Surface emission of neutron stars

NS Radii

- A NS with homogeneous surface temperature and local blackbody emission

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

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

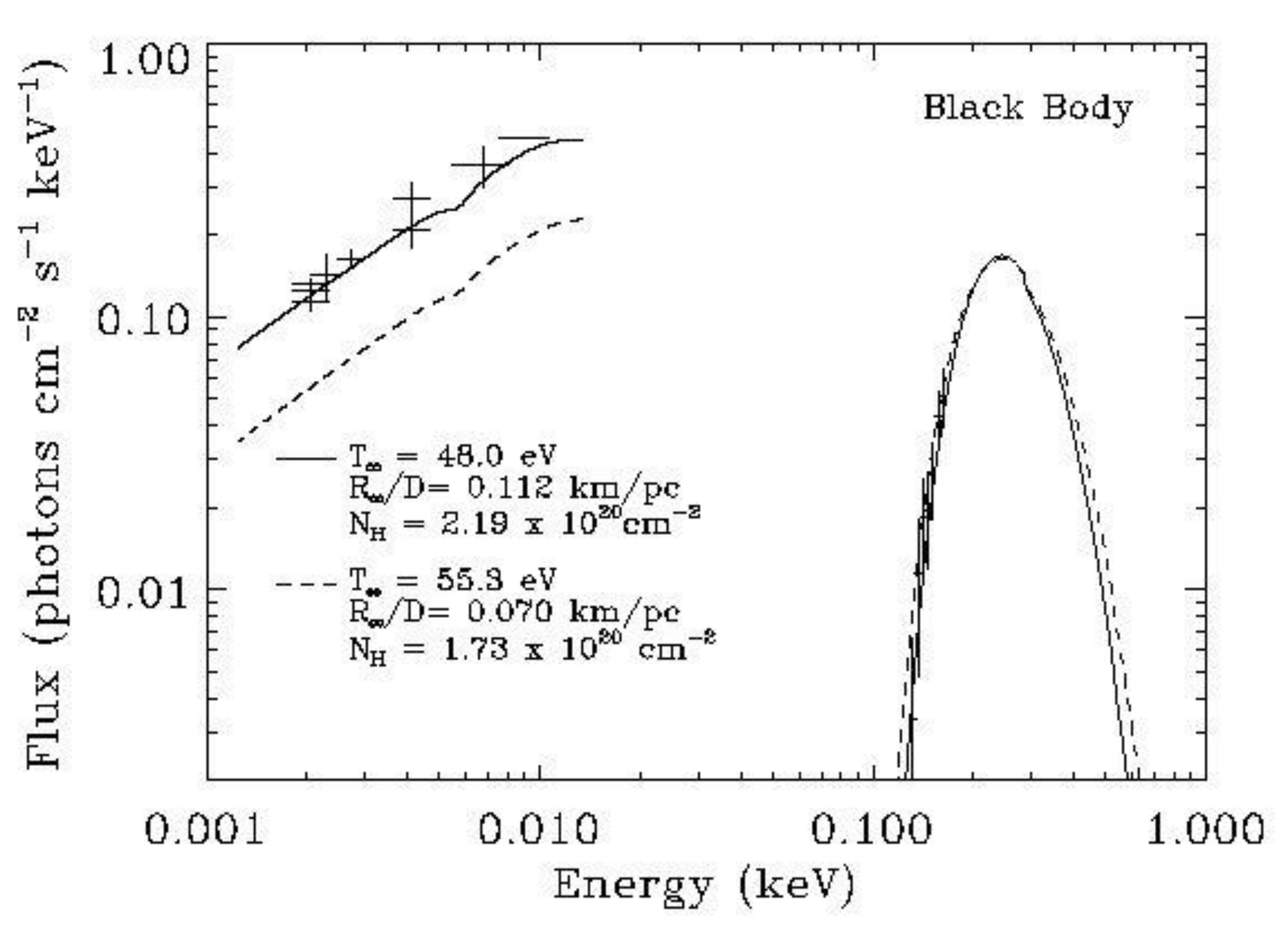
From dispersion measure

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

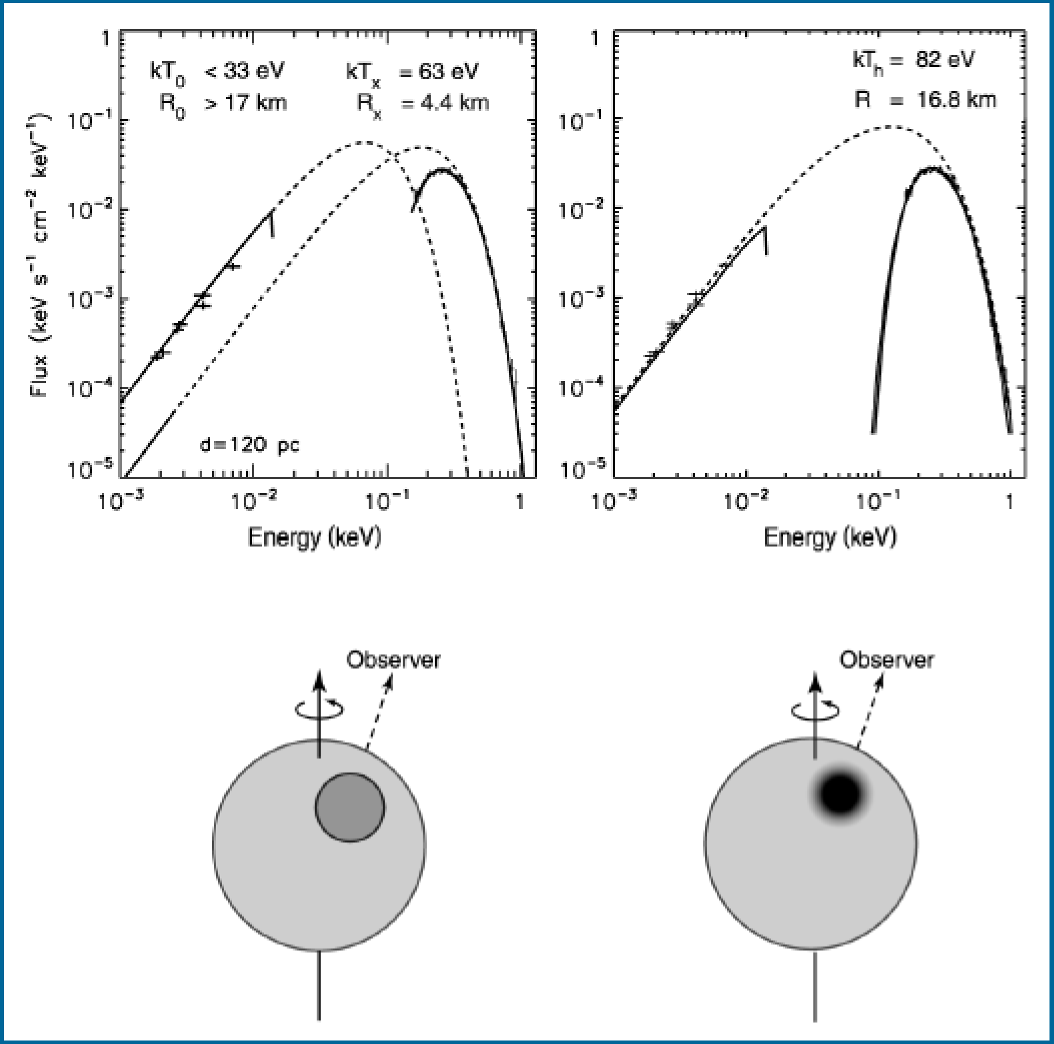
Uncertainties in temperature



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

(Pons et al. astro-ph/0107404)

Non-uniform temperature distribution



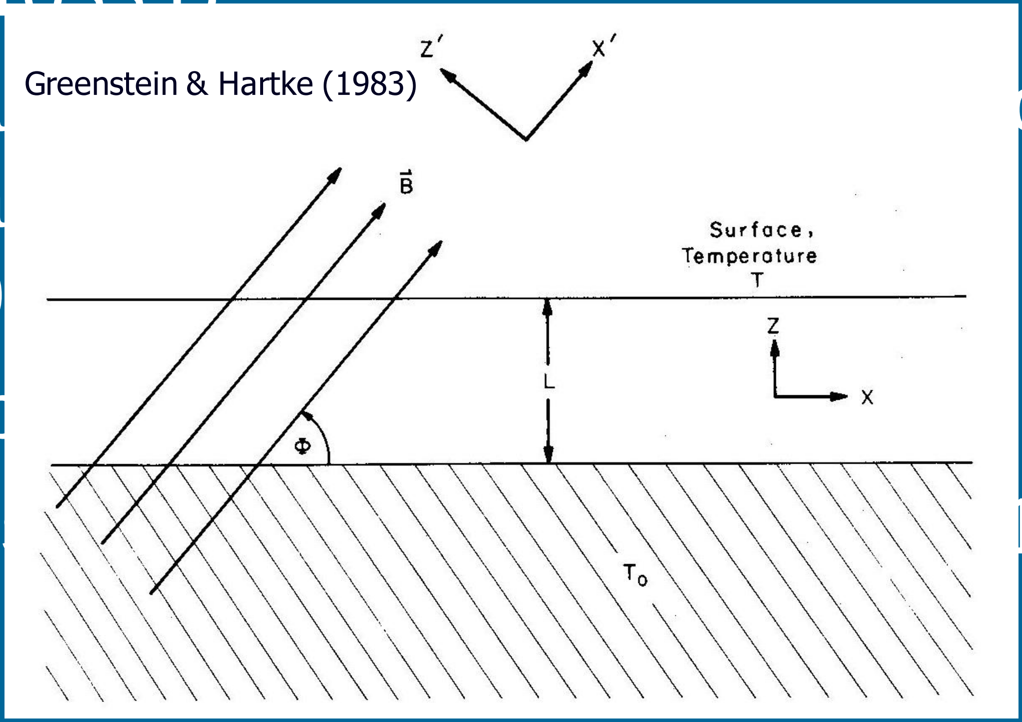
In the case of RX J1856 because of significant (~6) optical excess it was proposed that there is a spot, or there is a continuous temperature gradient.

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 ρ >> 10…
- Envelop… …,

B ~ con… …1D



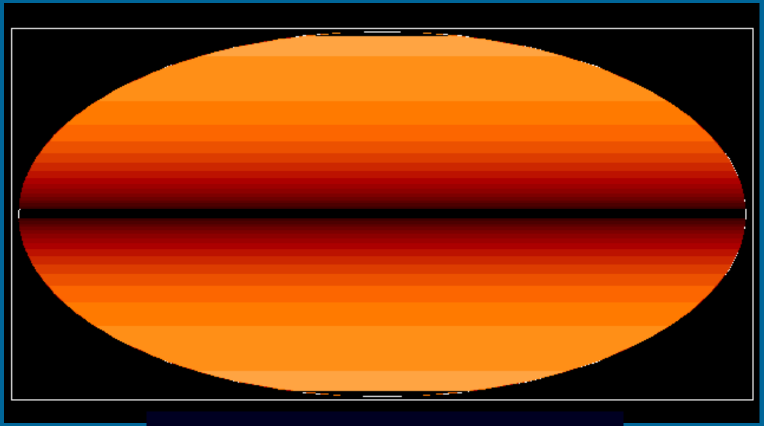
$$T_S = \left[\cos^2\Theta + \left(K_{perp}/K_{par}\right)\sin^2\Theta\right]^{1/4} T_{pole}$$

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

K - conductivity

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

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



Core centered dipole

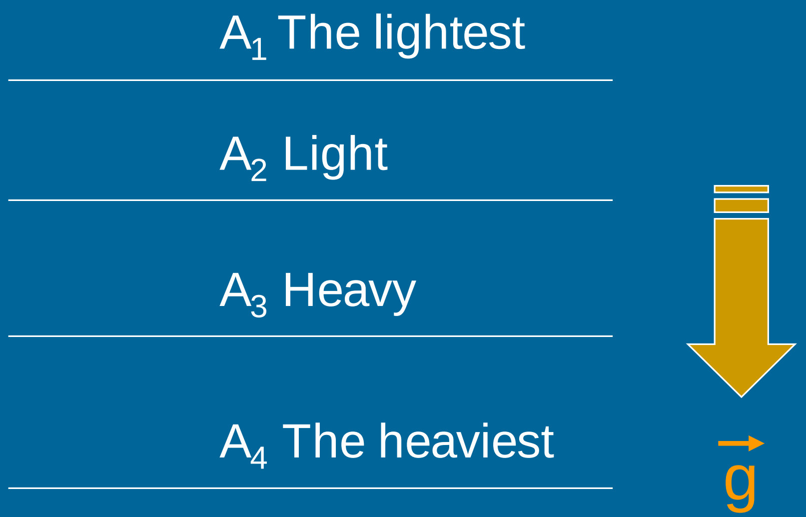
Core centered quadrupole

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}~kT/mg)
- Spectra depend on g, chemical composition and magnetic field
- Plane-parallel approximation (locally)

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.

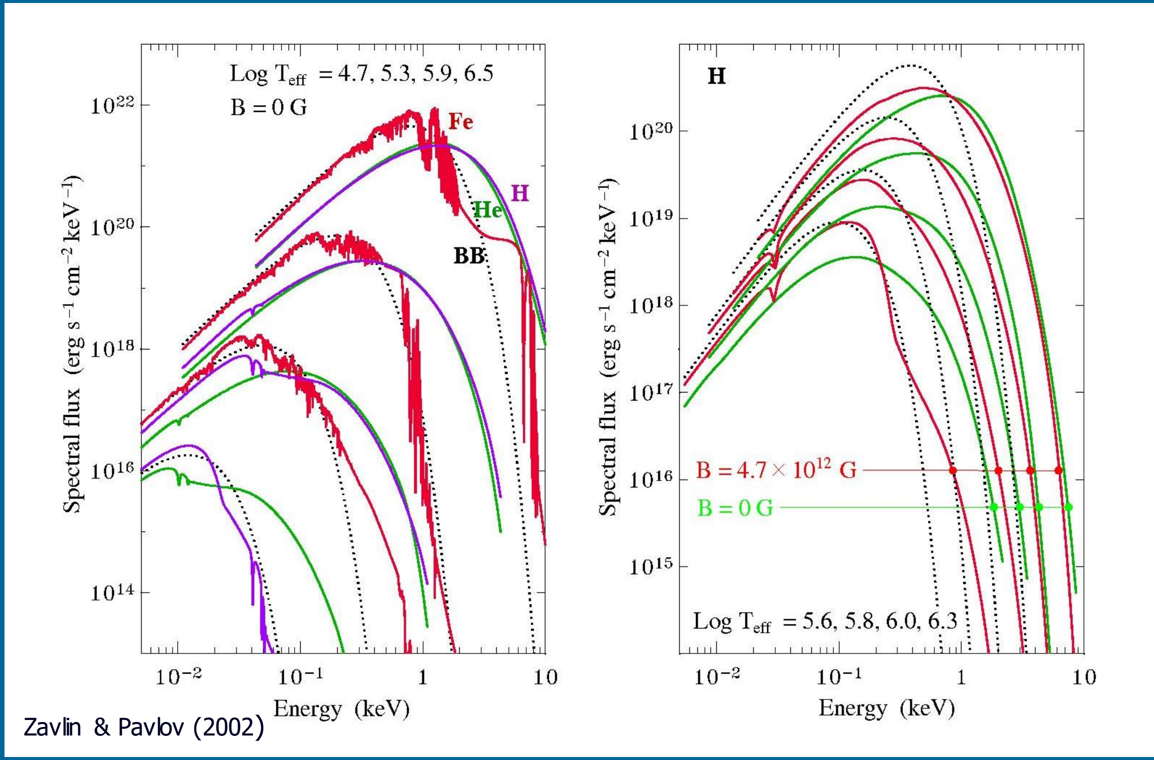
10^{-20} solar mass of hydrogen is enough to form a hydrogen atmosphere.

See astro-ph/ 0702426

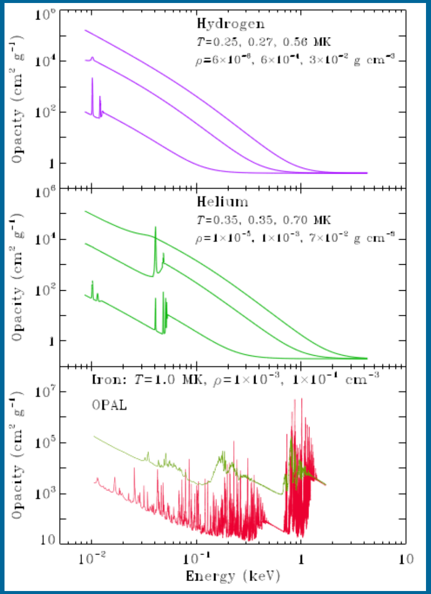
- Free-free absorption dominates

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

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

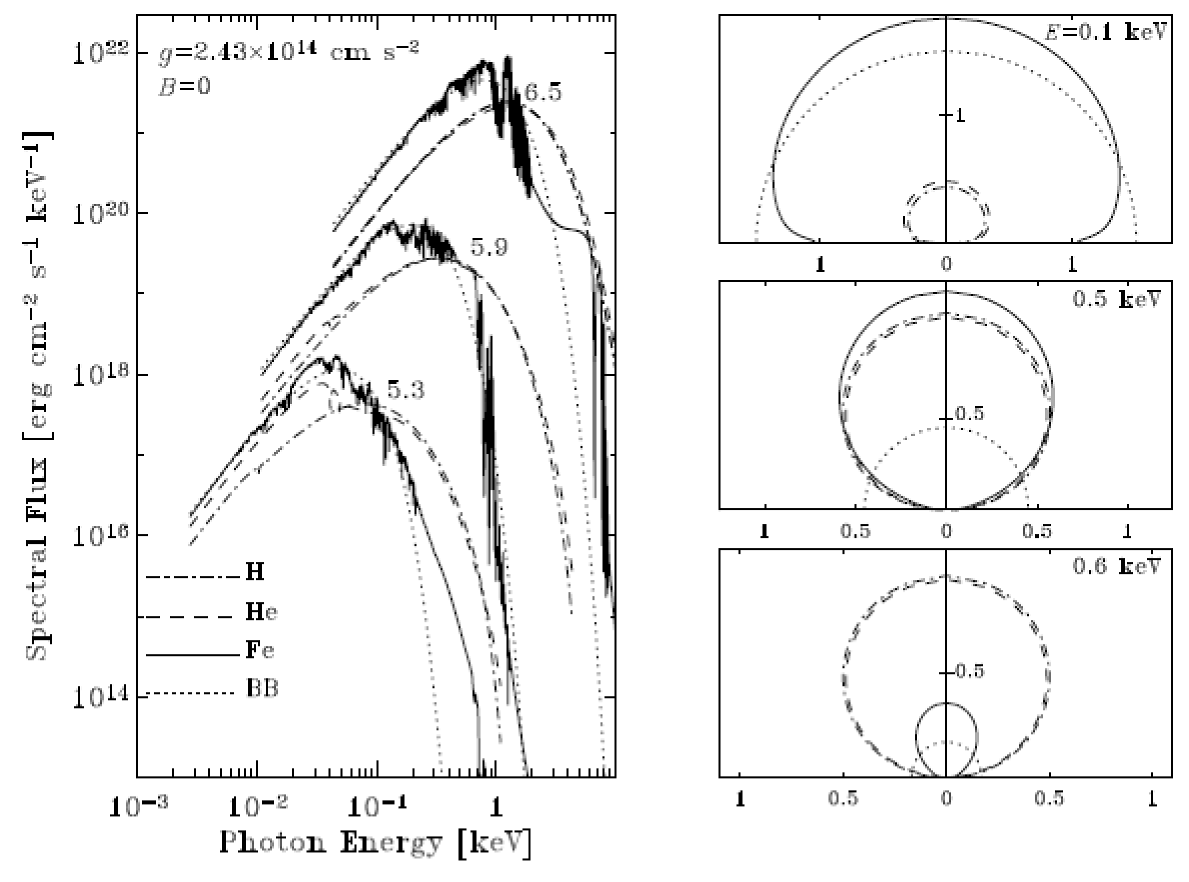


Rapid decrease of the light-element opacities with energy (~E^{-3})



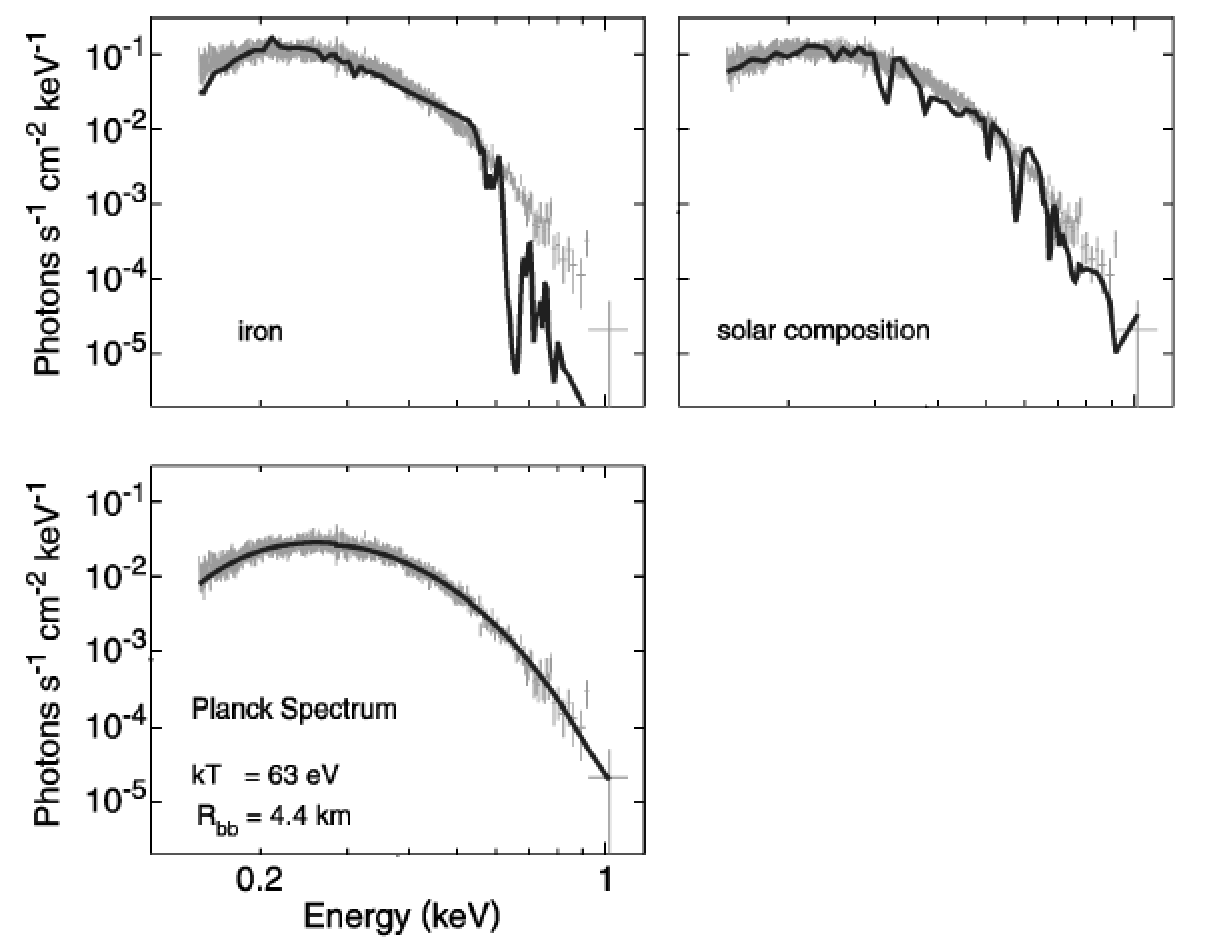
astro-ph/0206025

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

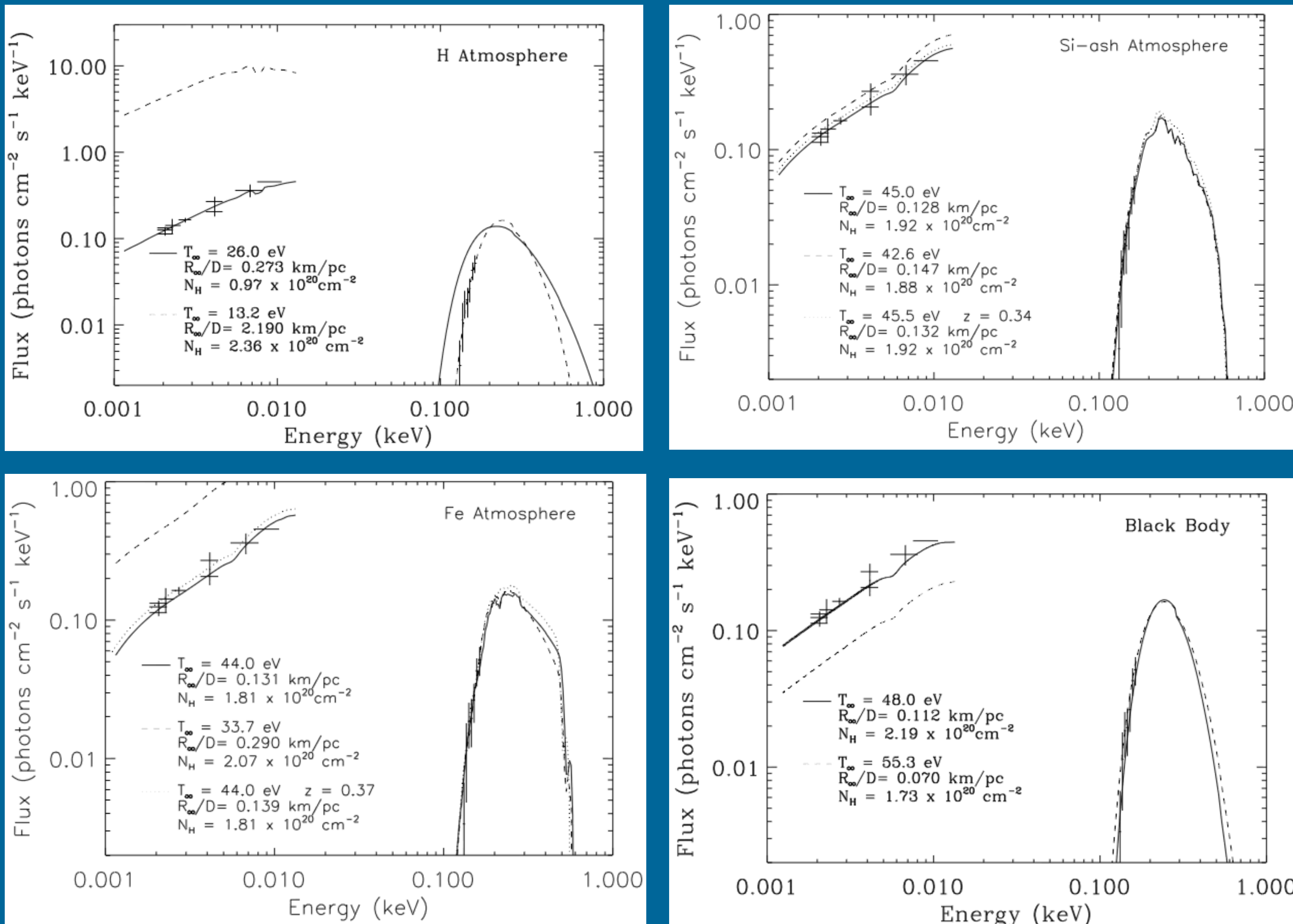
[a] 3 σ ranges, assuming $z = 0.305$. Weighting of the data is discussed in the text.
[b] Uncertainty does not include uncertainty in distance.
[c] The likelihood that the X-ray and optical parameters are the same.

Pons et al. 2002

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}~$2T_H$

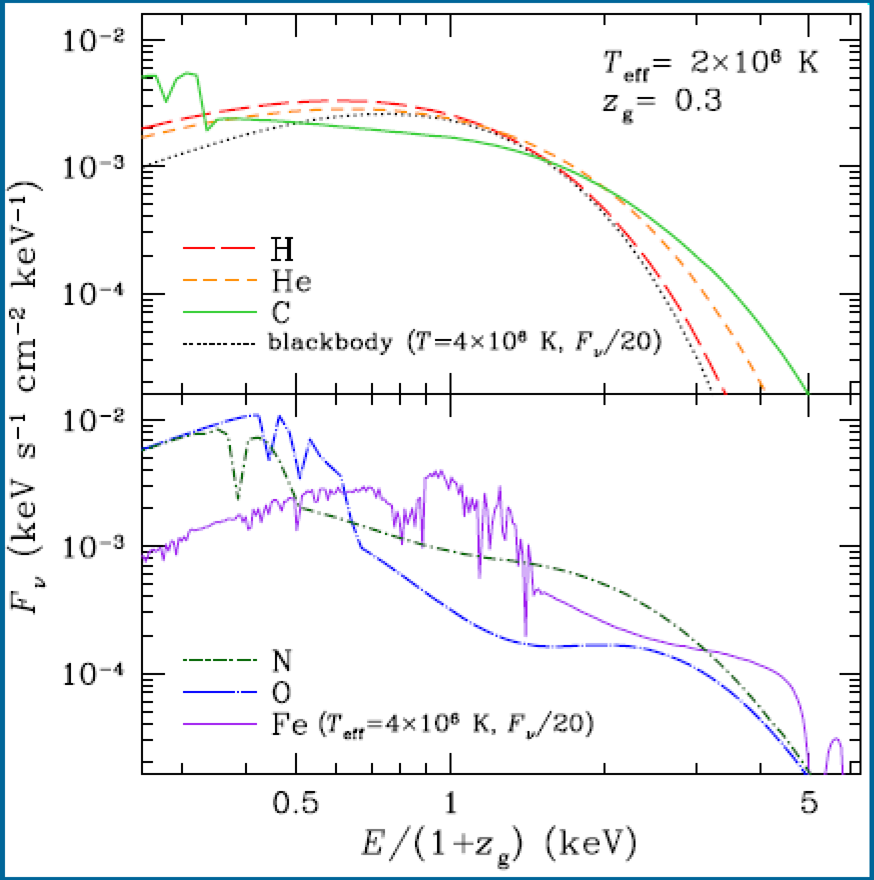
Different fits

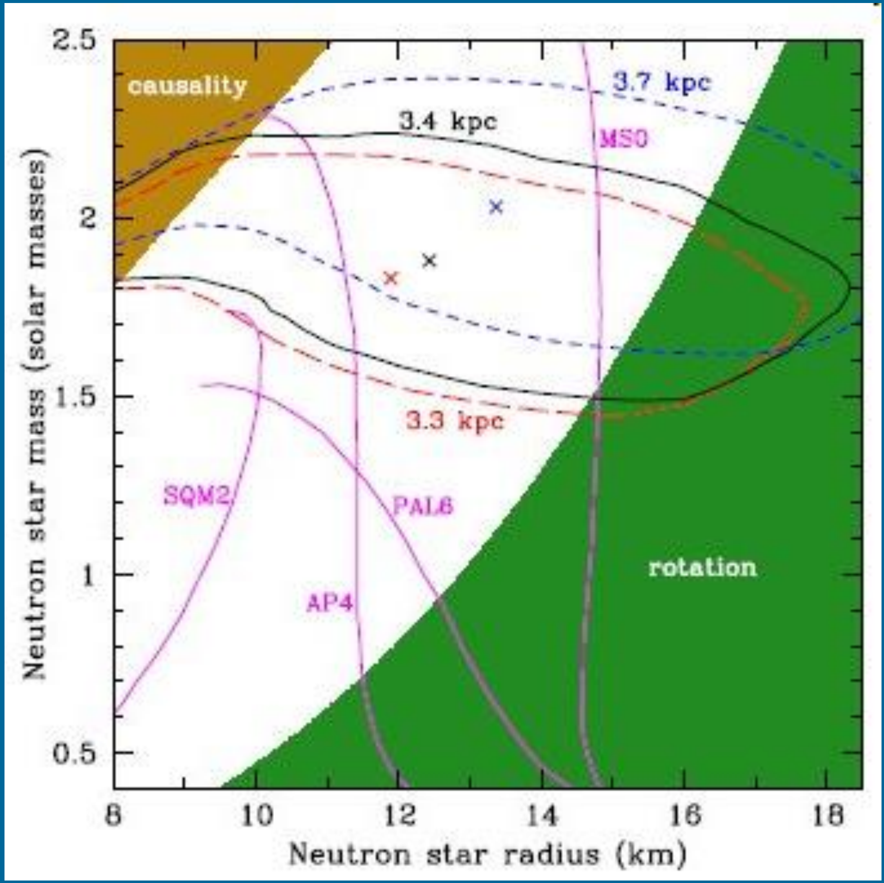


Pons et al. 2002

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

Cas A carbon atmosphere



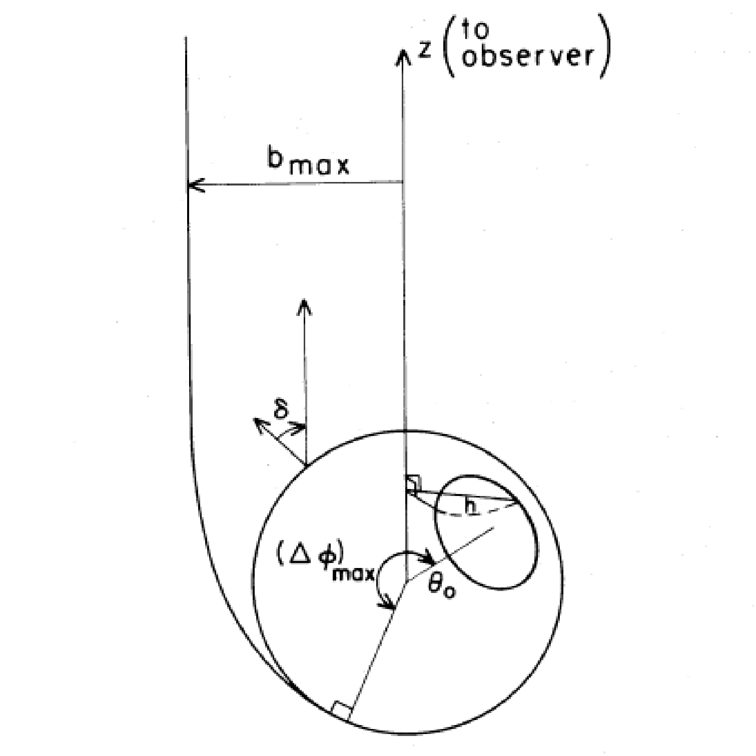


Low-field carbon atmosphere can fit the data.
Before all fits provided a very small emitting area.

0911.0672

Gravity Effects

- Redshift
- Ray bending

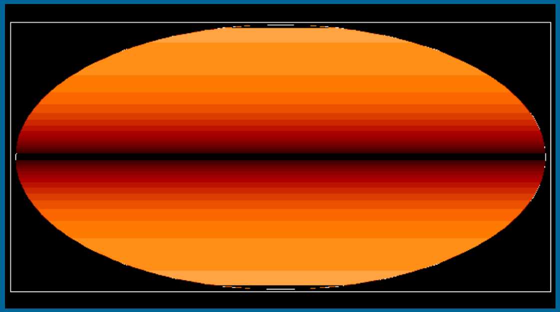


$$L_\infty = 4\pi R_\infty^2 \sigma T_\infty^4$$

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

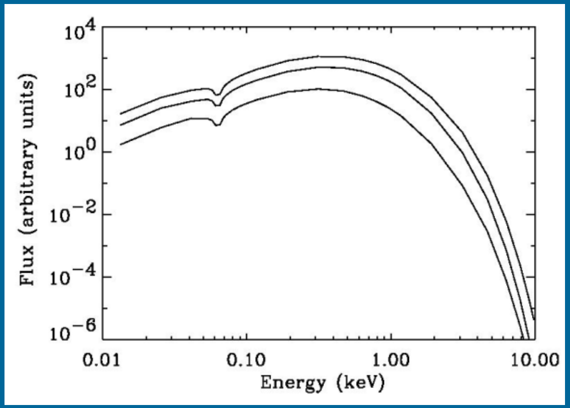
STEP 1

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



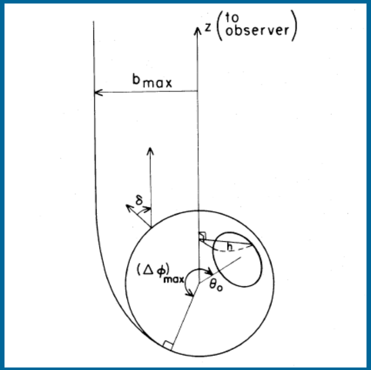
STEP 2

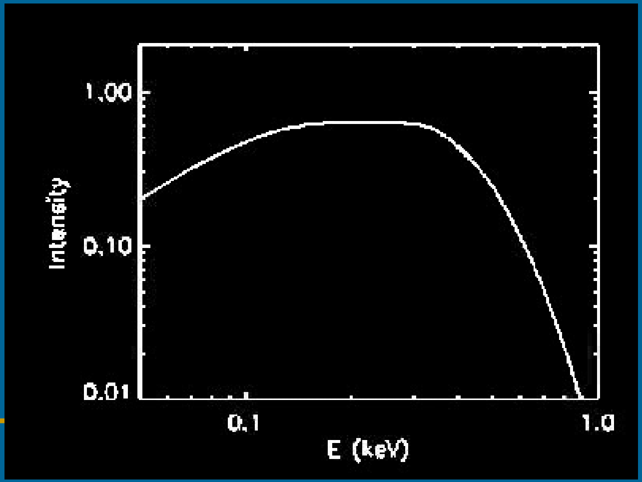
Compute emission from every surface patch



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 ≈ 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≈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

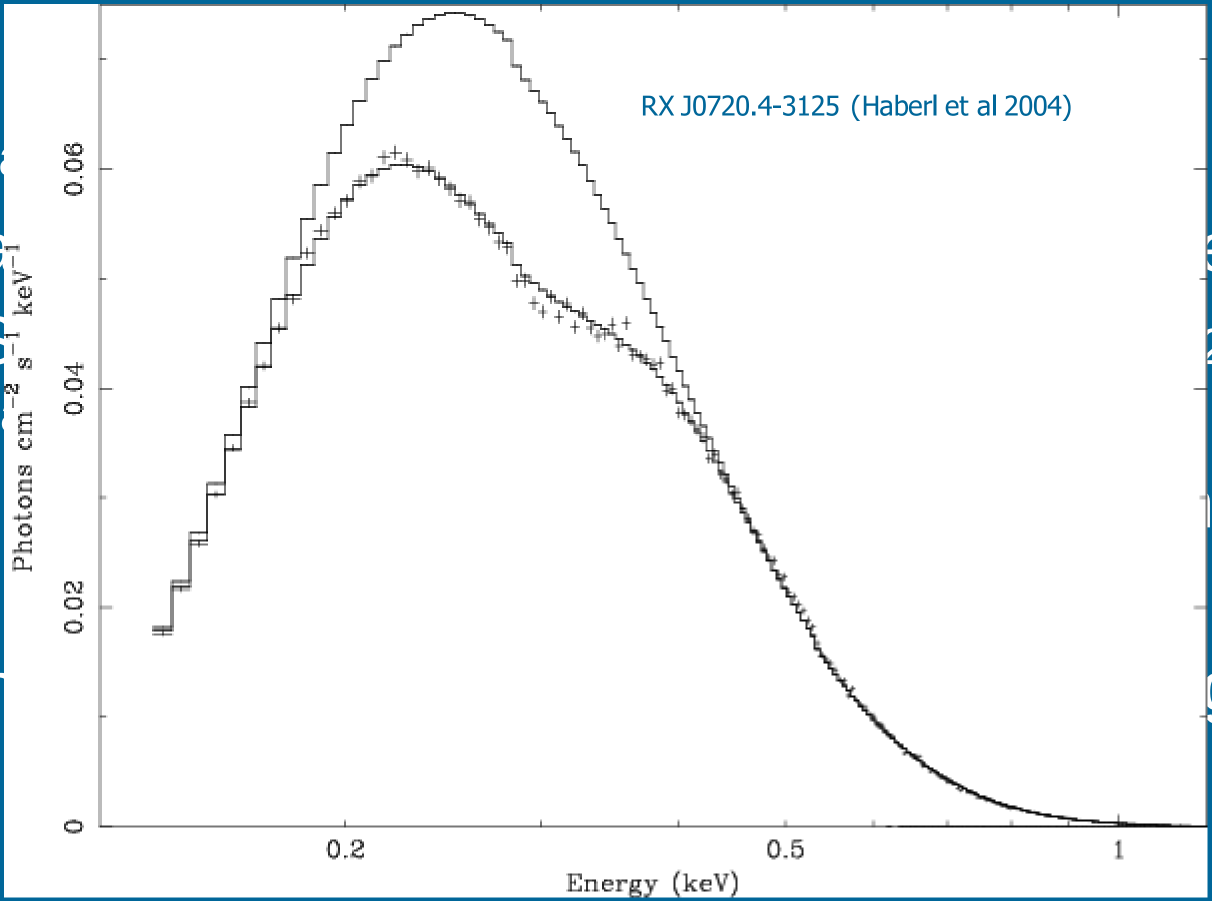
The Magnificent Seven

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	6.88?	??	m_{50CCD} = 26.8
1RXS J214303.7+065419 (RBS 1774)	104	9.43	4%	B=27.4

(*) variable source

Featureless ? No Thanks !

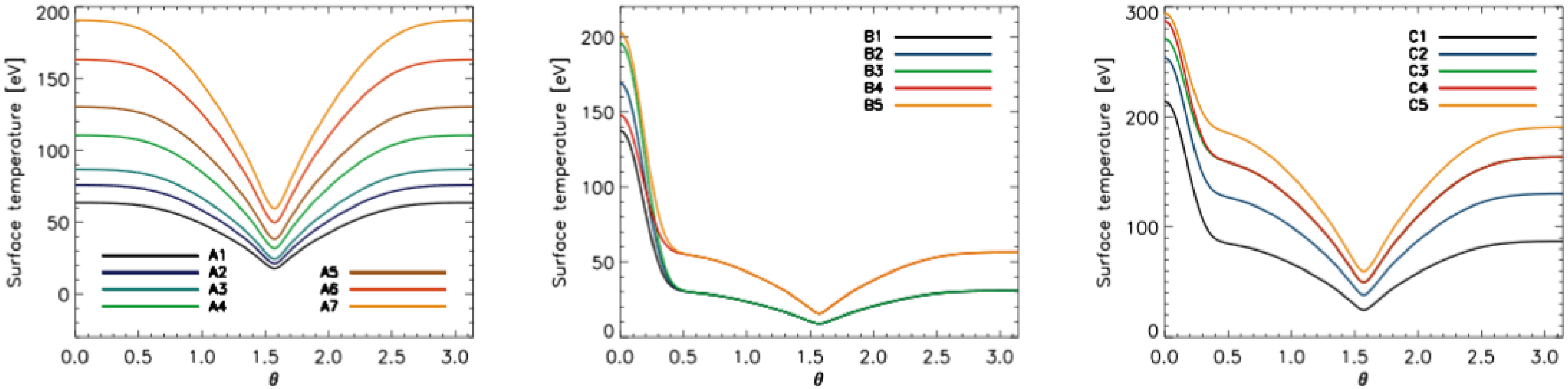
- RX J1
  (Chandr
- A broa er
  ICoNS 2004;
  Zane et
- E_{line} ~ E_1 ~
  $2E_2$ in
- Proton gh B
  ?



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	-

Non-uniform temperature distribution

Source	Class	B_{dip} $[10^{12}$G]	N_H $[10^{20}$cm$^{-2}]$	kT_{bb} [eV]	E_0 [eV]	$\lvert E_w \rvert$ [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]

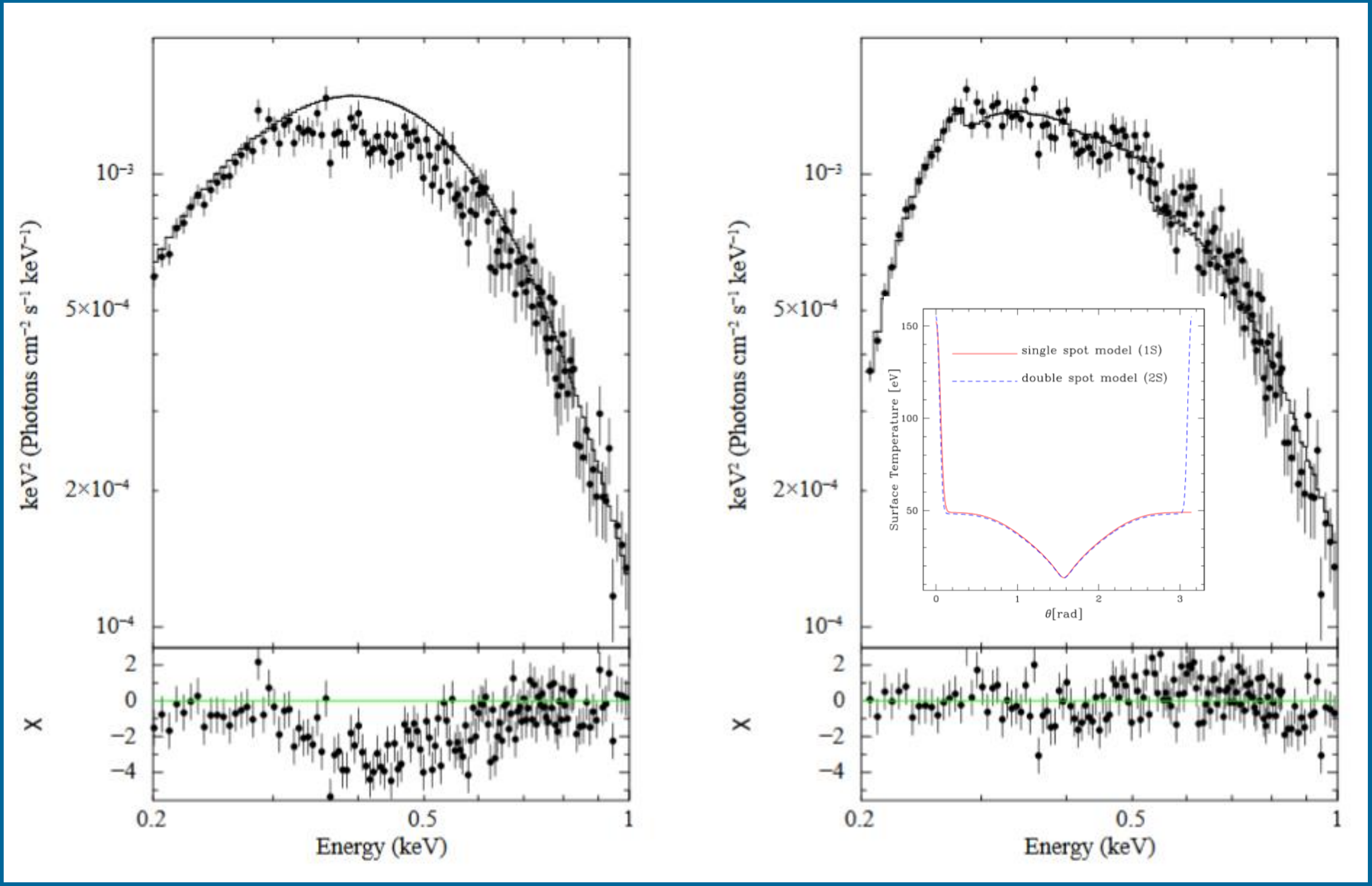


1406.0874

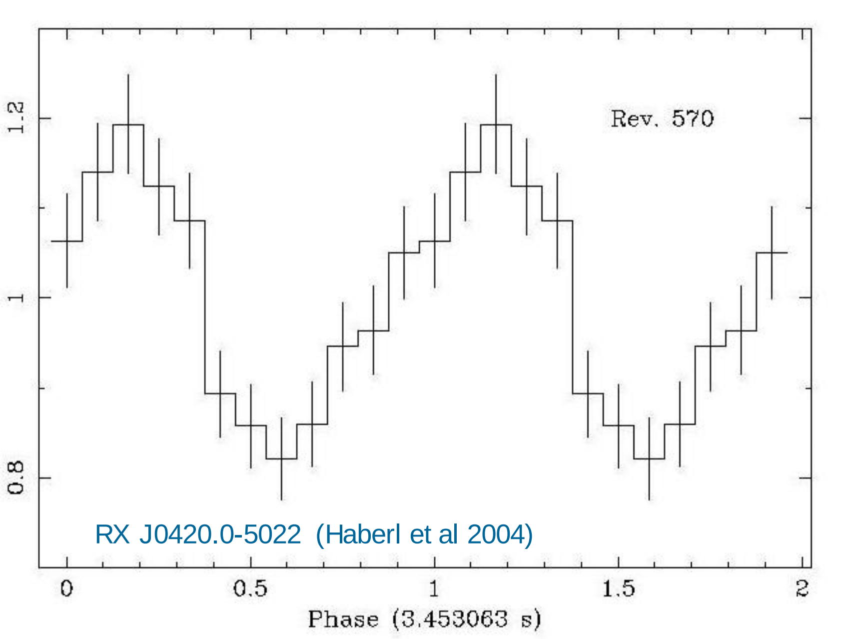
RX J0806.4-412

BB+line

Non-uniform distrubution



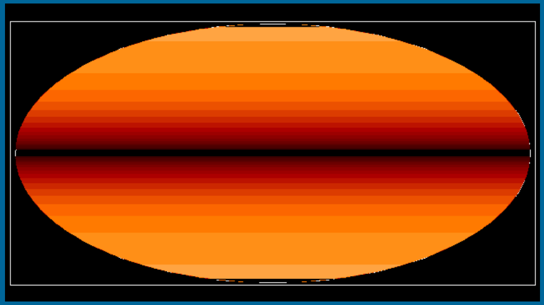
Pulsating ICoNS - I



- 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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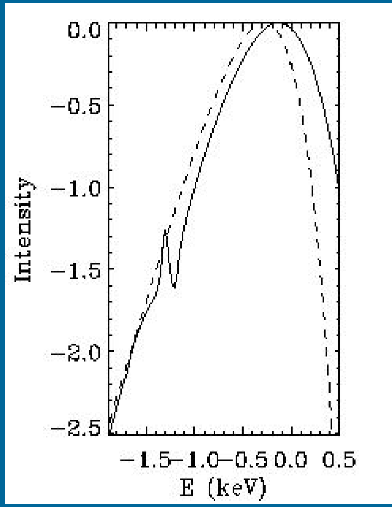

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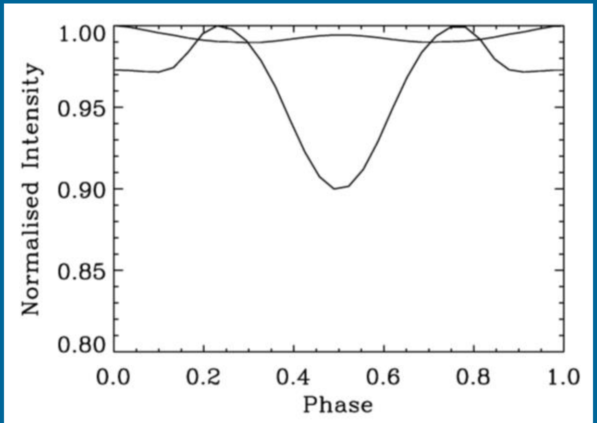
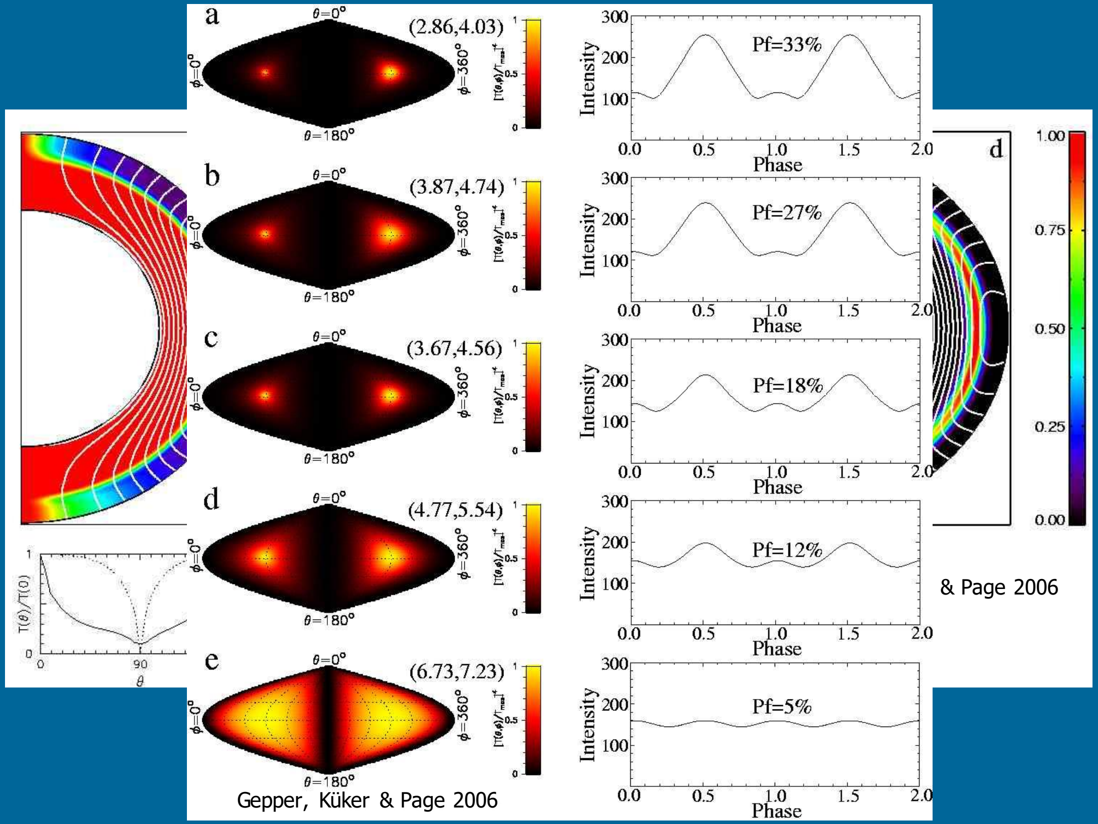
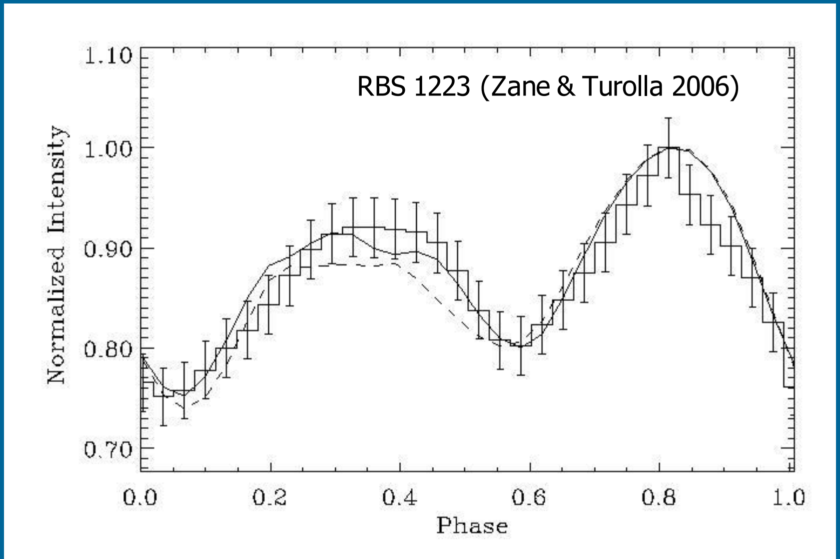
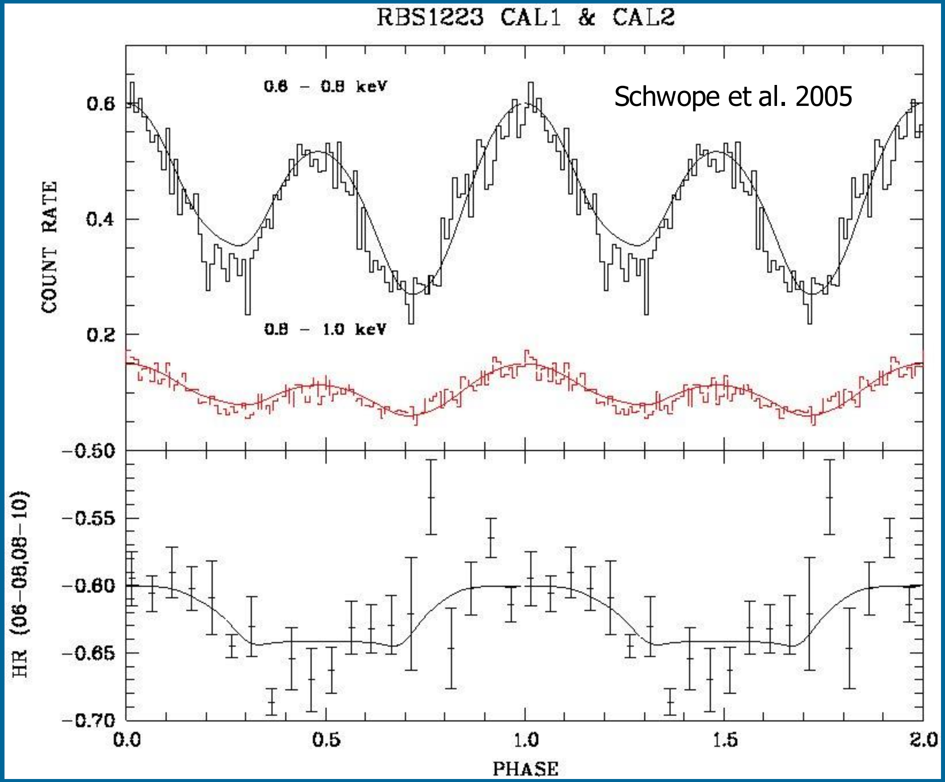


Crustal Magnetic Fields

- 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





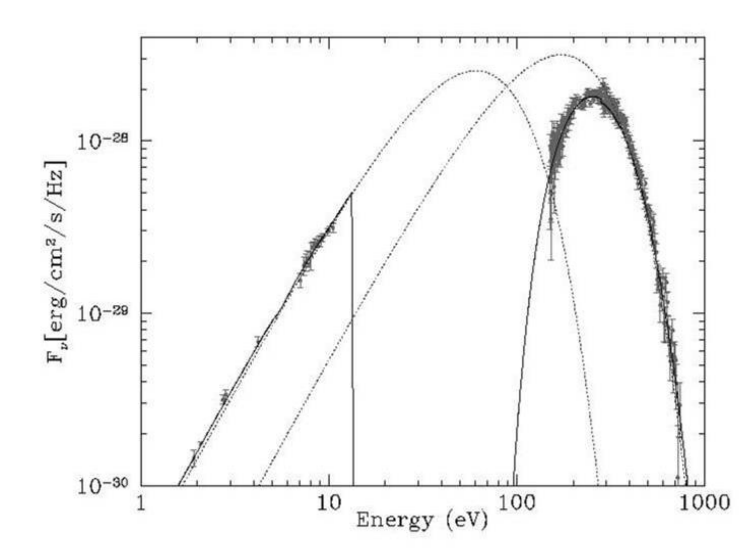


Indications for non-antipodal caps (Schwope et al 2005)

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

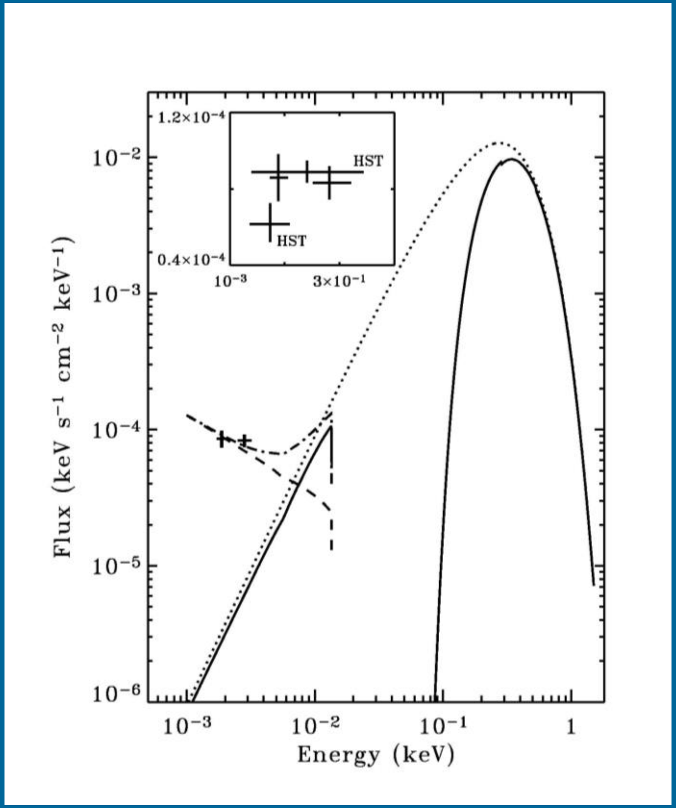
- A quark star (Drake et al 2002; Xu 2002; 2003)
- A NS w… and cooler equato… et al 2002; Braje & Romani 2002; Trűmper et al 2005)

  What spectrum ?
  The optical excess ?

- A bare NS (Burwitz et al 2003; Turolla, Zane & Drake 2004; Van Adelsberg et al 2005; Perez-Azorin, Mi… 2005)

  A perfect BB ?

The Optical Excess

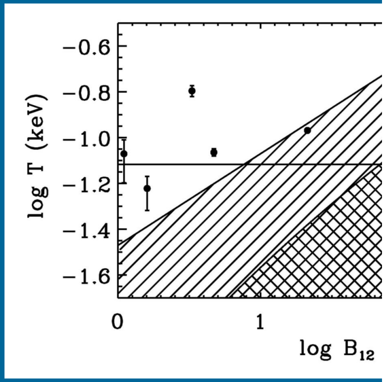


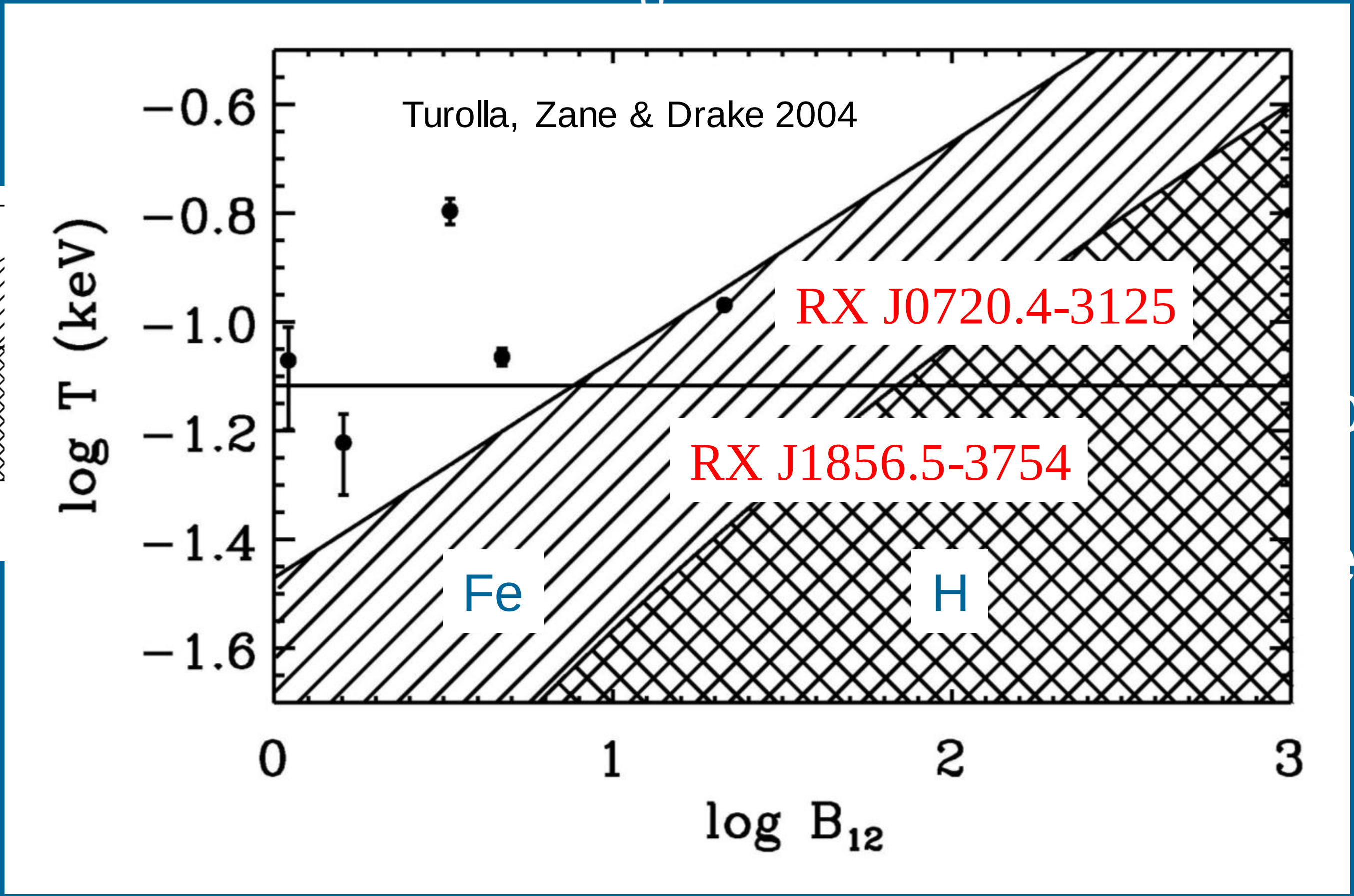
RX J1605 multiwavelength SED (Motch et al 2005)

- 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

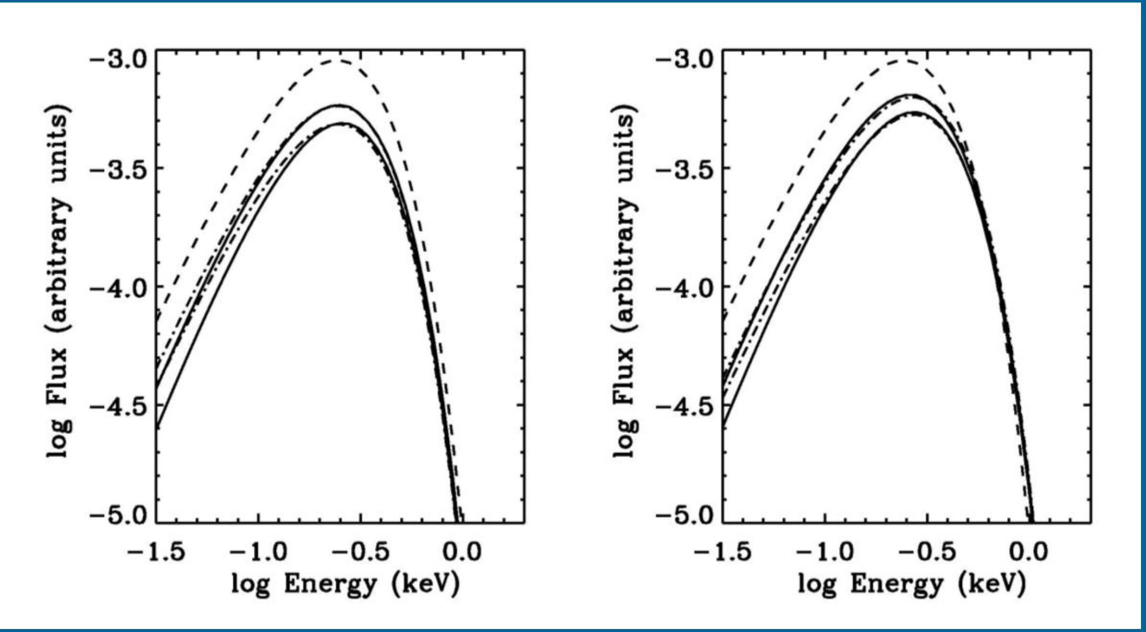




Spectra from Bare NSs - I

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.

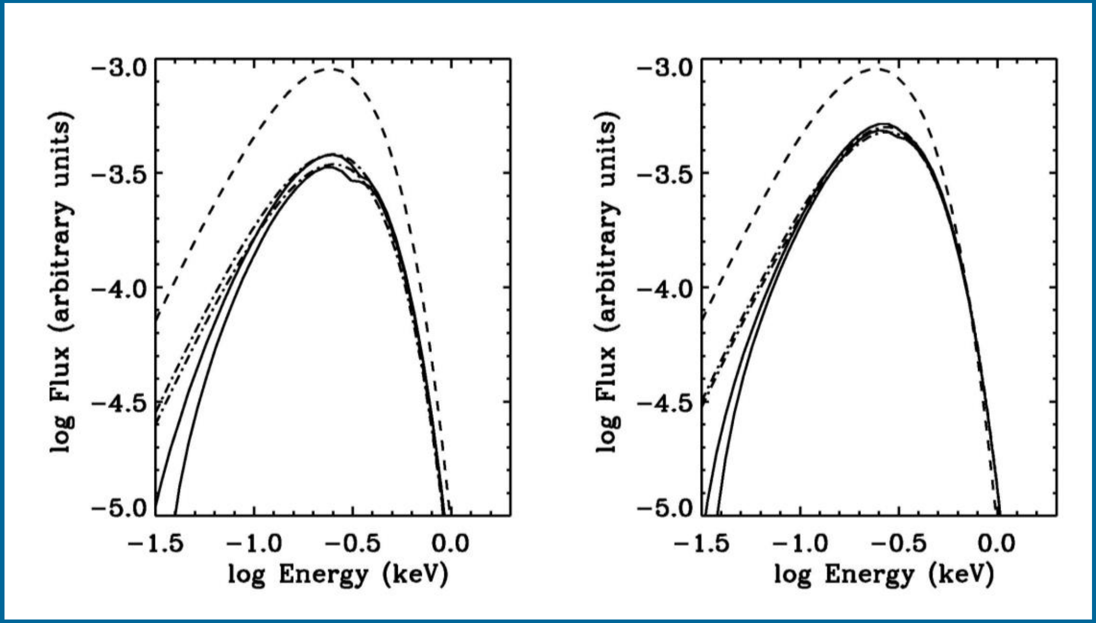


Turolla, Zane & Drake (2004)

Spectra from Bare NS - II

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

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

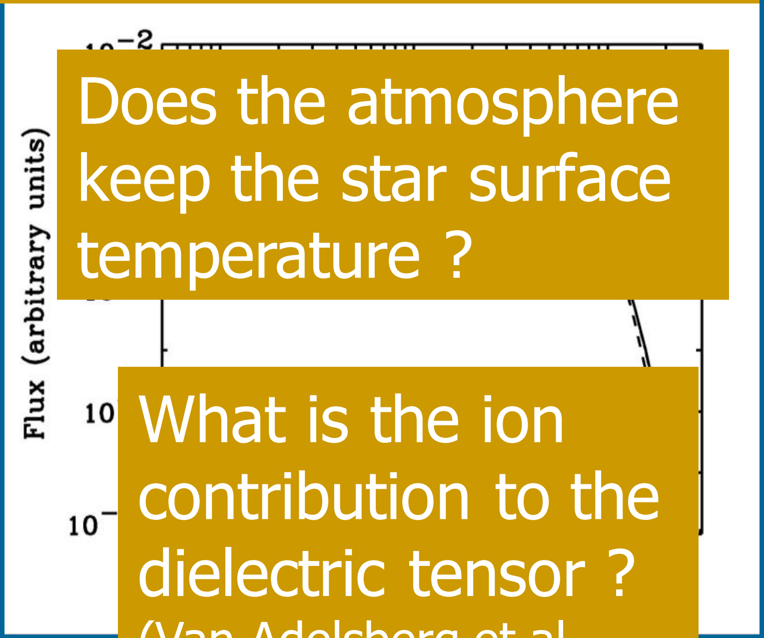


Turolla, Zane & Drake (2004)

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)

Is RX J1856.5-3754 Bare ?

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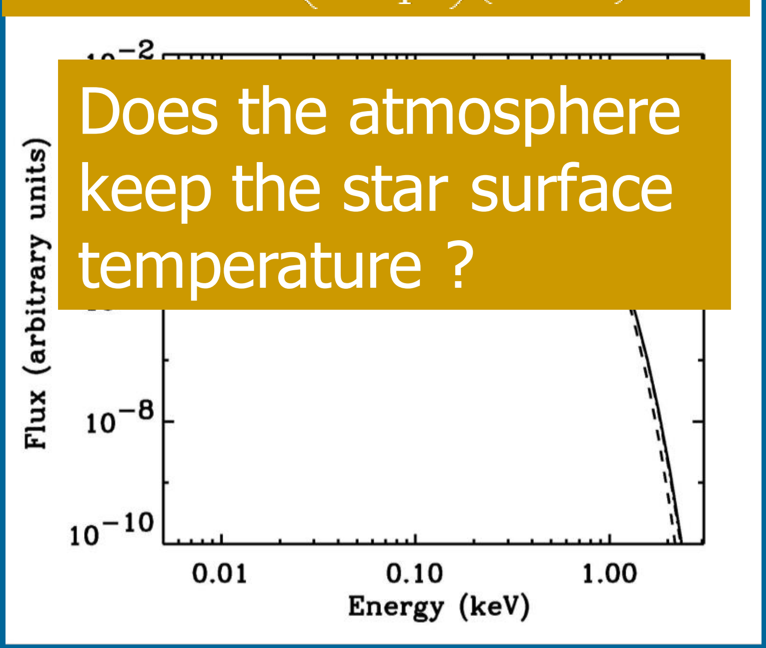
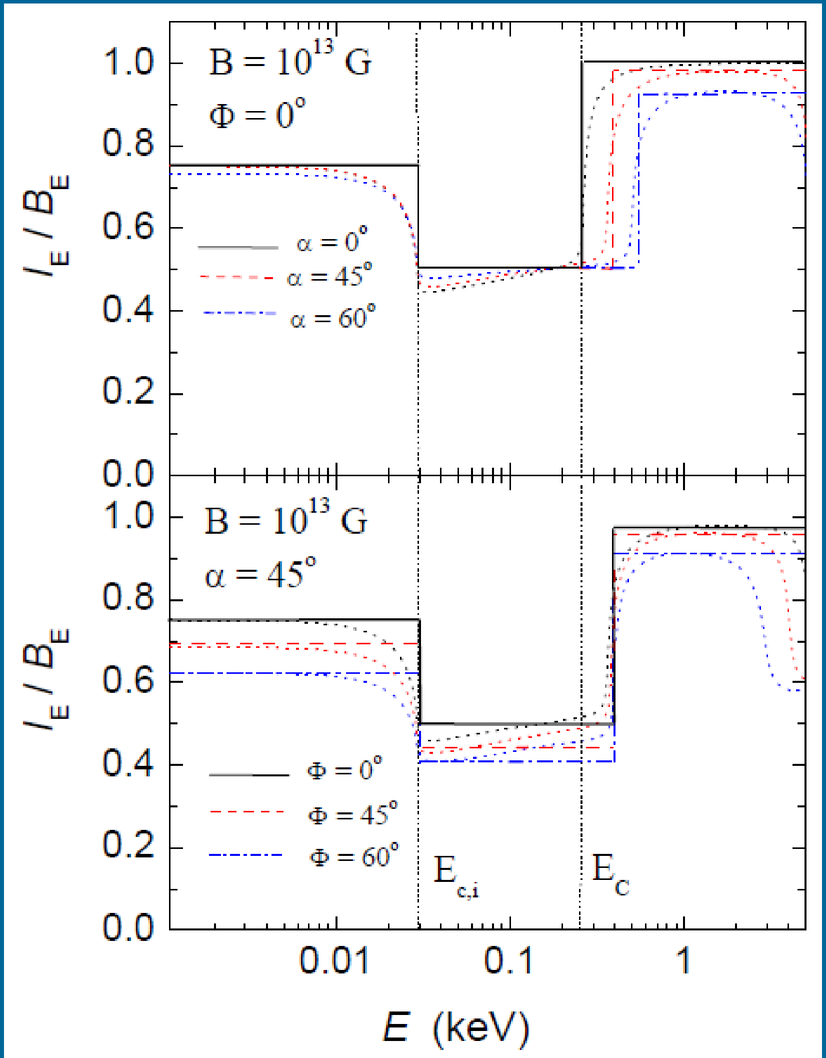


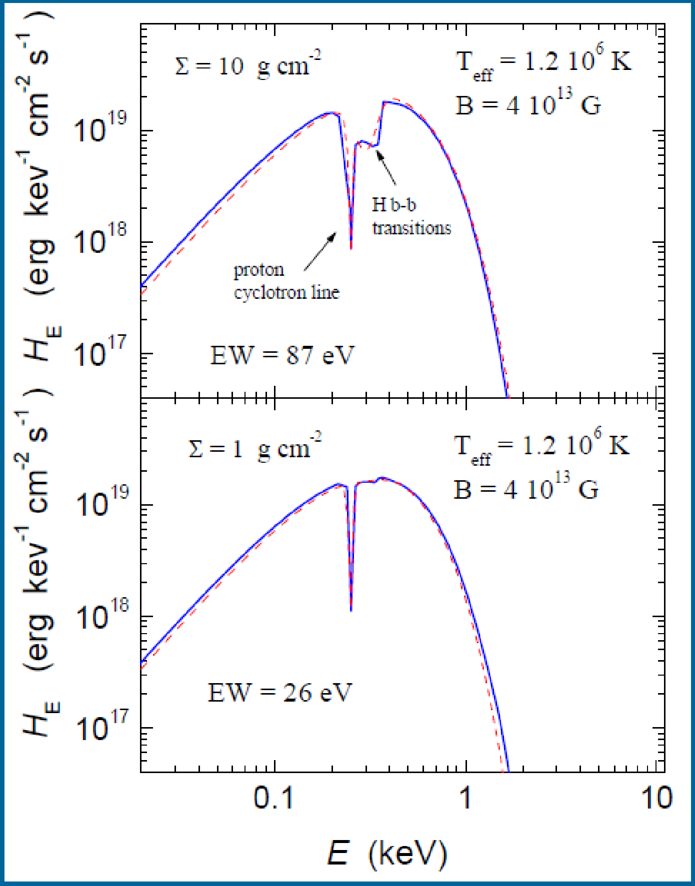
Condensed iron surface emissivity

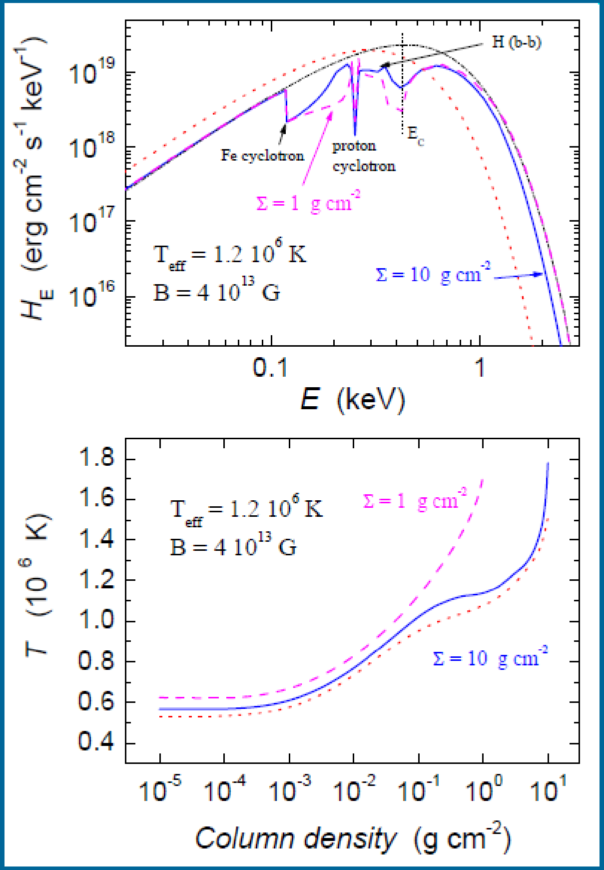


Free ions approximation.

1006.3292

Thin hydrogen magnetized atmosphere above blackbody and iron condensed surface



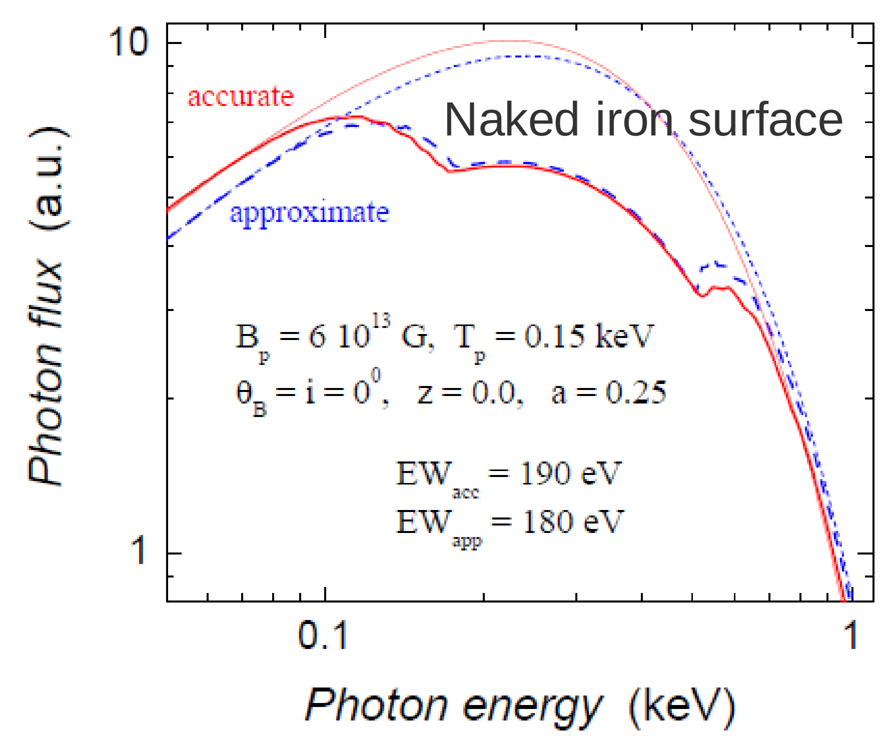


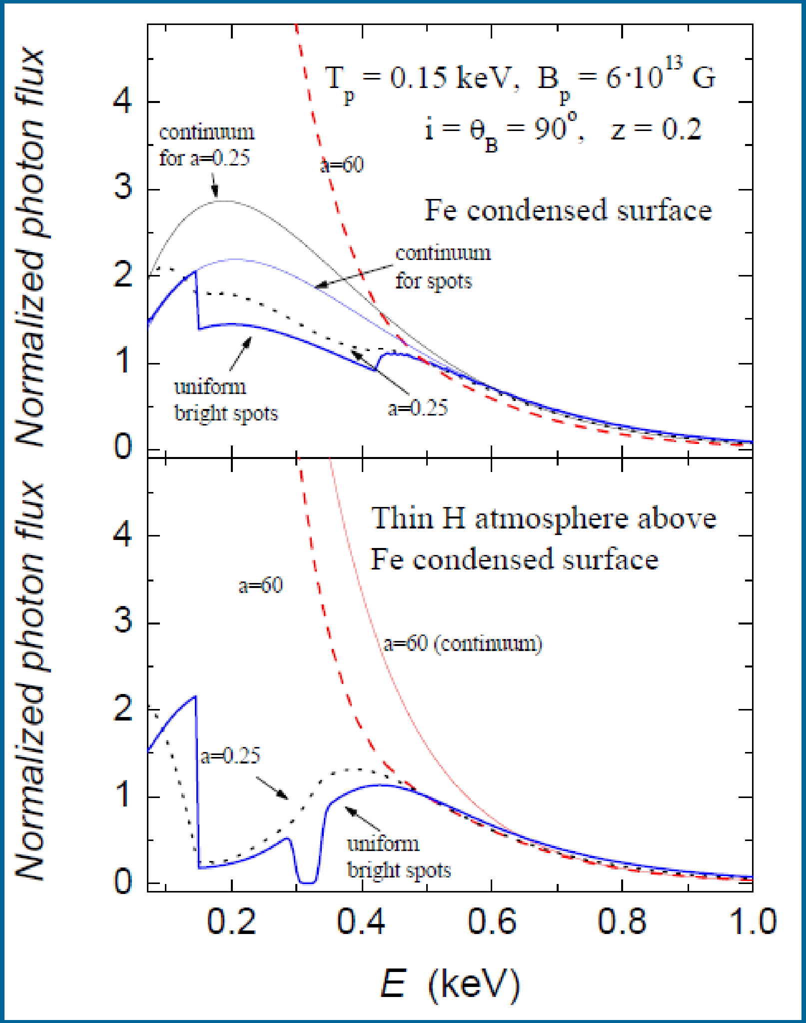
Below atmosphere was a blackbody spectrum

Below – iron condensed surface

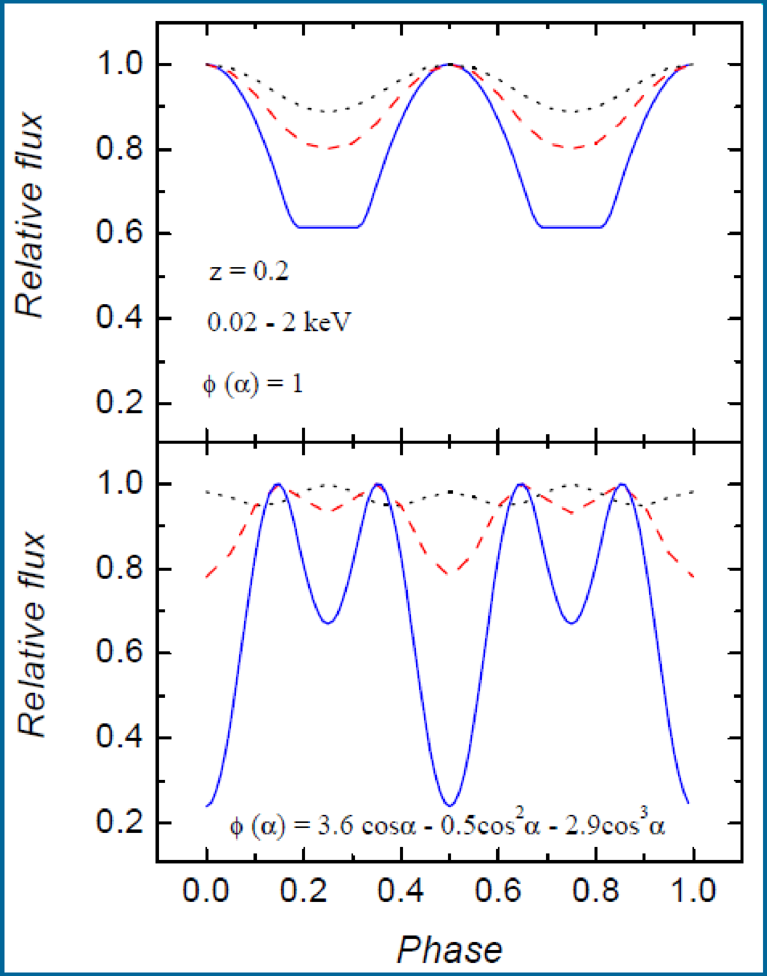
1006.3292

Let us make it realistic

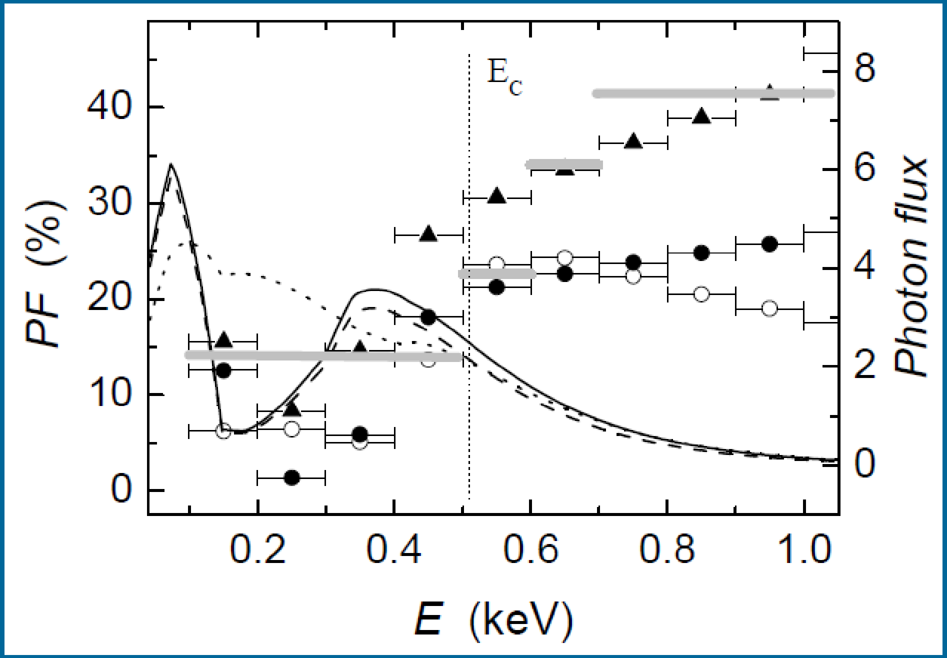




Light curves and pulsed fraction



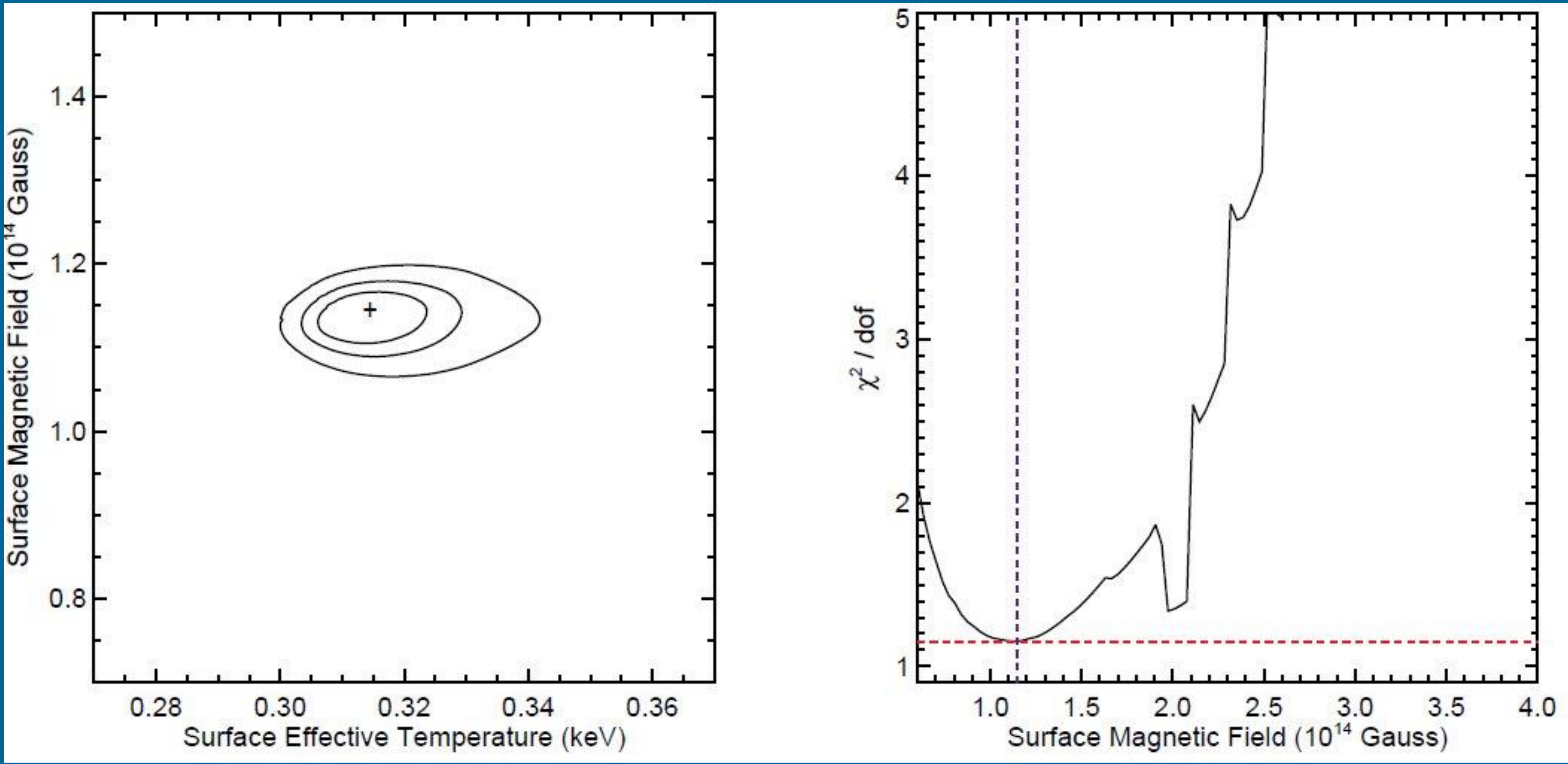
1006.3292



1010.0125

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.

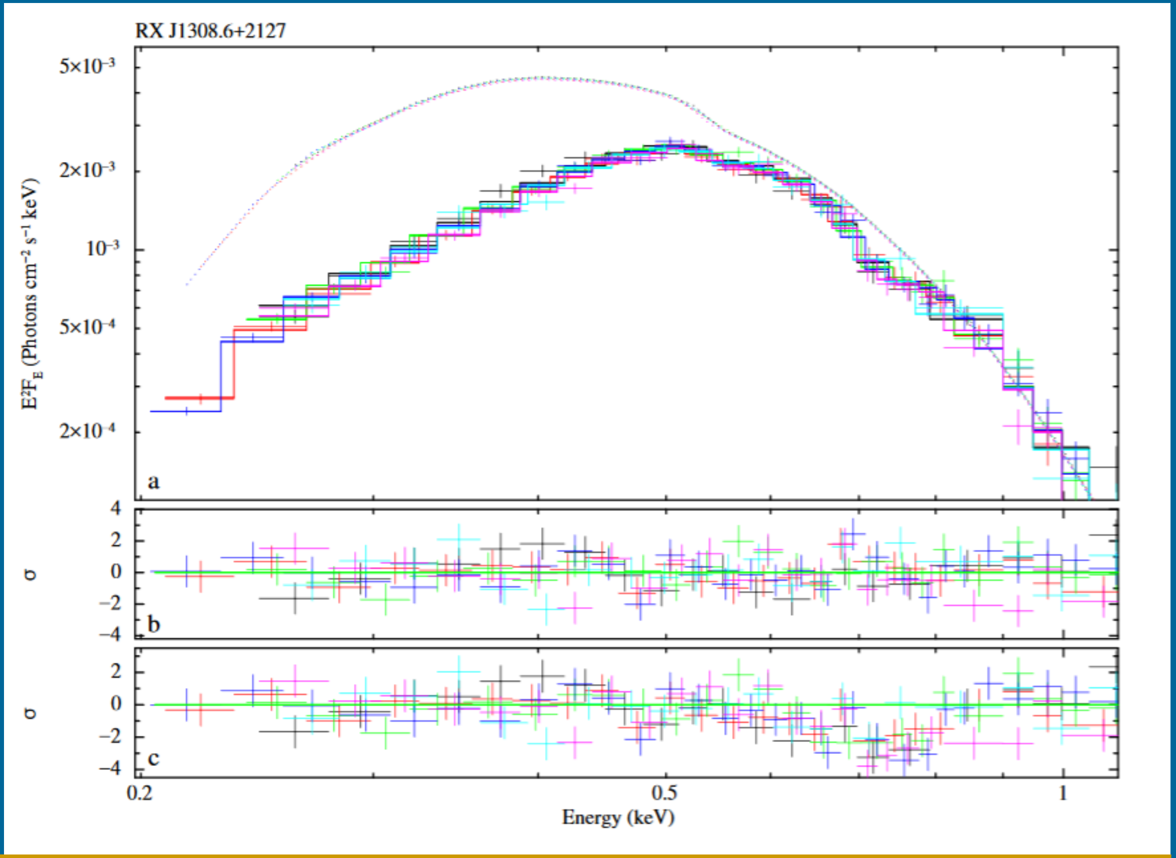


1103.3024

New results in 1507.02689

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

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

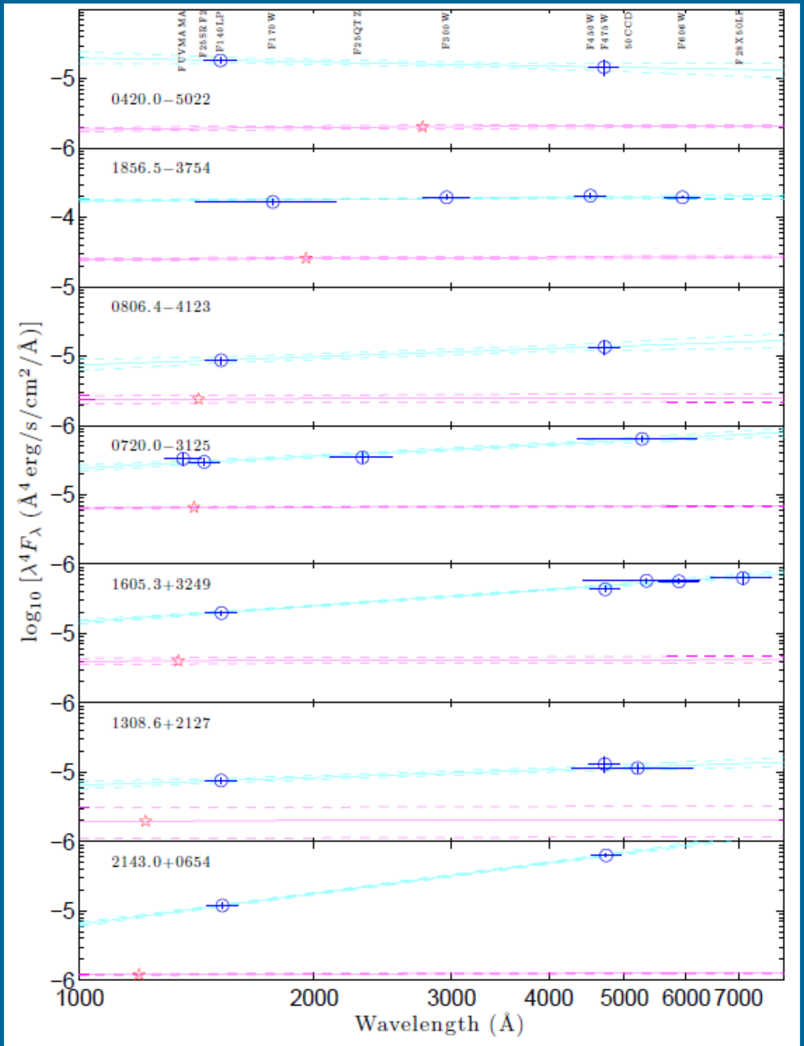
- astro-ph/0702426 ←
- arXiv: 0801.1143
  or astro-ph/0609066 } Reviews on the M7
- astro-ph/0206025 ←
- arXiv: 0905.3276 } Recent calculations of spectra from magnetized atmos.
- arXiv: 1006.3292
- arXiv: 1210.0916 - review

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