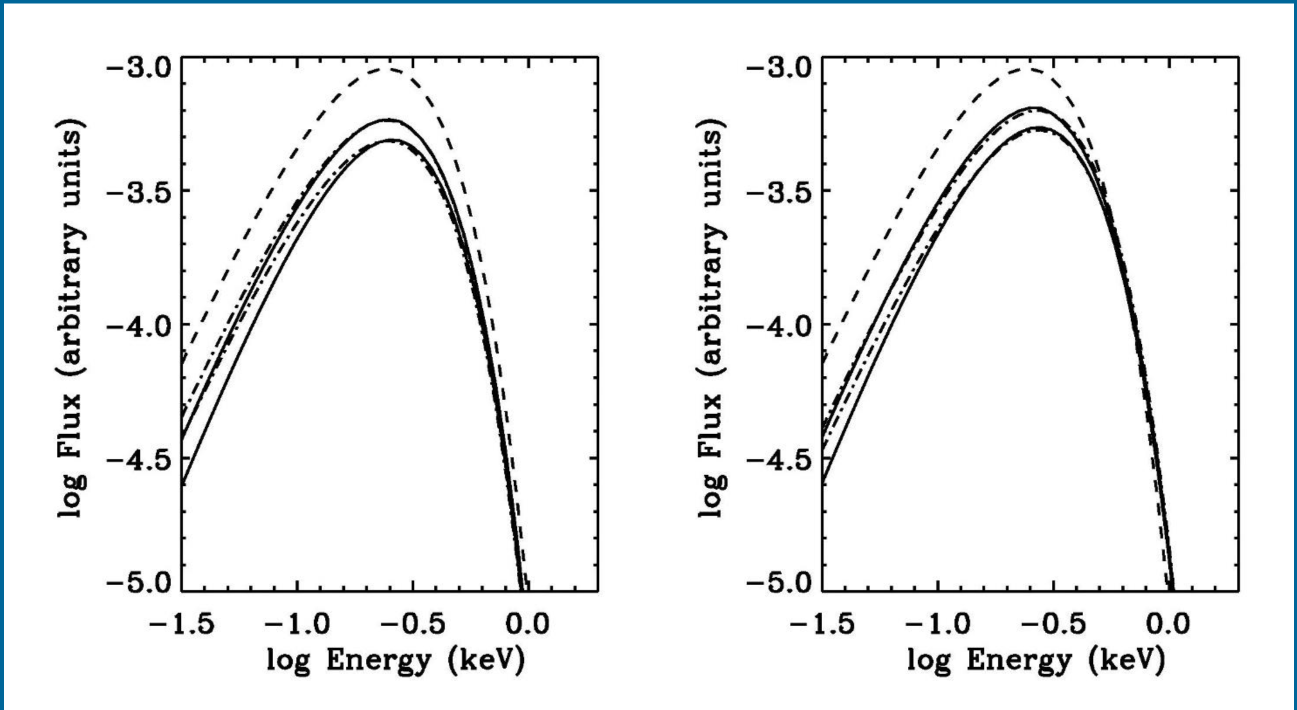
of a

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.

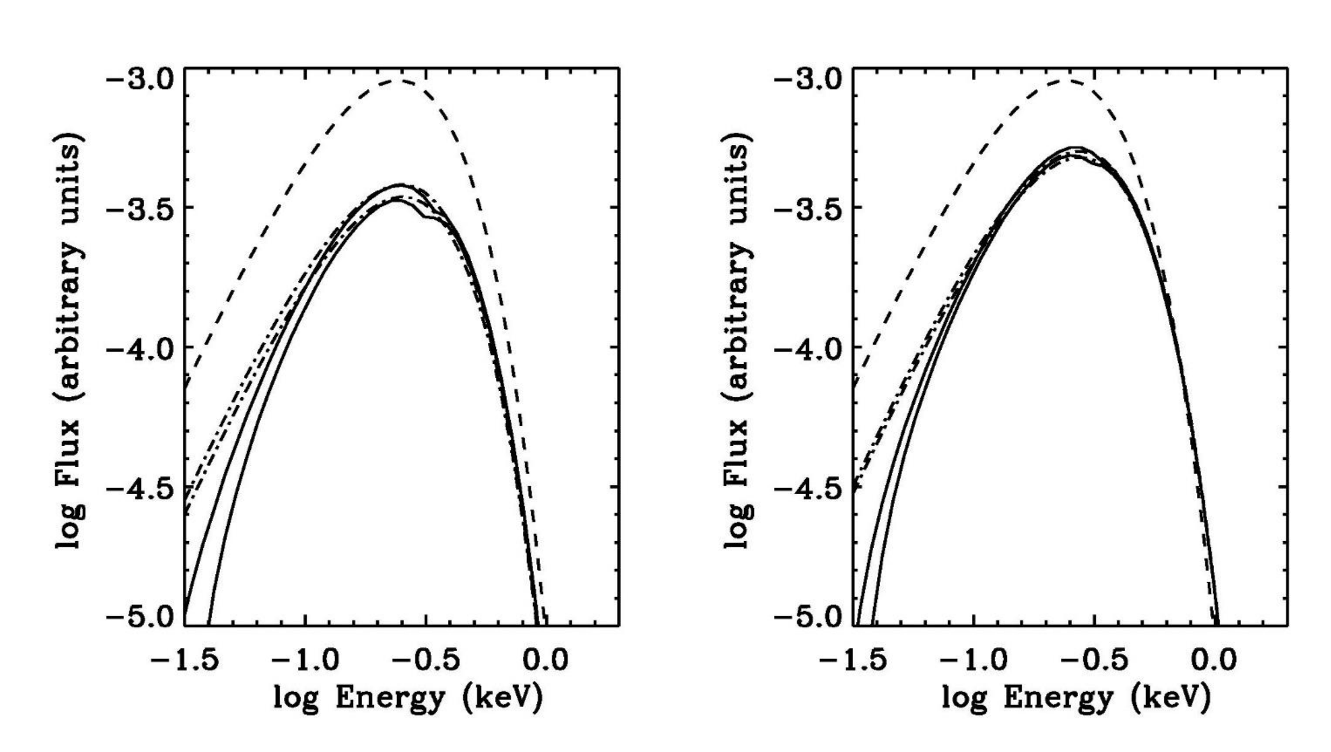


Turolla, Zane & Drake (2004)

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.

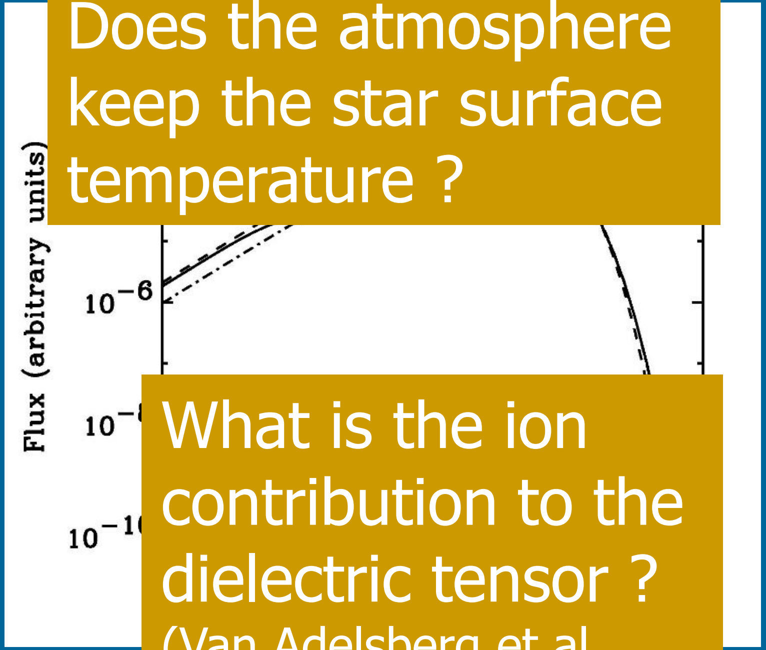


Turolla, Zane & Drake (2004)

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)
- Details of spectral shape (features, low-energy behaviour) still uncertain

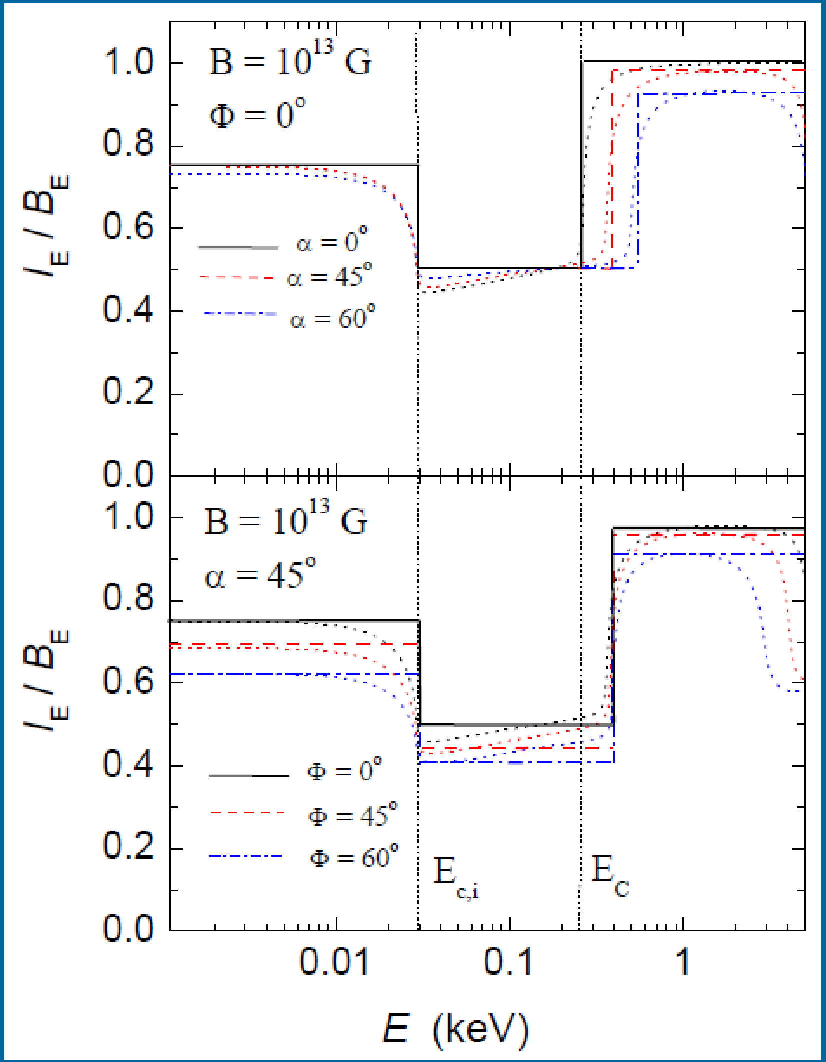
$$R_\infty = 4.25\, f_E^{-1/2} \left(\frac{D}{100\ \mathrm{pc}}\right)\left(\frac{T_{BB}}{60\ \mathrm{keV}}\right)^{-2}\ \mathrm{km}$$



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)

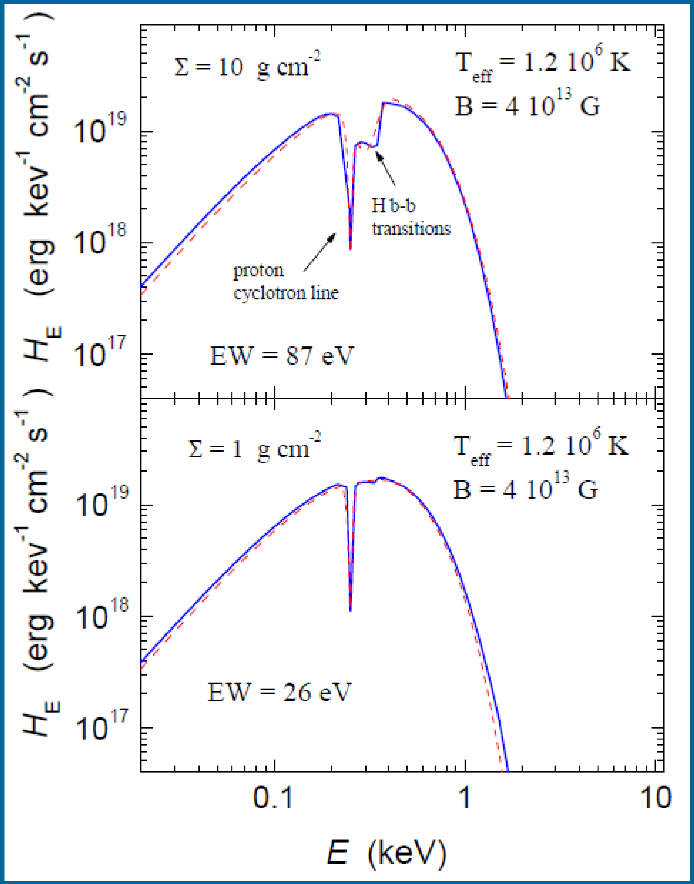
Condensed iron surface emissivity



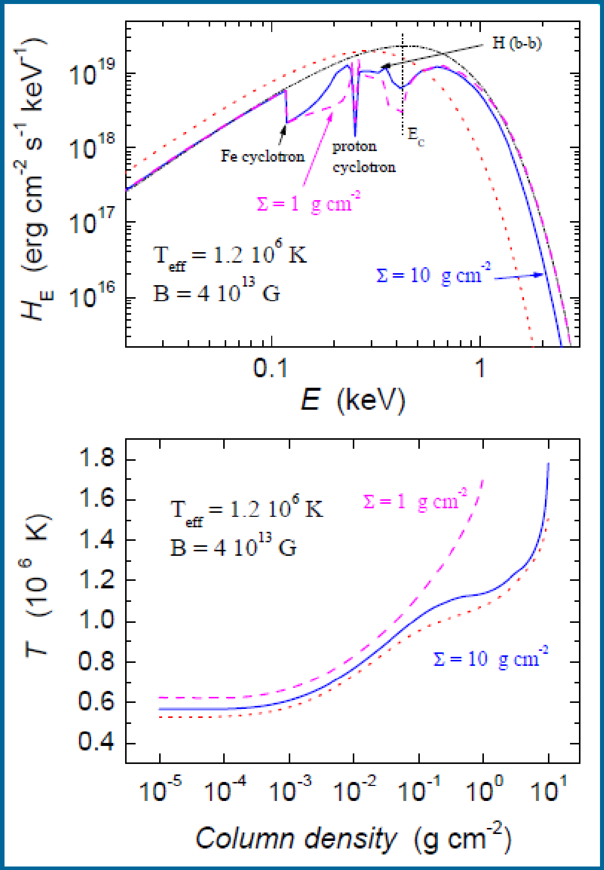
Free ions approximation.

1006.3292

Thin hydrogen magnetized atmosphere above blackbody and iron condensed surface



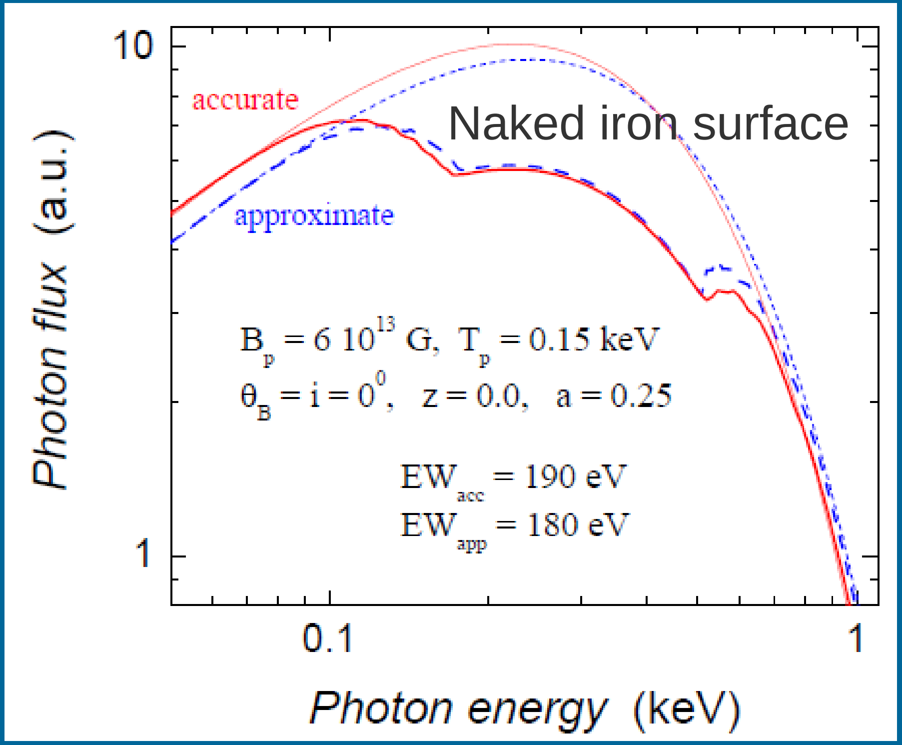
Below atmosphere was a blackbody spectrum

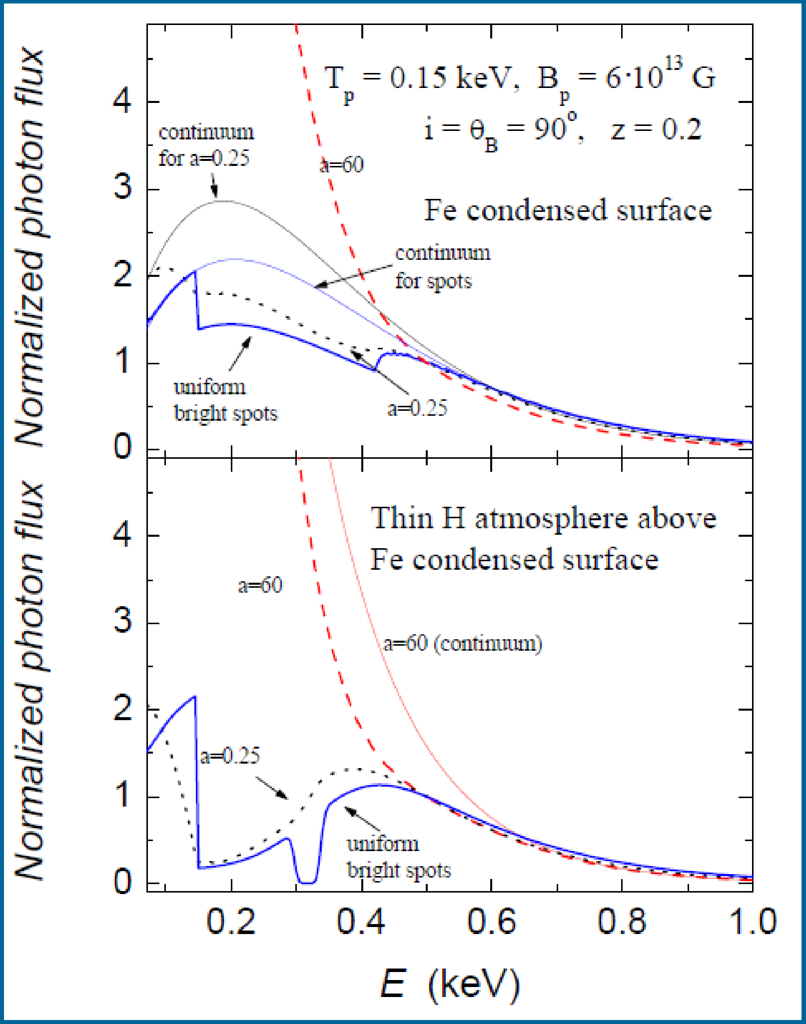


Below – iron condensed surface

1006.3292

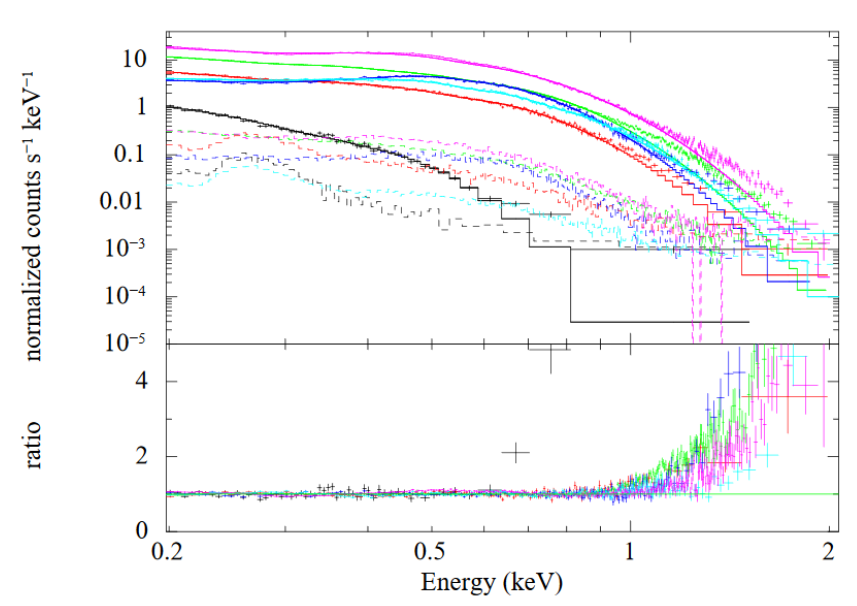
Let us make it realistic

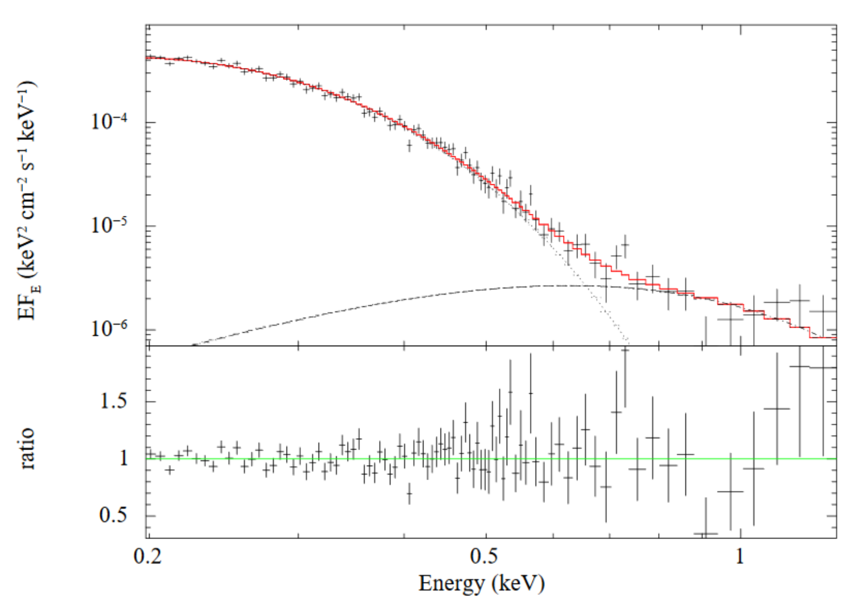




Excess at >1 keV?

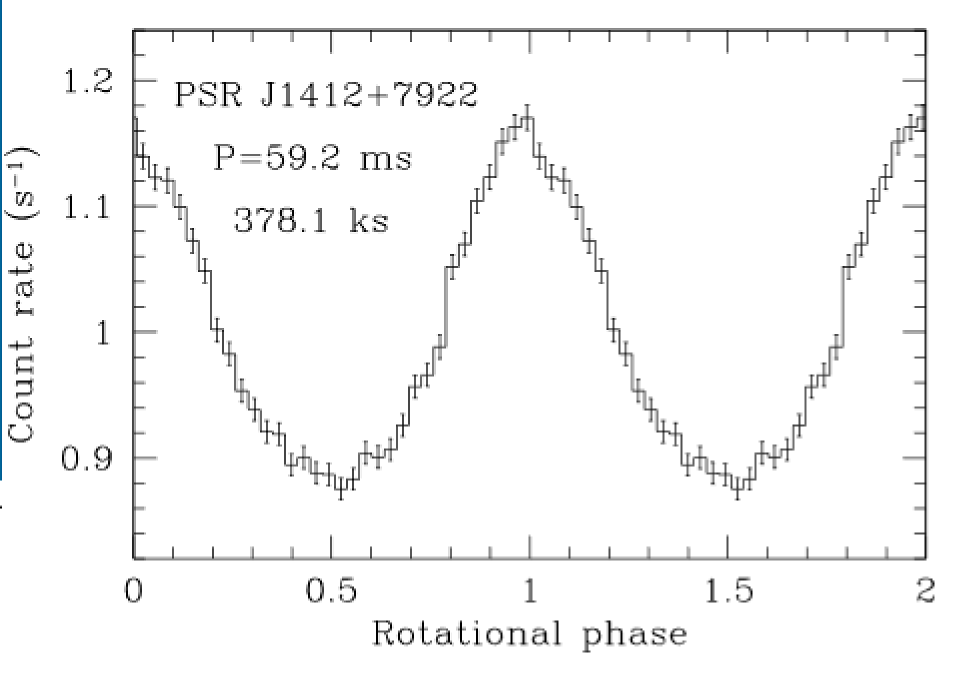
Analysis of spectra of M7 demonstrated a strange excess at energies > 1 keV. This is somehow similar to what magnetars demonstrate.

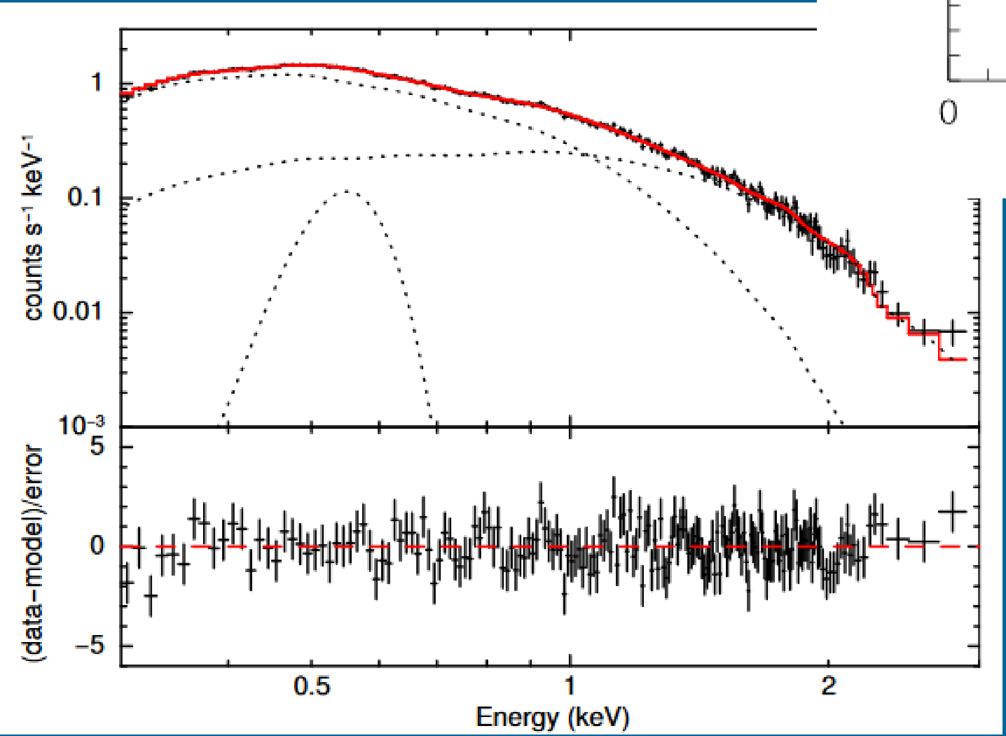




1811.11982

Calvera spectrum

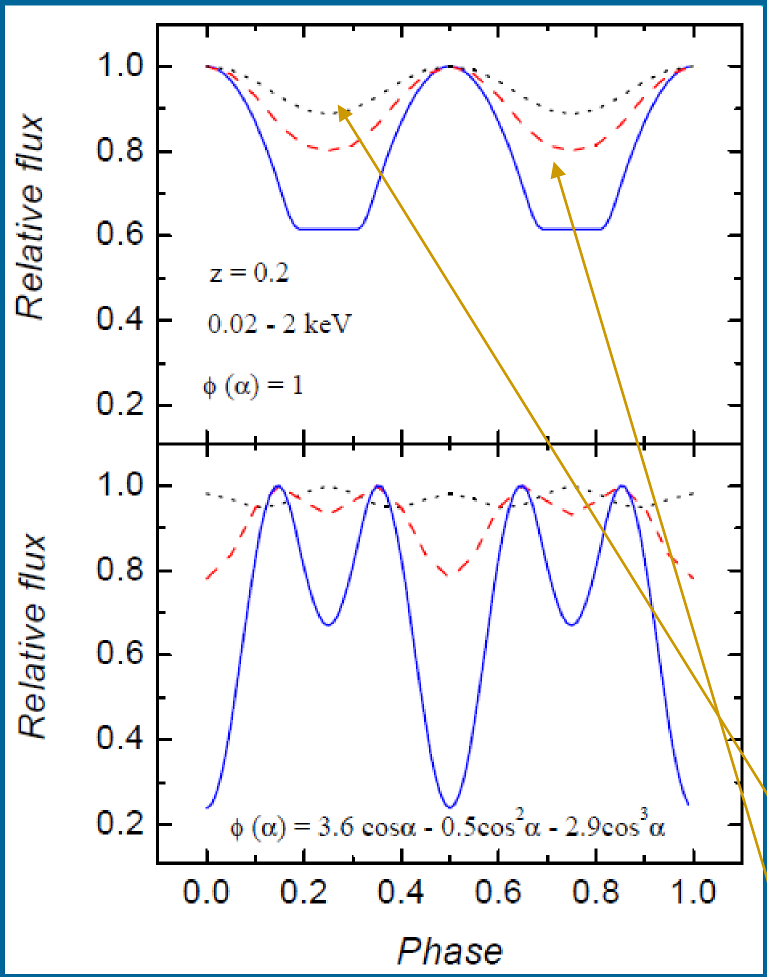


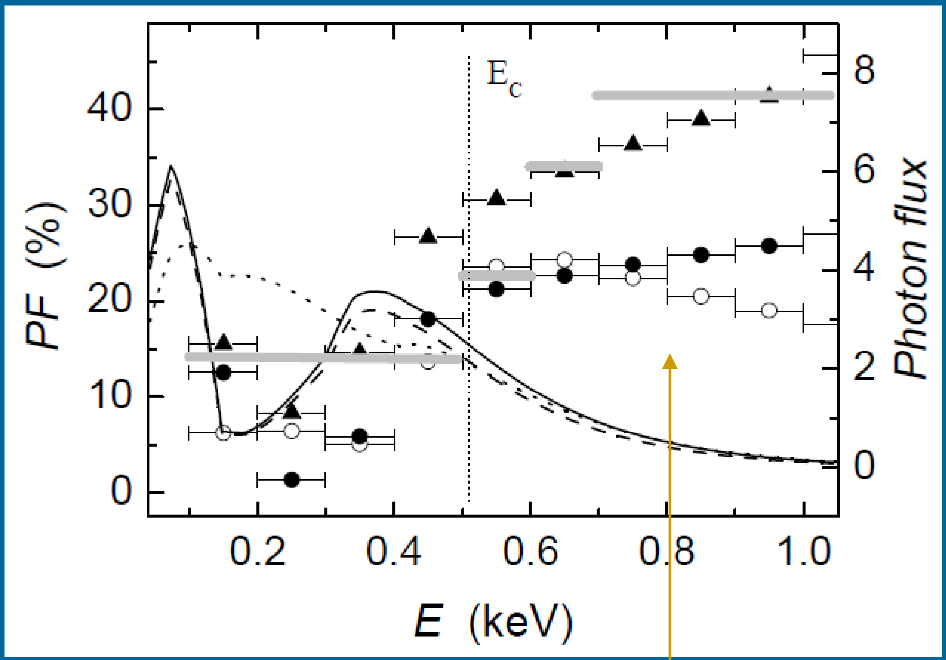


kT_1 (keV)	0.154 ± 0.004
R_1 (km) [b]	$2.21^{+0.08}_{-0.07}$
kT_2 (keV)	$0.319^{+0.013}_{-0.012}$
R_2 (km) [b]	0.37 ± 0.04

1902.00144

Light curves and pulsed fraction





1010.0125

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

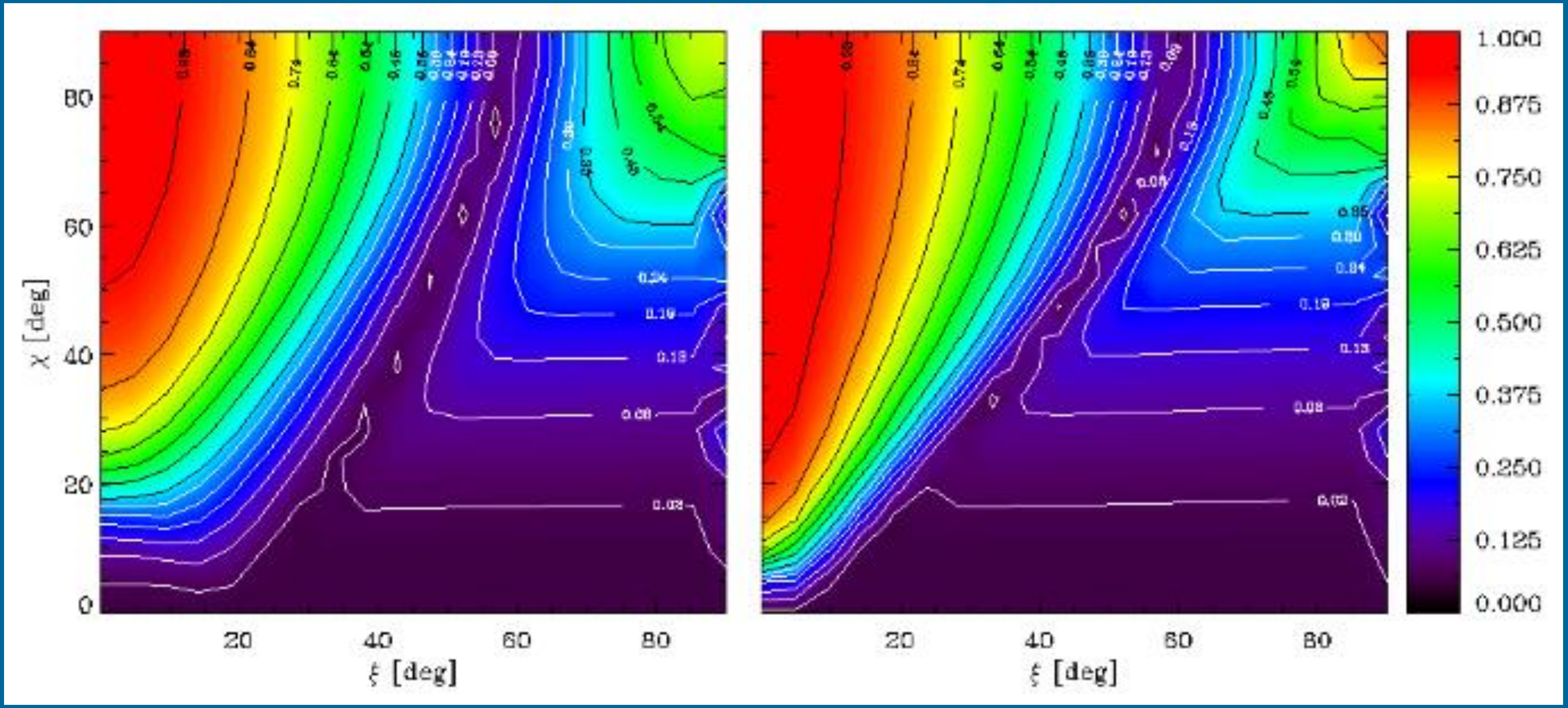
$$a_1 = a_2 = 0.25 \text{ (dotted curves)}$$

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

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)

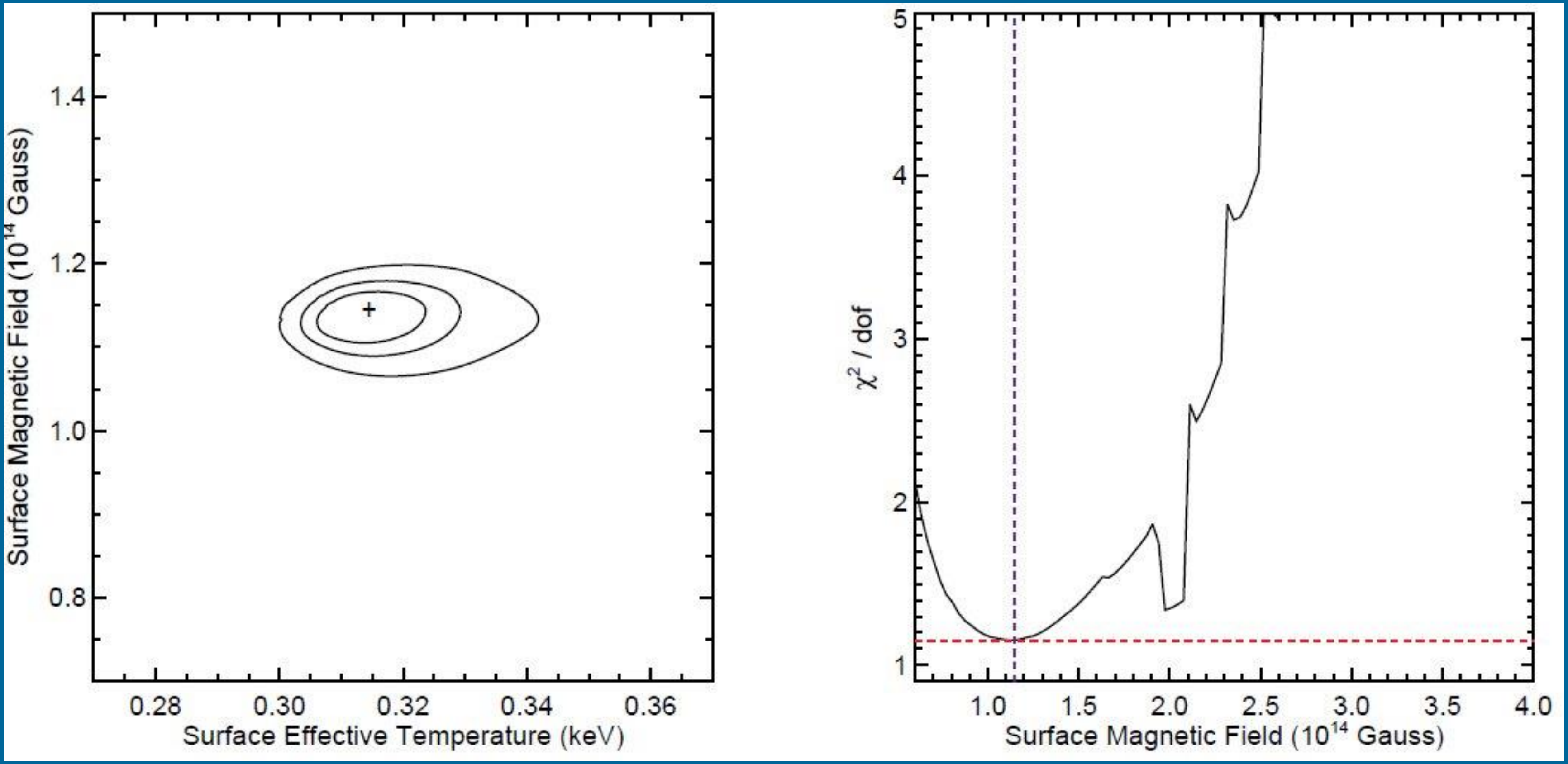


For RX J1856 polarization was detected in optics: 1610.08323.

1509.05023, see 2001.07663 about polarization in magnetars

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

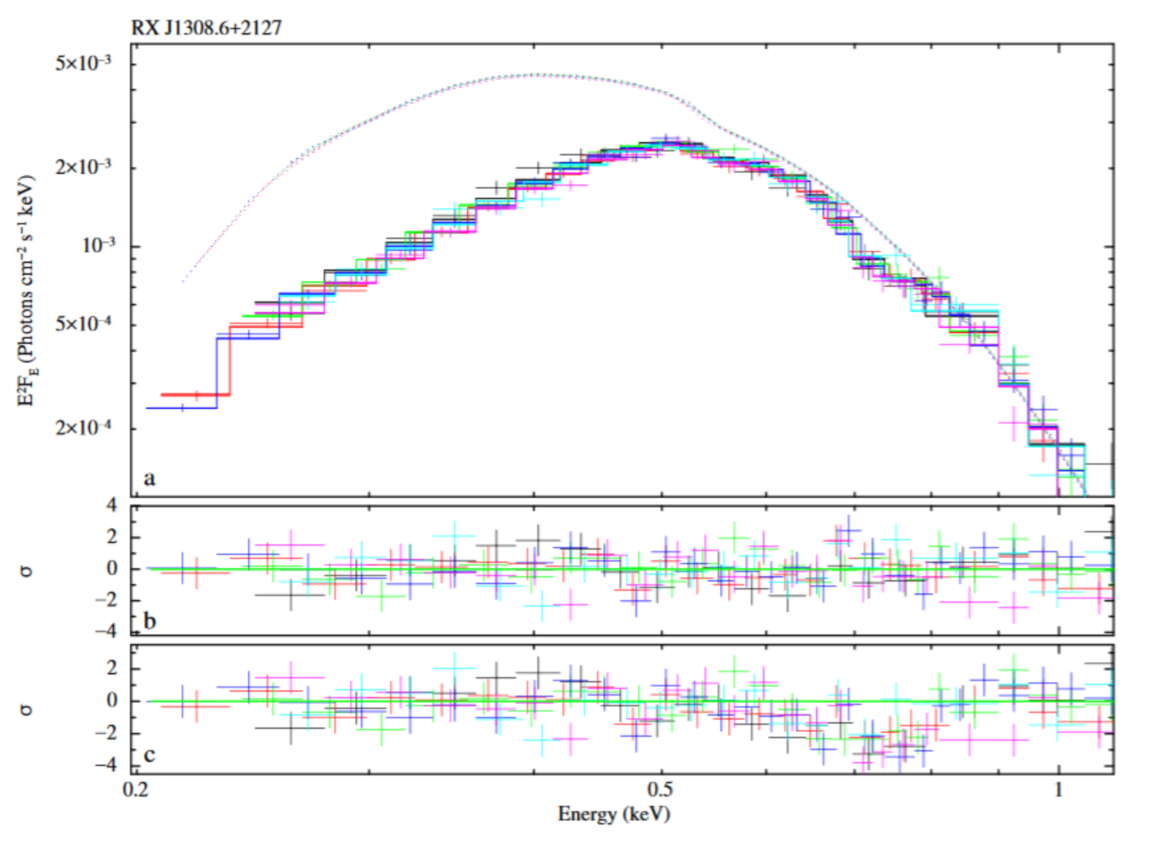
- Emission from cooling NSs is more complicated than a simple blackbody
- Light bending (gravity)
- Atmospheres
- Magnetic field distribution - effects on properties of atmospheres and emission
- Magnetic field (including toroidal) in the crust – non-uniform temp.distr.
- Condensate
- Rotation at ~msec 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
- arXiv: 1006.3292 } Recent calculations of spectra from magnetized atmos.
- arXiv: 1210.0916 – review
- arXiv: 1409.7666 – review
- arXiv: 1403.0074 УФН (2014) А. Потехин – обзор

Phase-resolved spectra and features

RX J1308.6+2127
A feature at the energy of ~ 740 eV
and an equivalent width of ~15 eV



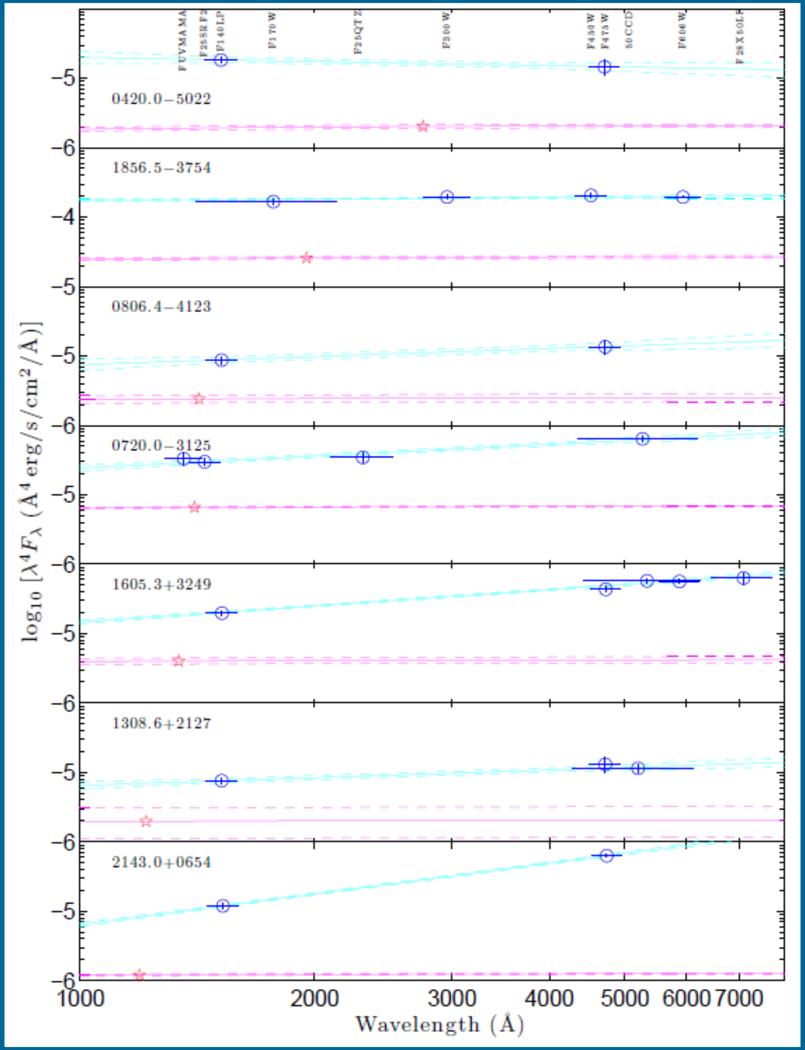
1703.05336

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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