Surface emission of neutron stars

NS Radii

- A NS with homogeneous surface temperature and local blackbody emission

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

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

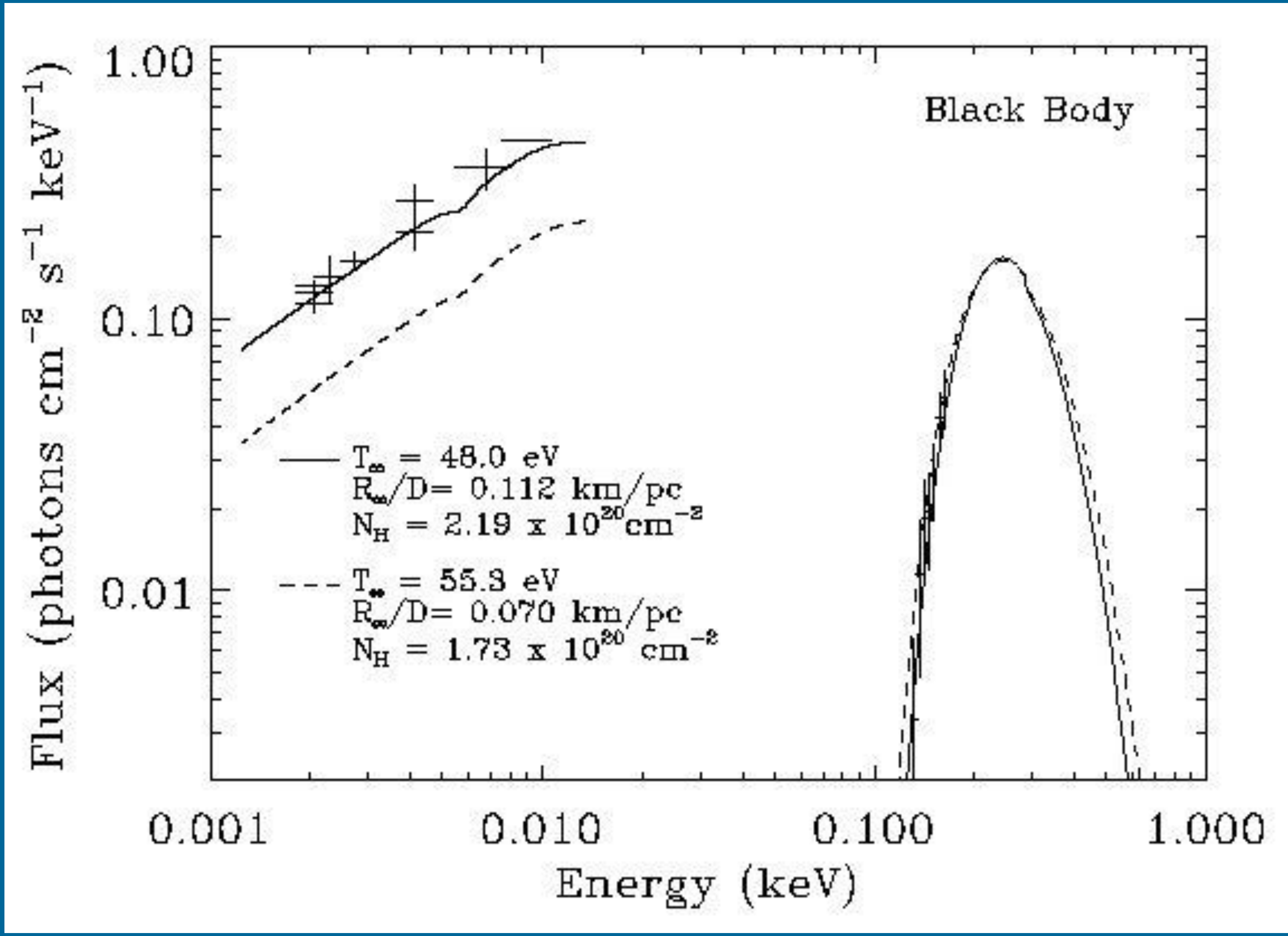
From dispersion measure

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

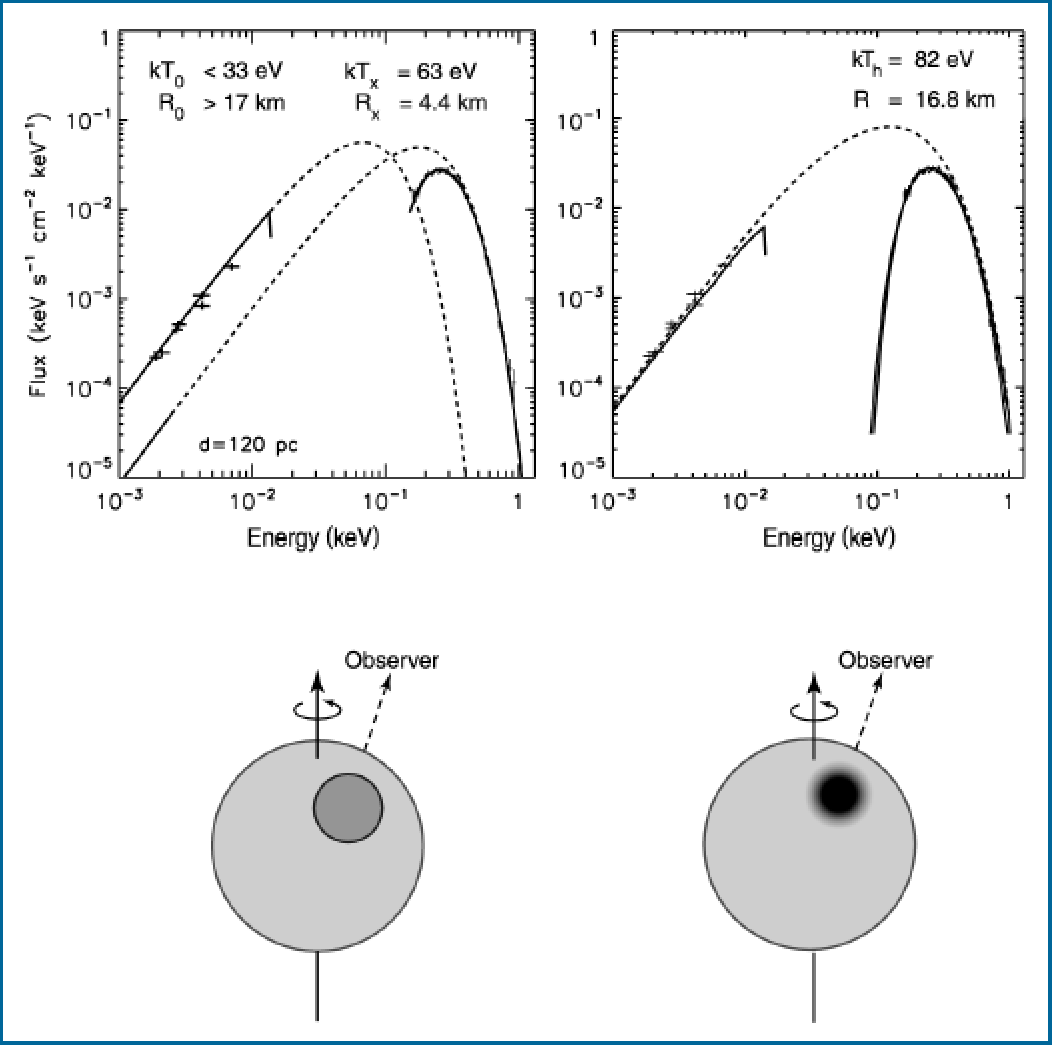
Uncertainties in temperature



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

(Pons et al. astro-ph/0107404)

Non-uniform temperature distribution

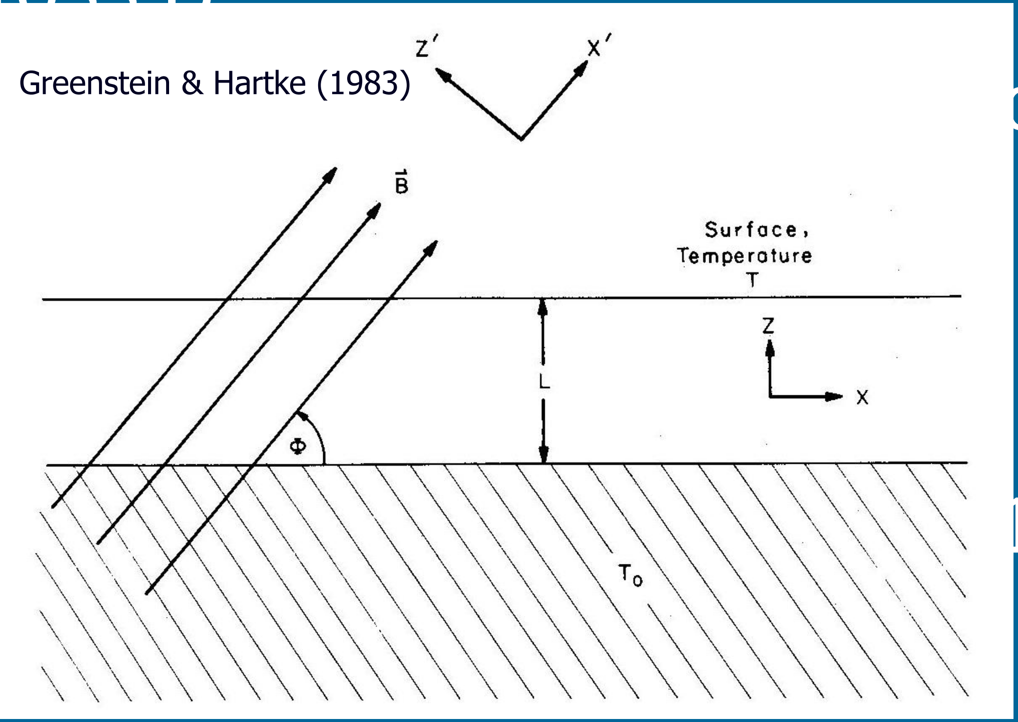


In the case of RX J1856 because of significant (~6) optical excess it was proposed that there is a spot, or there is a continuous temperature gradient.

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 $\rho >> 10$ …
- Envelop … ,
  B ~ con … 1D



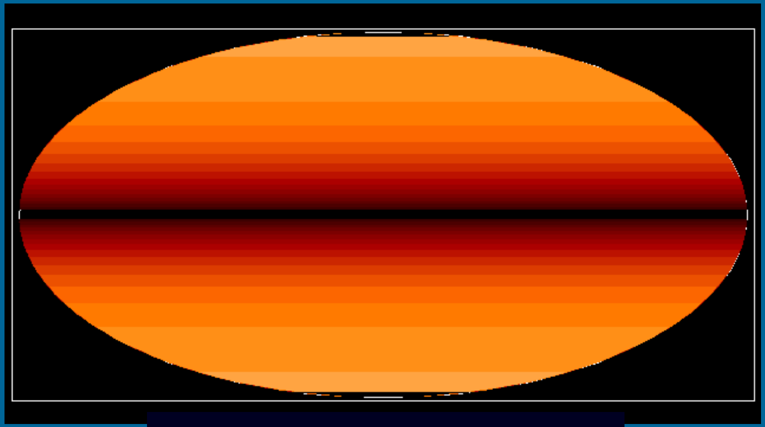
$$T_S = \left[\cos^2\Theta + \left(K_{perp}/K_{par}\right)\sin^2\Theta\right]^{1/4} T_{pole}$$

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

K - conductivity

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

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



Core centered dipole

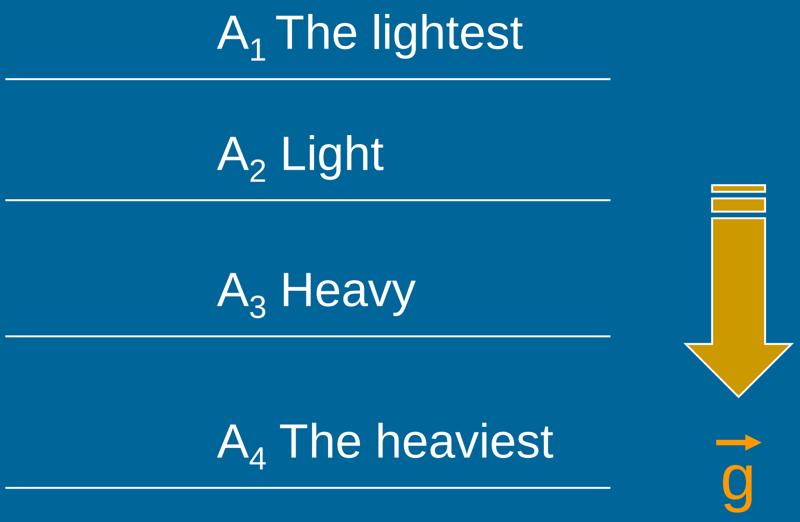
Core centered quadrupole

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, $h_{atm} \approx$ 1-10 cm ($h_{atm} \sim kT/mg$)
- 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.

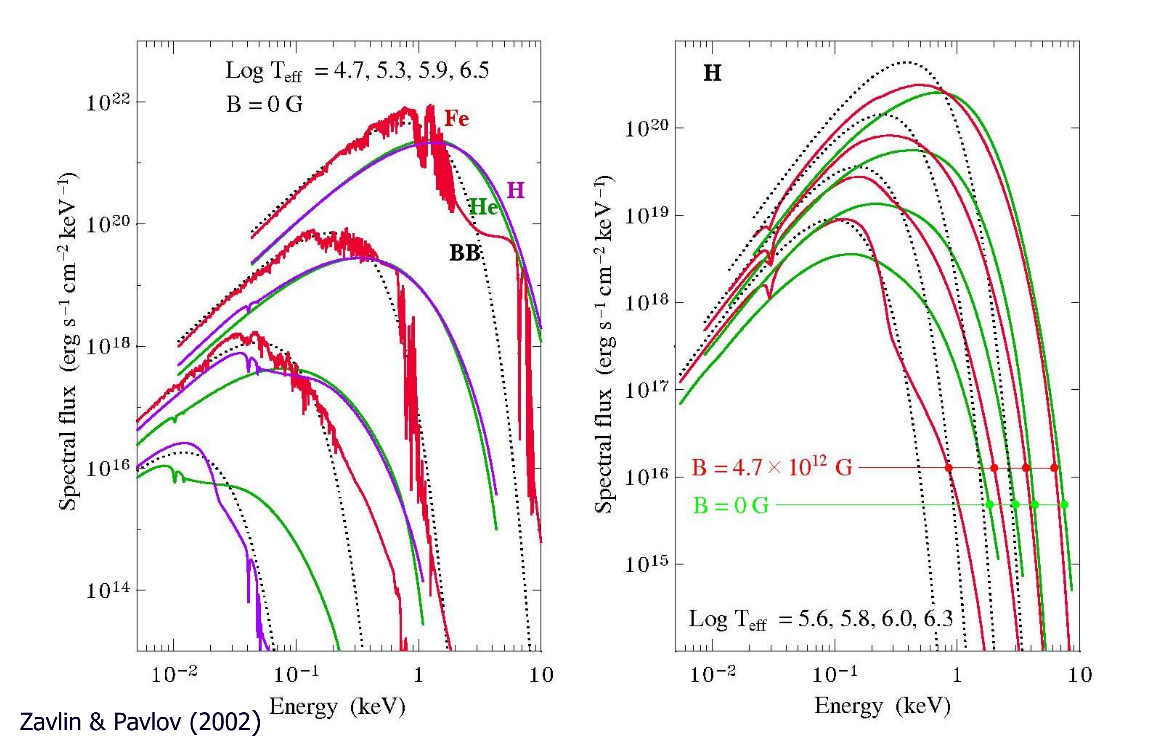
10^{-20} solar mass of hydrogen is enough to form a hydrogen atmosphere.

See astro-ph/ 0702426

- Free-free absorption dominates

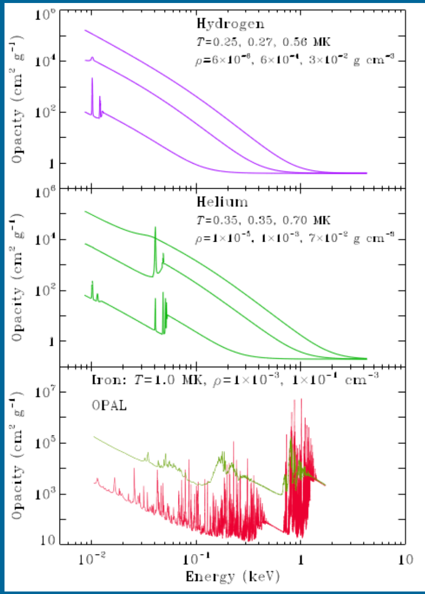
$$\kappa_\nu \propto \nu^{-3}, h\nu >> kT$$

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



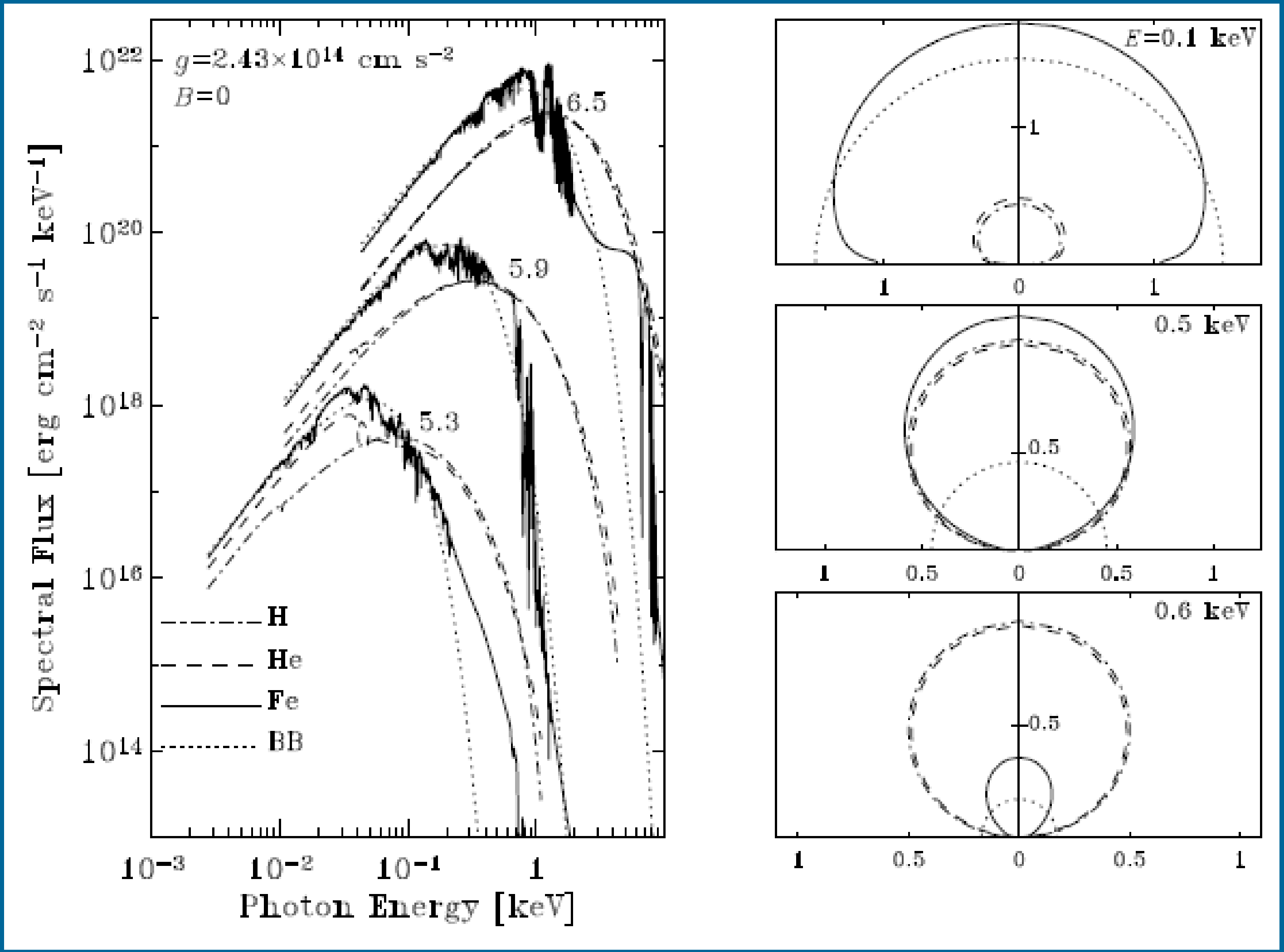
Zavlin & Pavlov (2002)

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



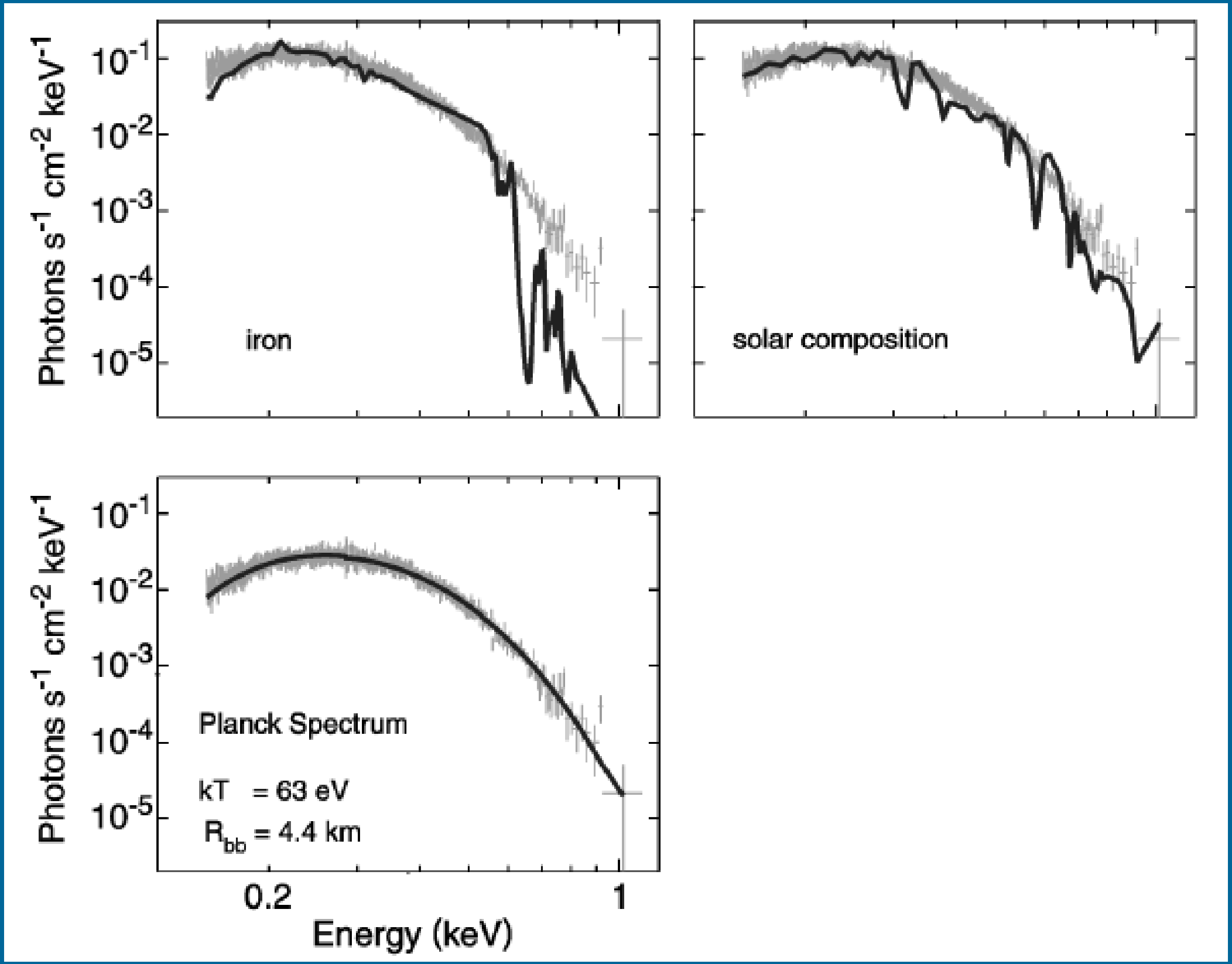
astro-ph/0206025

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

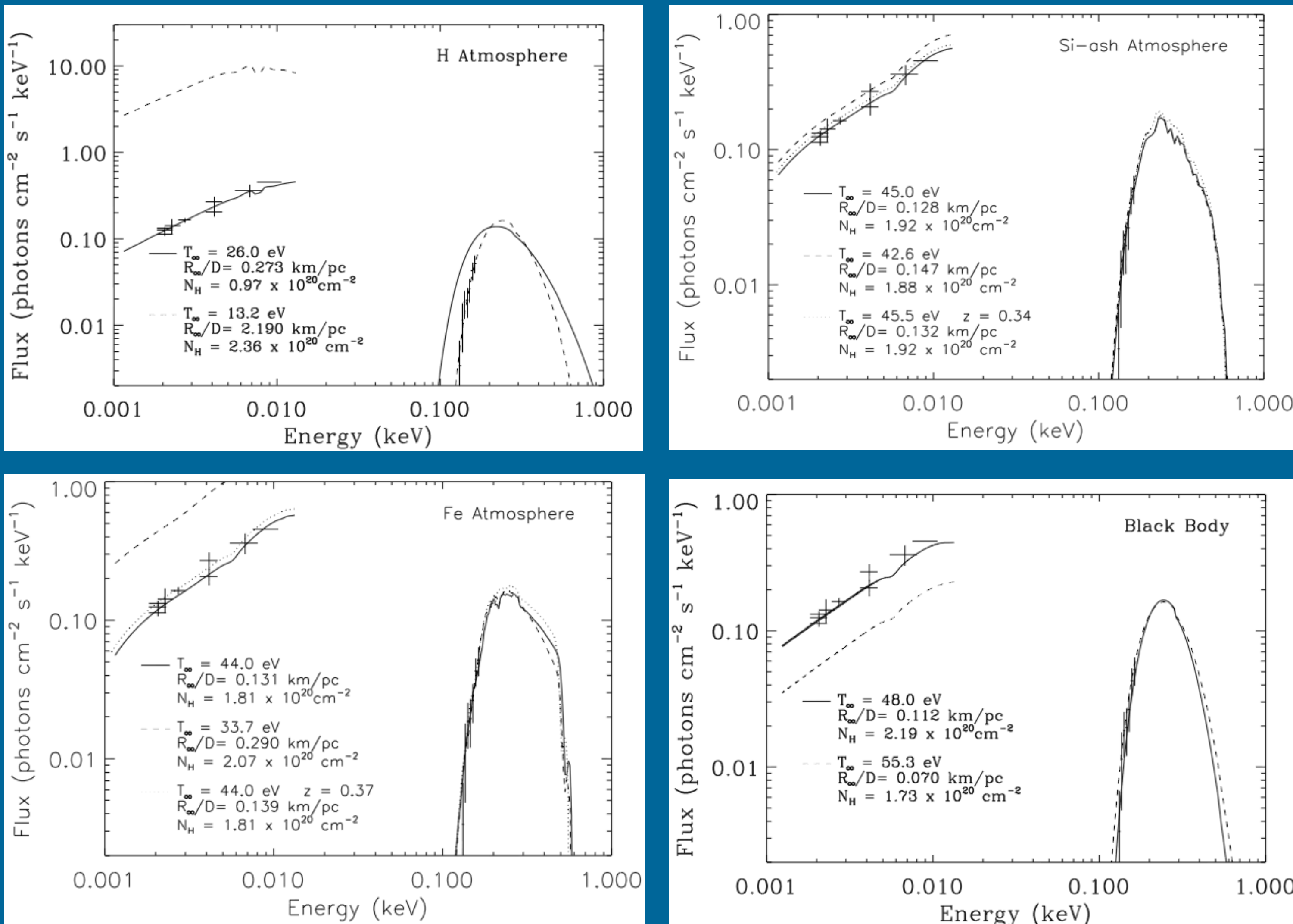
[a] 3 σ ranges, assuming $z = 0.305$. Weighting of the data is discussed in the text.
[b] Uncertainty does not include uncertainty in distance.
[c] The likelihood that the X-ray and optical parameters are the same.

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

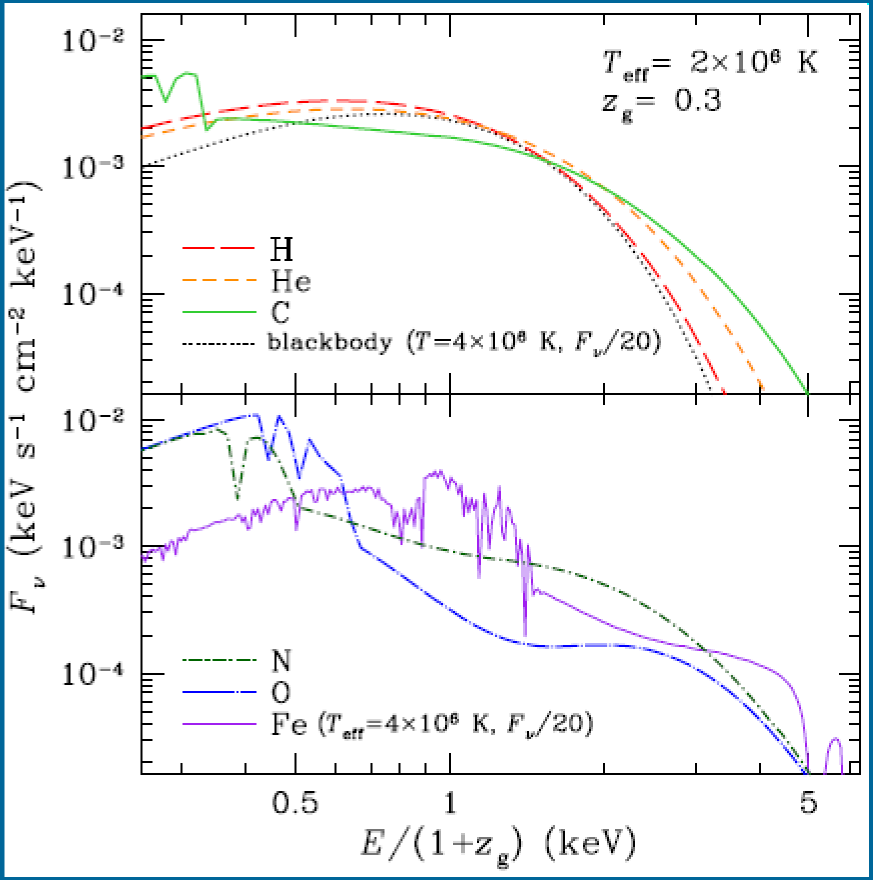
Different fits

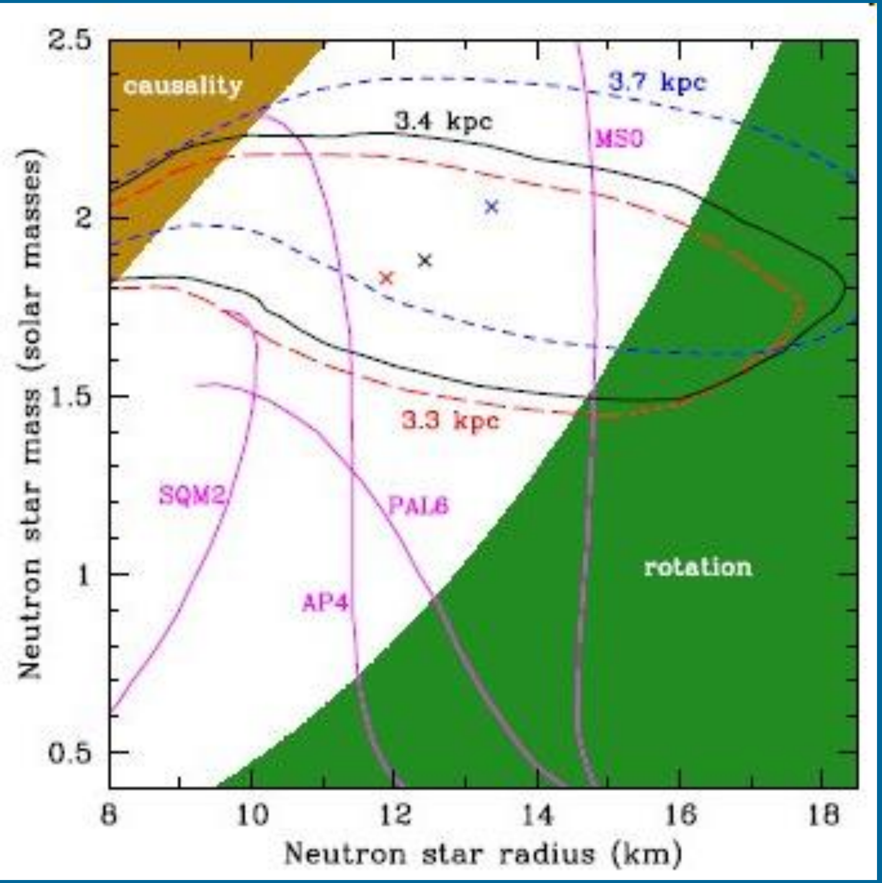


$T_{bb} \sim T_{Fe} > T_H$

Pons et al. 2002

Cas A carbon atmosphere



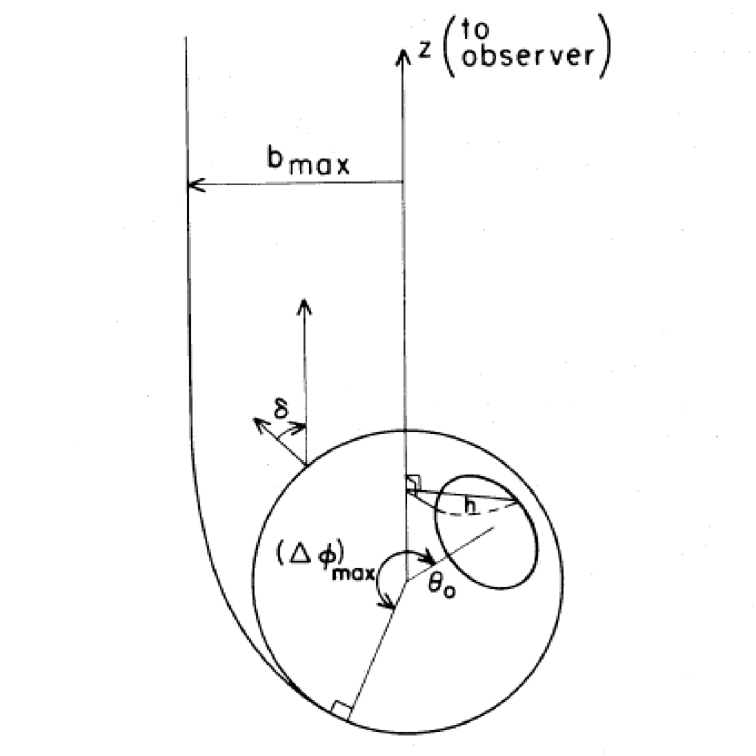


Low-field carbon atmosphere can fit the data.
Before all fits provided a very small emitting area.

0911.0672

Gravity Effects

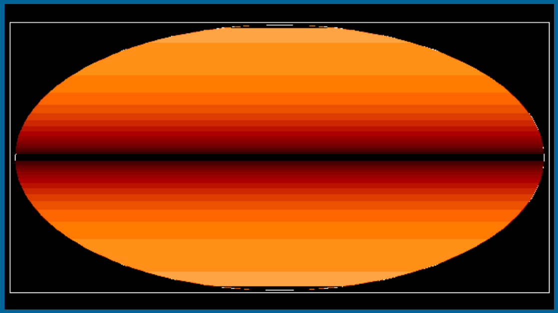
- Redshift
- Ray bending



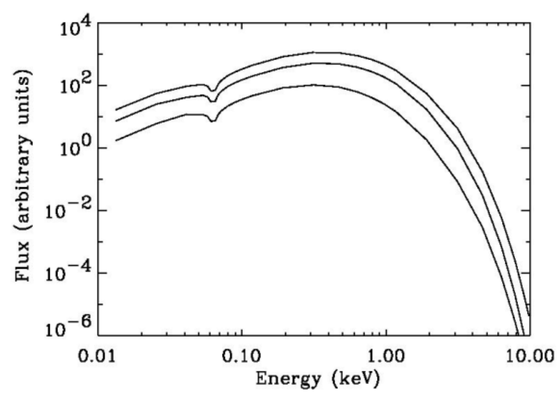
$$L_\infty = 4\pi\, R_\infty^2\, \sigma\, T_\infty^4$$

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

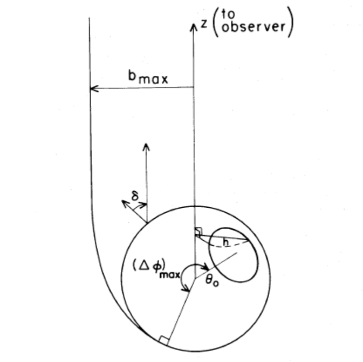
STEP 1
Specify viewing geometry and B-field topology; compute the surface temperature distribution

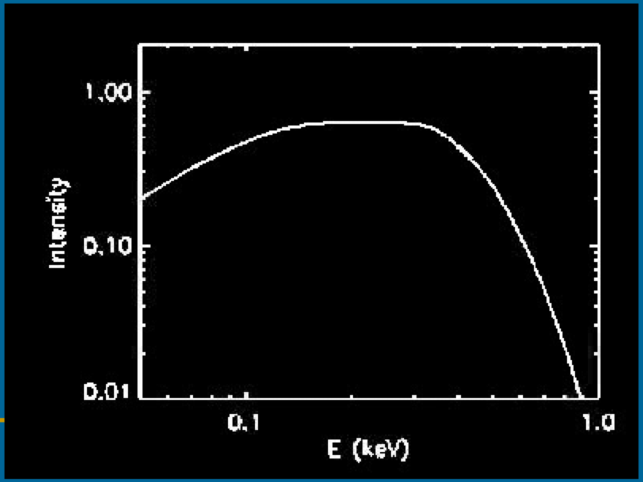


STEP 2
Compute emission from every surface patch



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 $\approx$ 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 ($P \approx 3\text{-}10$ 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?
  $\dot{M}_{Bondi} \sim n_{ISM}/v^3$ 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

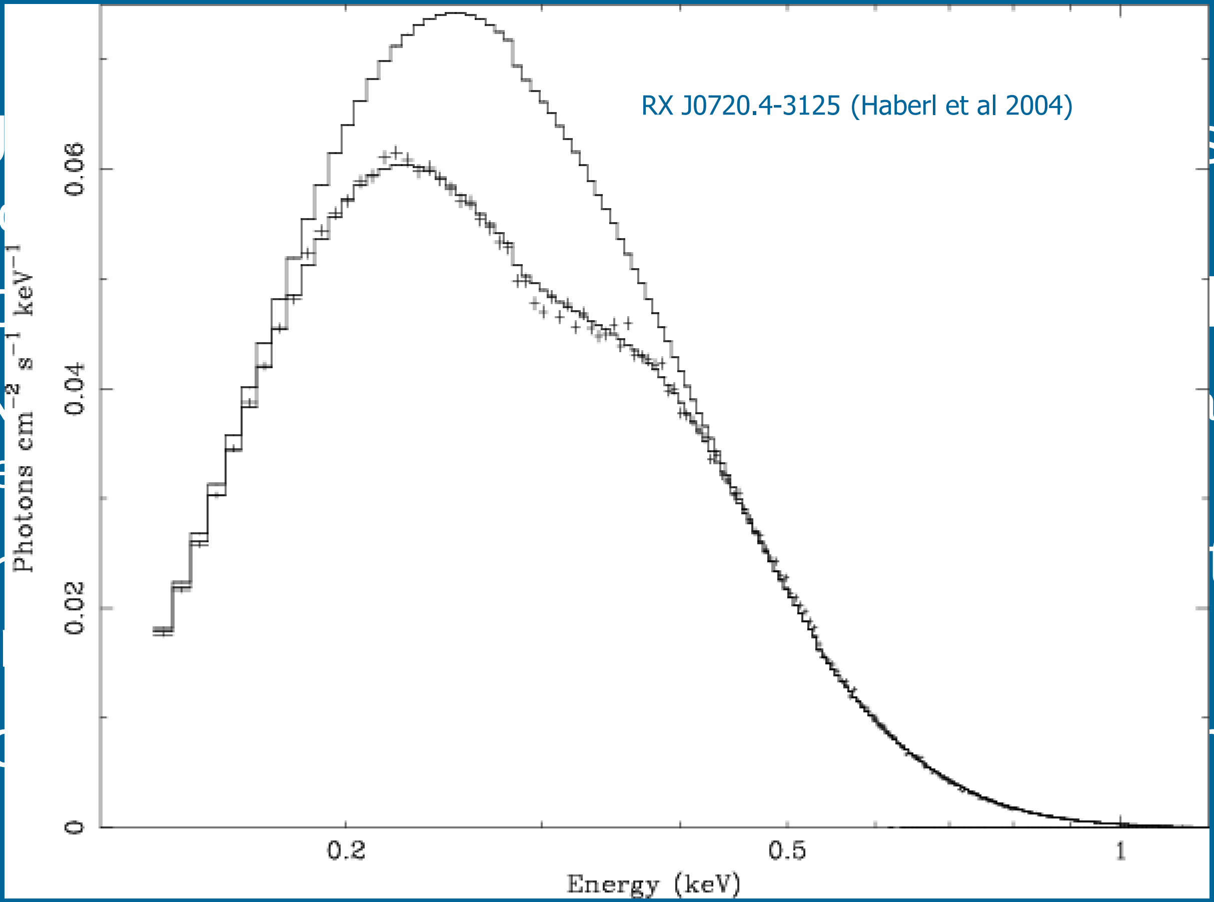
Note a claim for an excess at harder (keV) X-rays: 1703.05995

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 !

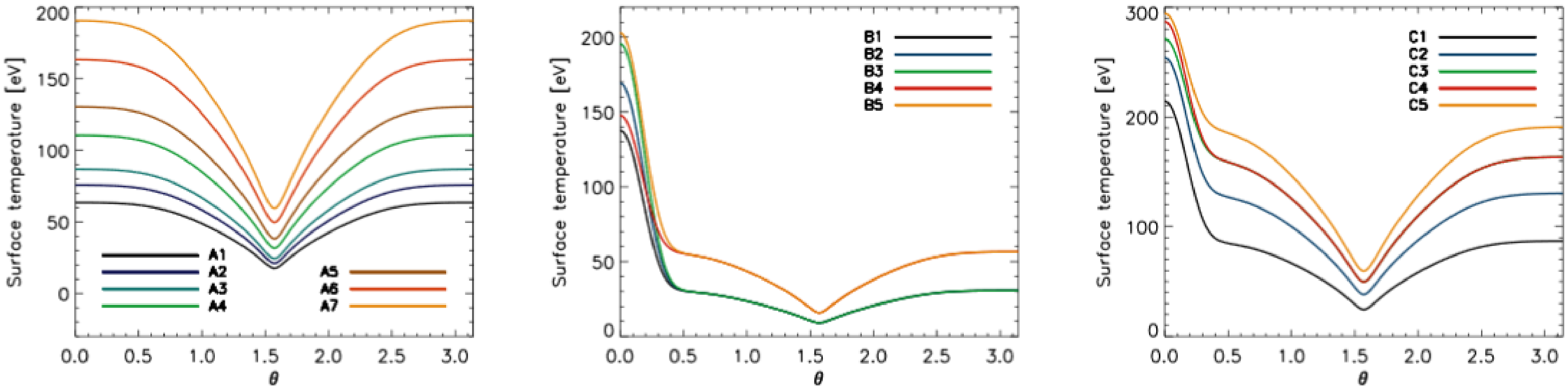


- RX J … s (Chanc …
- A bro … her ICoN … al 2004; Zane e …
- E_{line} … th E_1 ~ $2E_2$ i …
- Proto … high B ?

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	-

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]

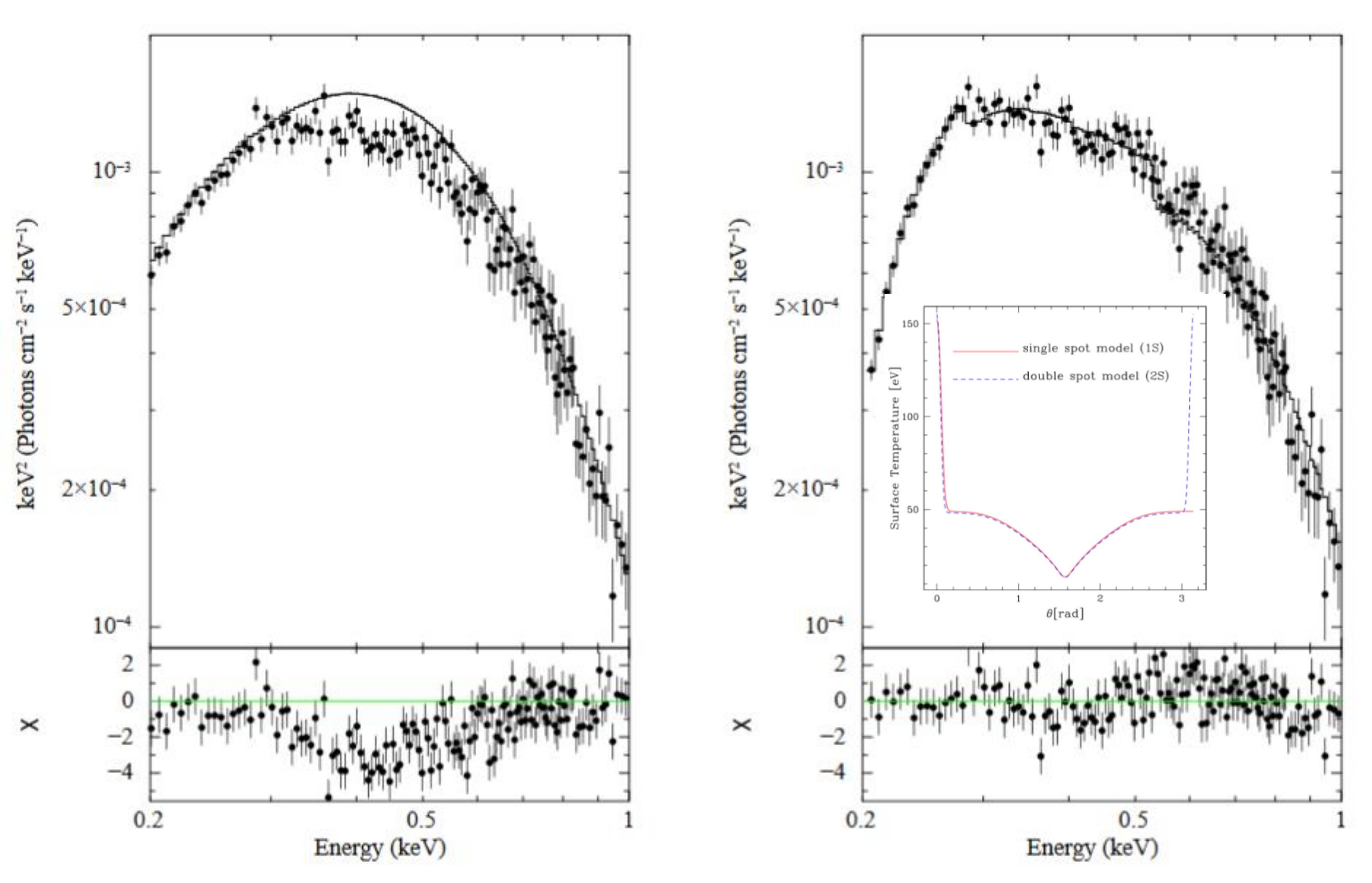


1406.0874

RX J0806.4-412

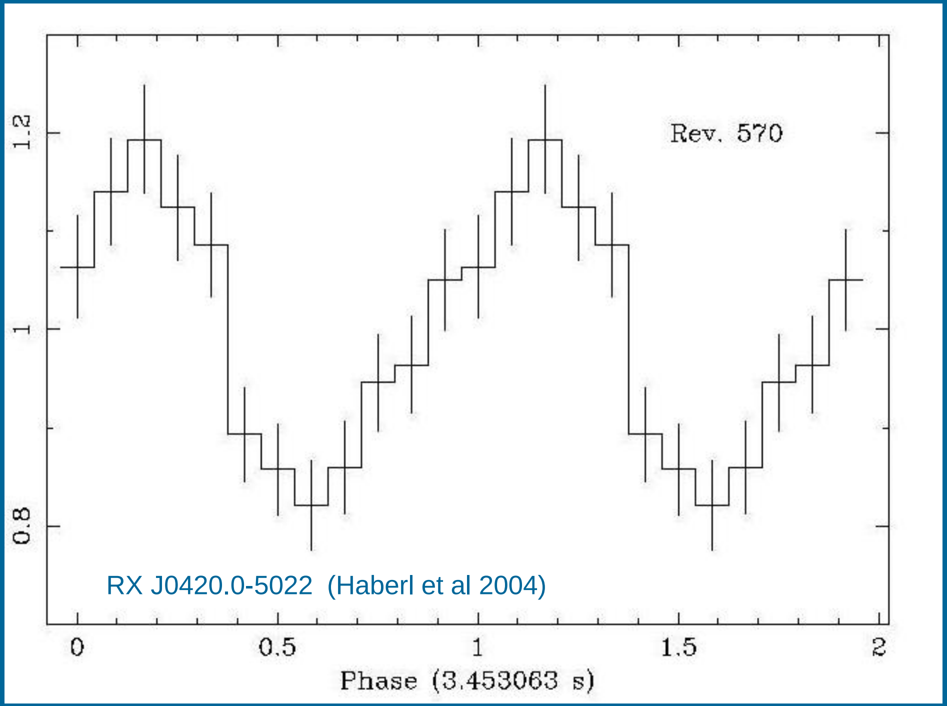
BB+line

Non-uniform distrubution



1406.0874

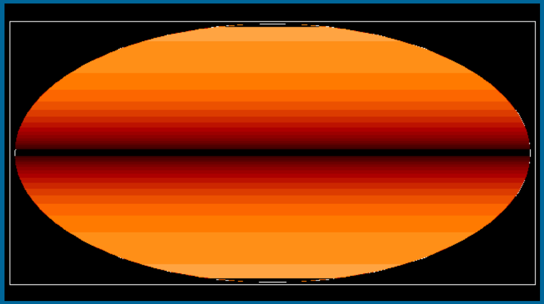
Pulsating ICoNS - I



- 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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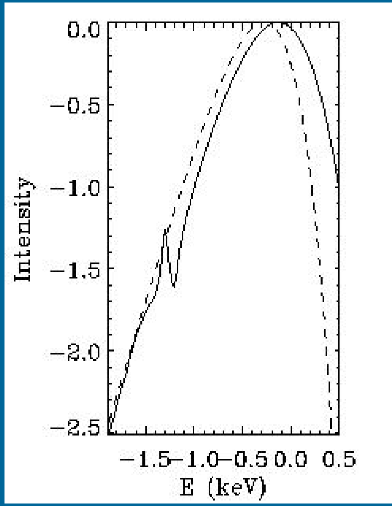

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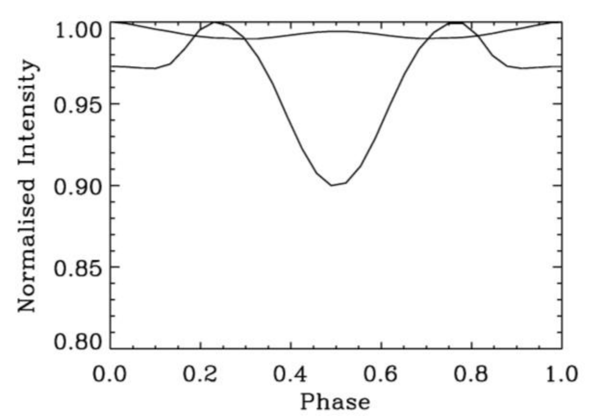
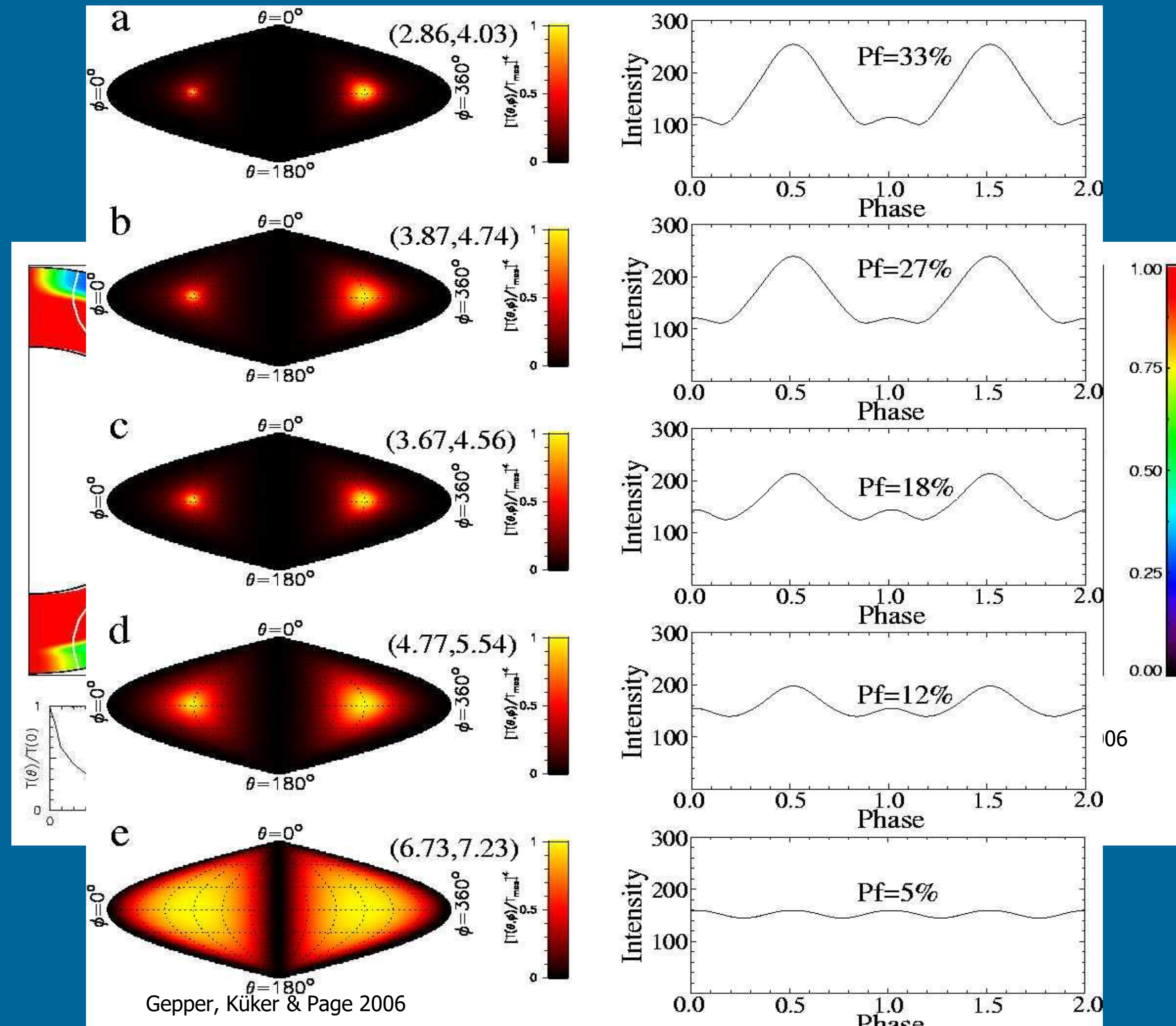
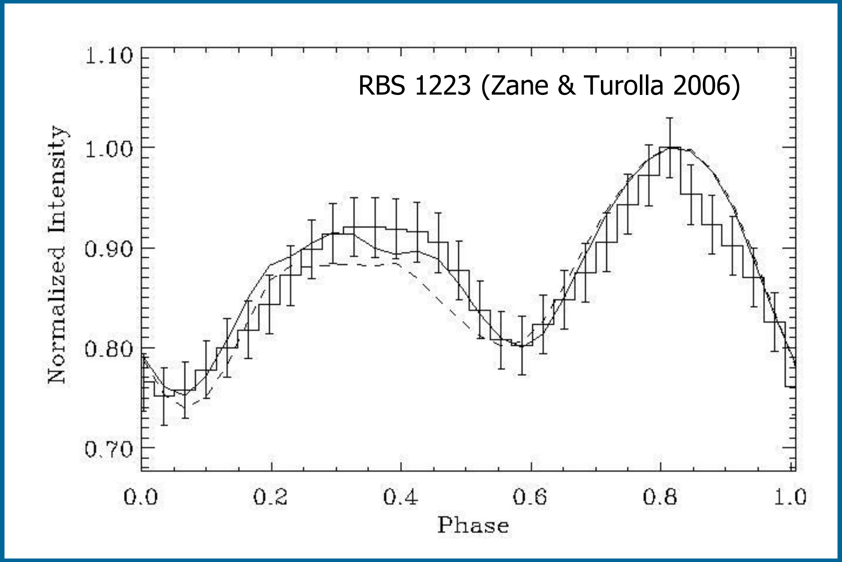
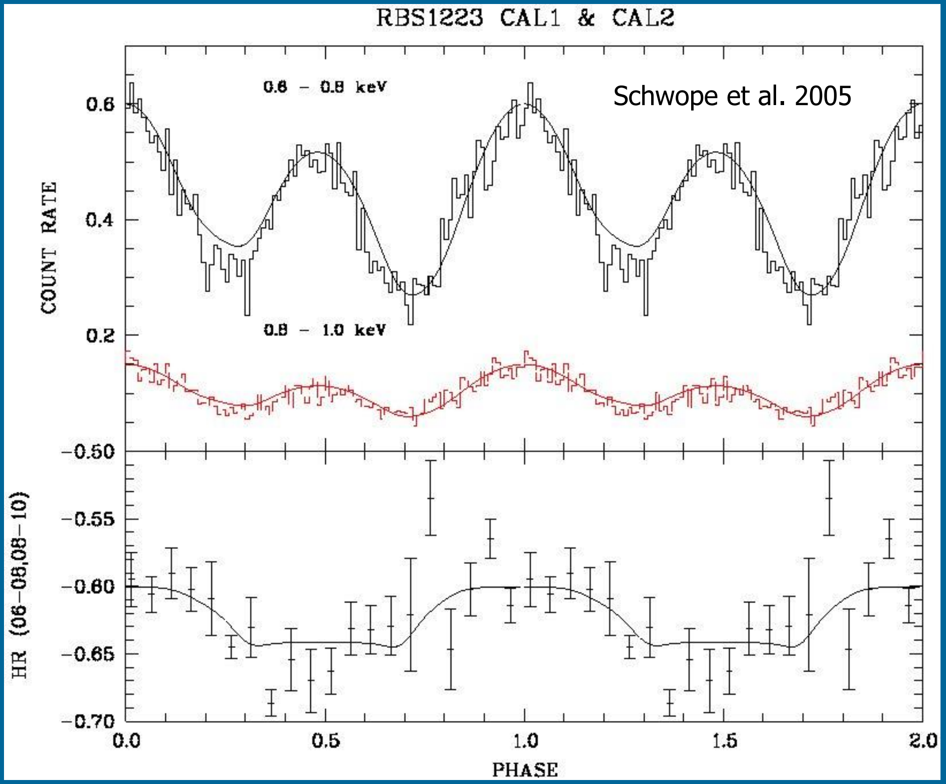


Crustal Magnetic Fields

- 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





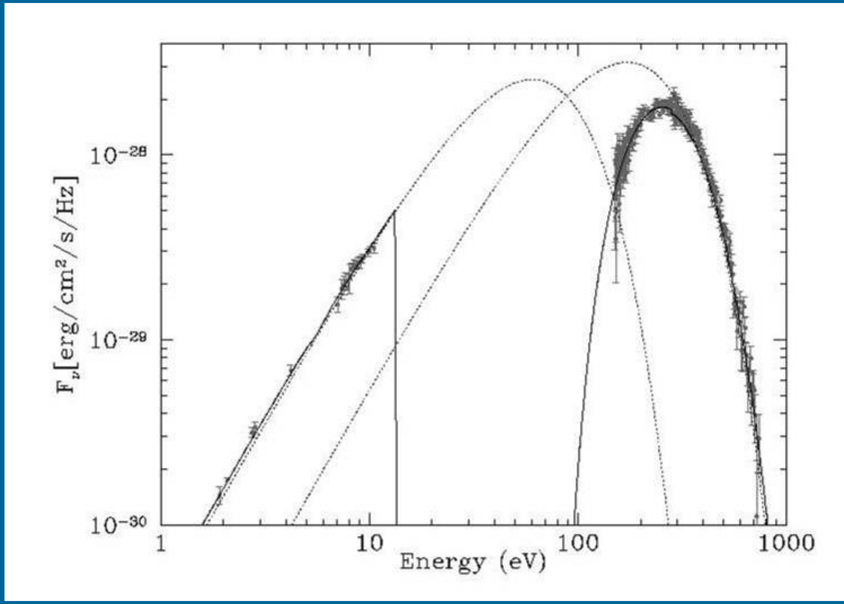


Indications for non-antipodal caps (Schwope et al 2005)

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

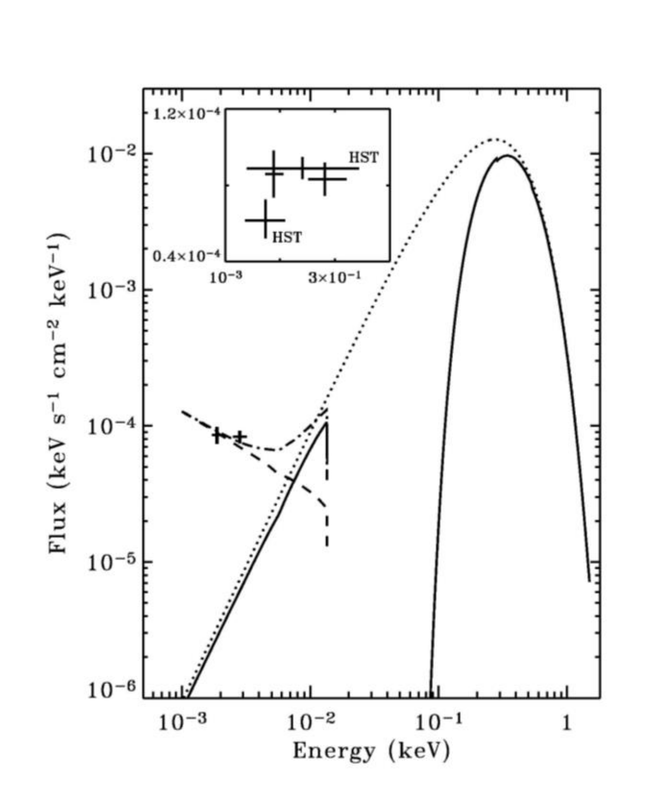
RX J1856.5-3754 - II

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)

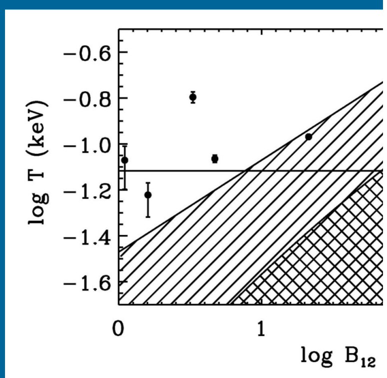
- In the most of the sources with a confirmed optical counterpart $F_{opt} \approx$ 5-10 x $B_\nu(T_{BB,X})$
- $F_{opt} \approx \nu^2$?
- Deviations from a Rayleigh-Jeans continuum in RX J0720 (Kaplan et al 2003) and RX J1605 (Motch et al 2005). A non-thermal power law ?

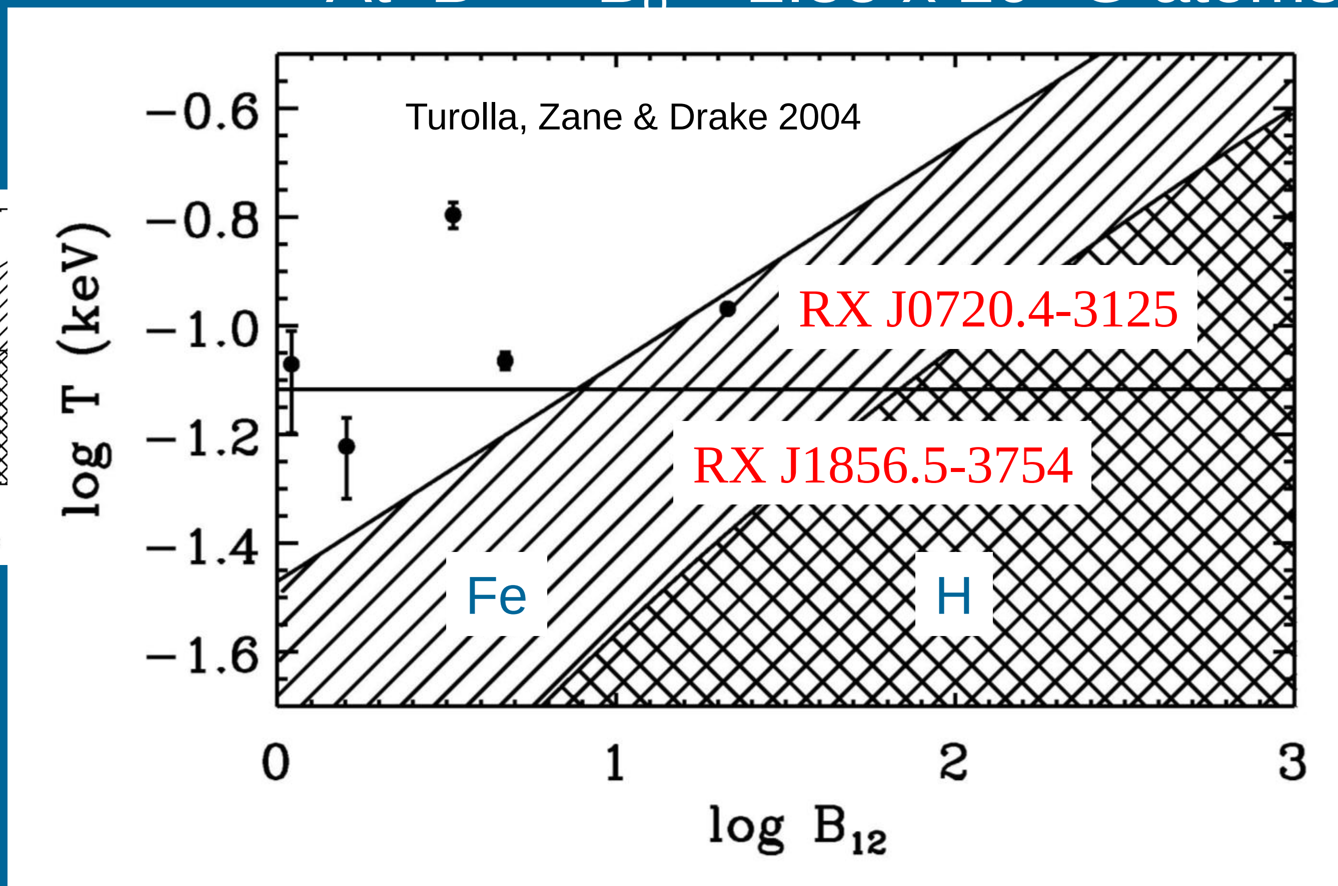
Bare Neutron Stars

- At B >> B_0 ~ 2.35 x 10^9 G atoms

of a

e

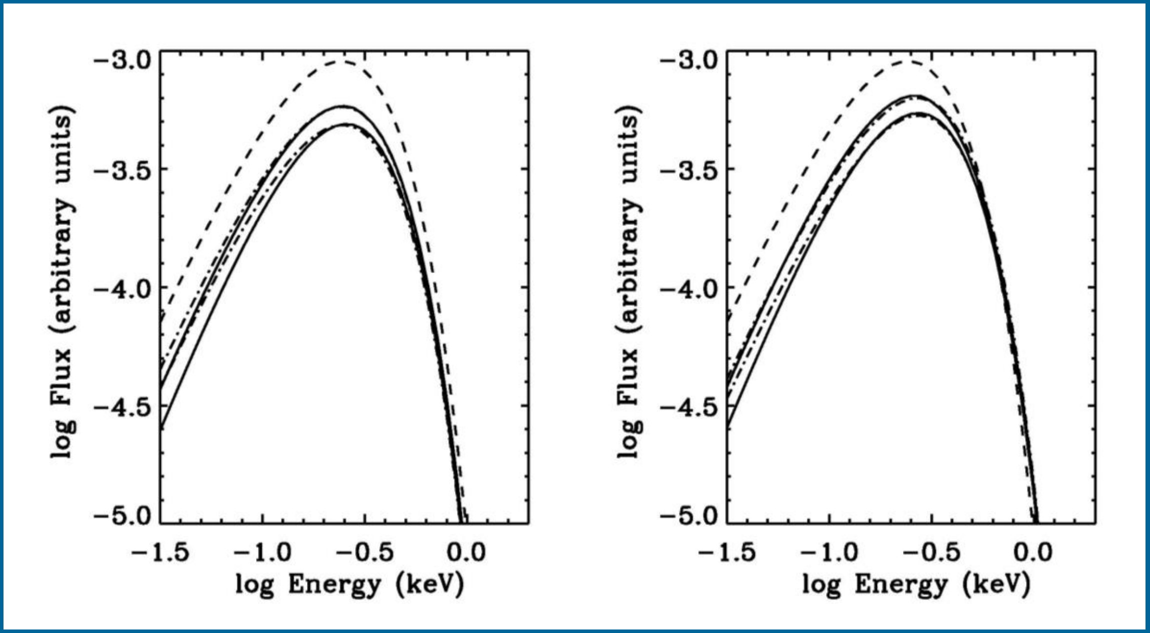




Spectra from Bare NSs - I

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.

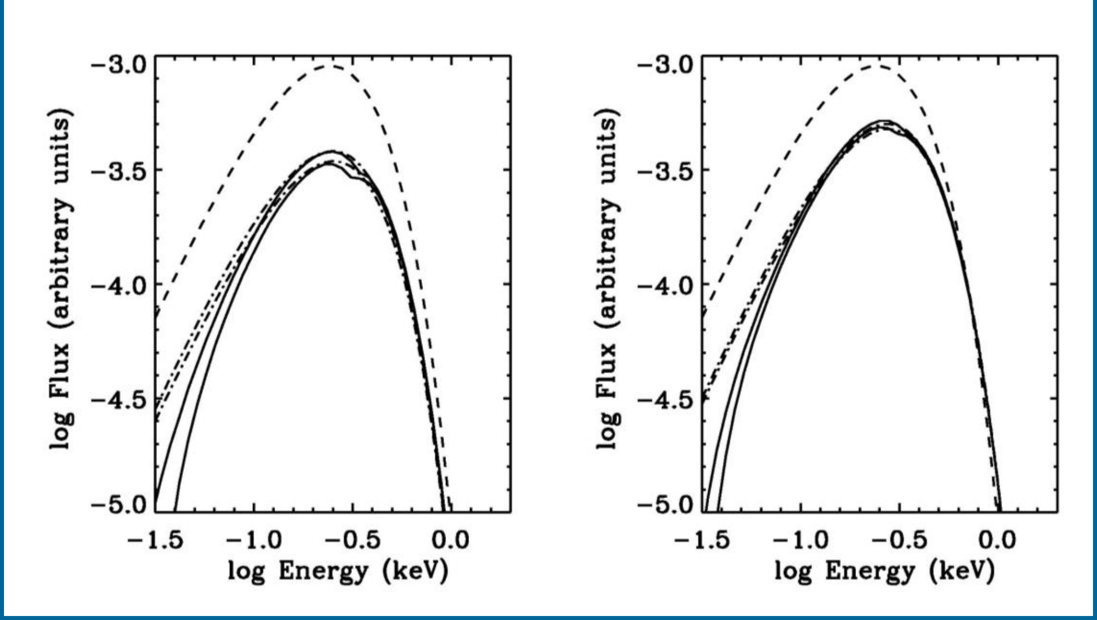


Turolla, Zane & Drake (2004)

Spectra from Bare NS - II

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

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

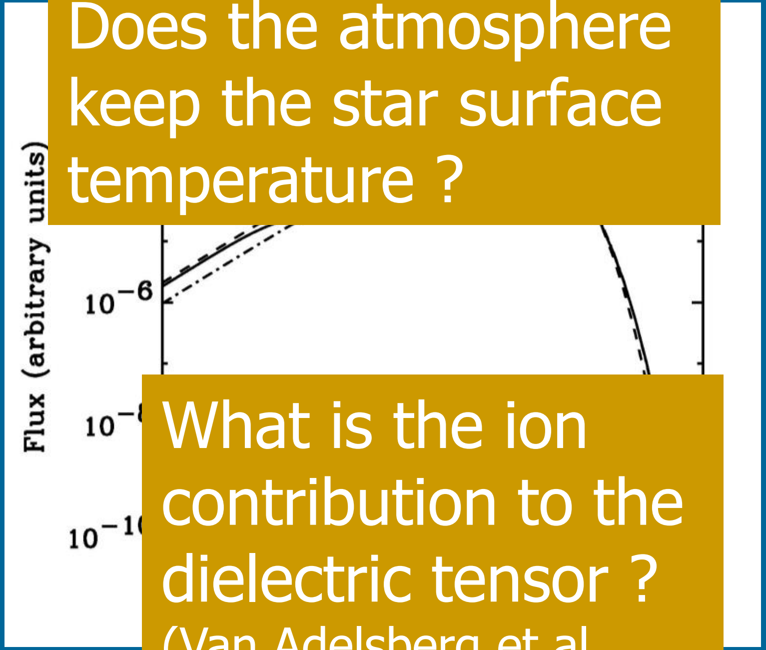


Turolla, Zane & Drake (2004)

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

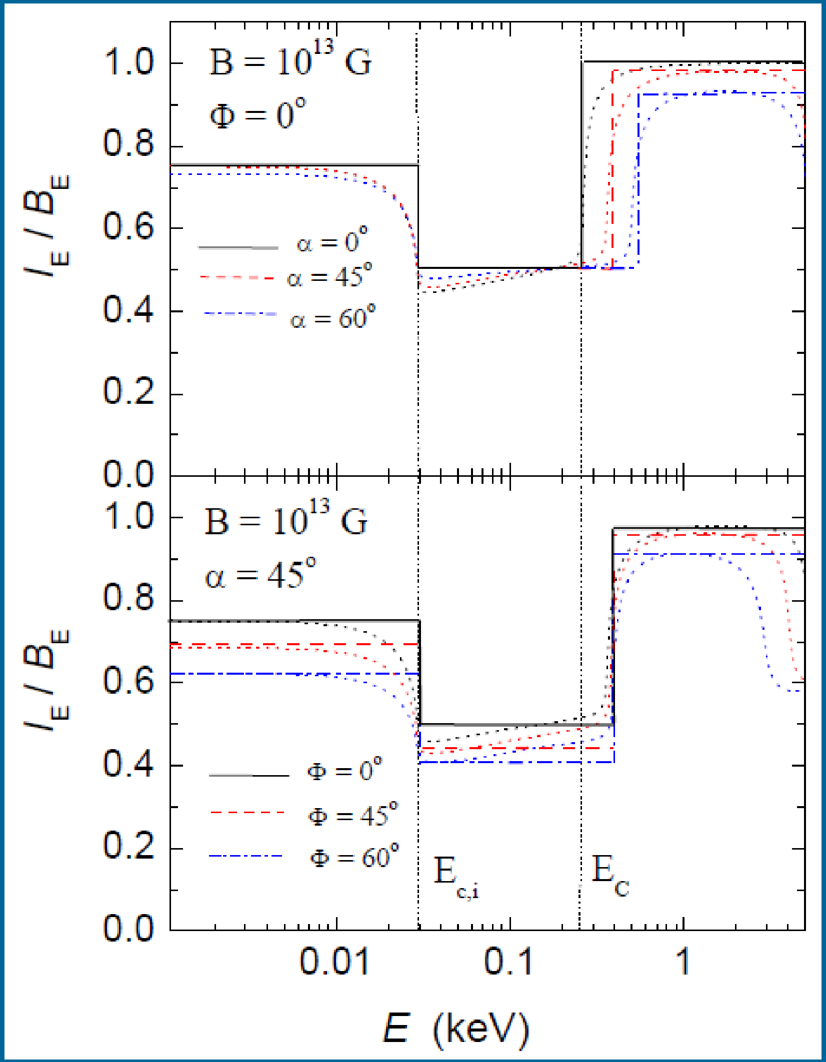
$$R_\infty = 4.25\, f_E^{-1/2} \left(\frac{D}{100\ \mathrm{pc}} \right) \left(\frac{T_{BB}}{60\ \mathrm{keV}} \right)^{-2} \mathrm{km}$$



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)

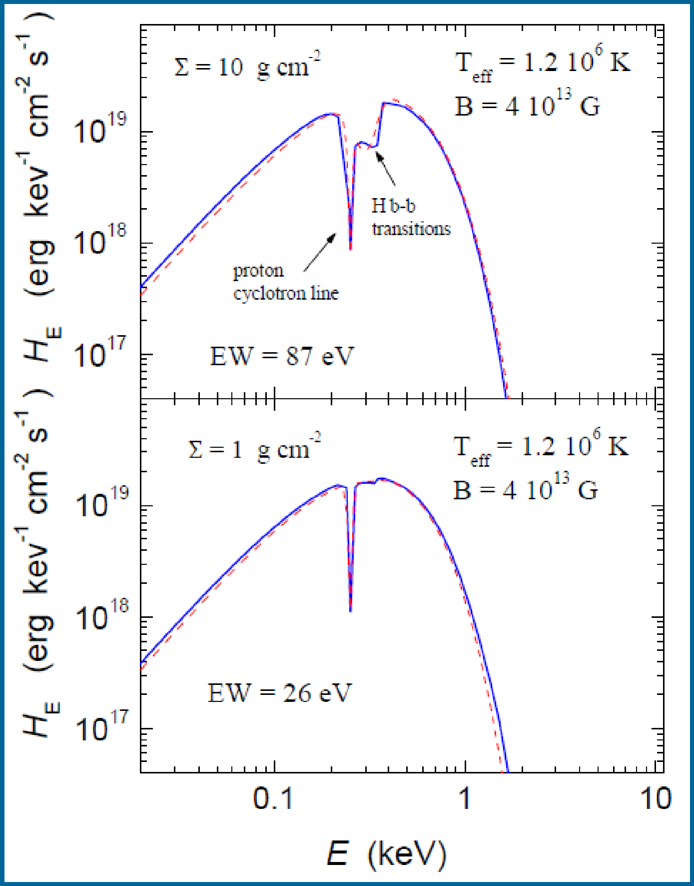
Condensed iron surface emissivity

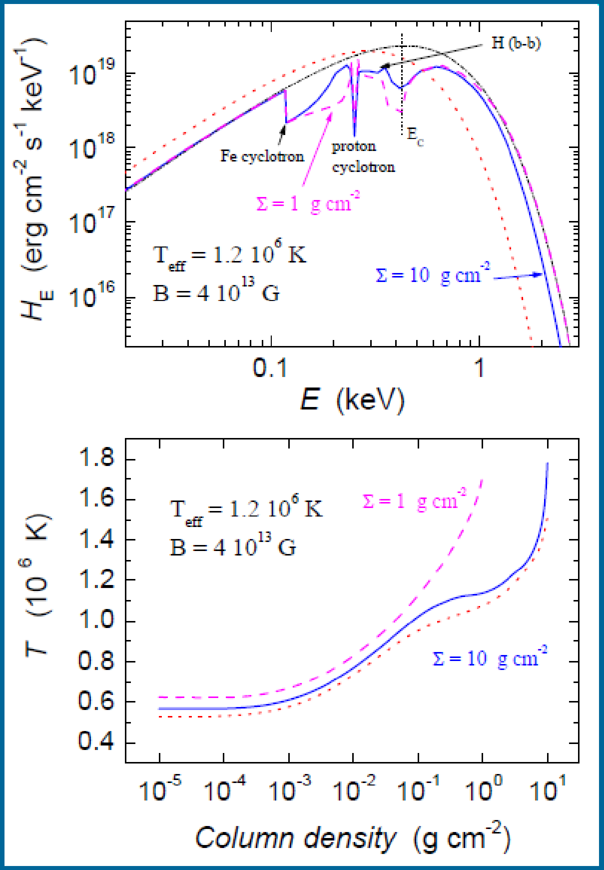


Free ions approximation.

1006.3292

Thin hydrogen magnetized atmosphere above blackbody and iron condensed surface



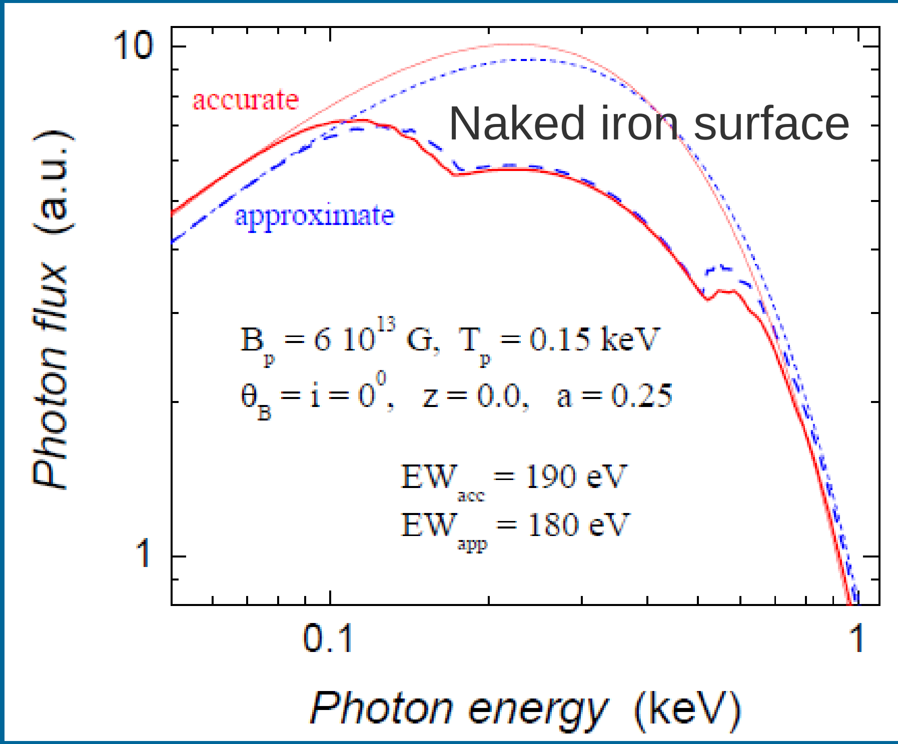


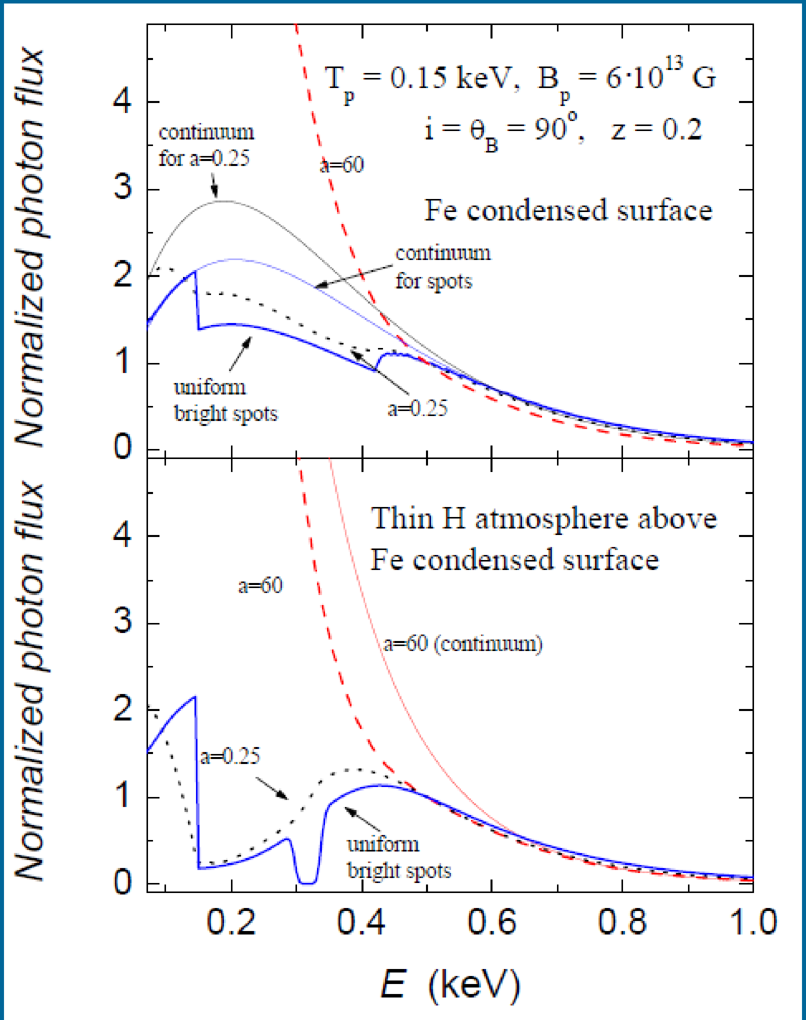
Below atmosphere was a blackbody spectrum

Below – iron condensed surface

1006.3292

Let us make it realistic





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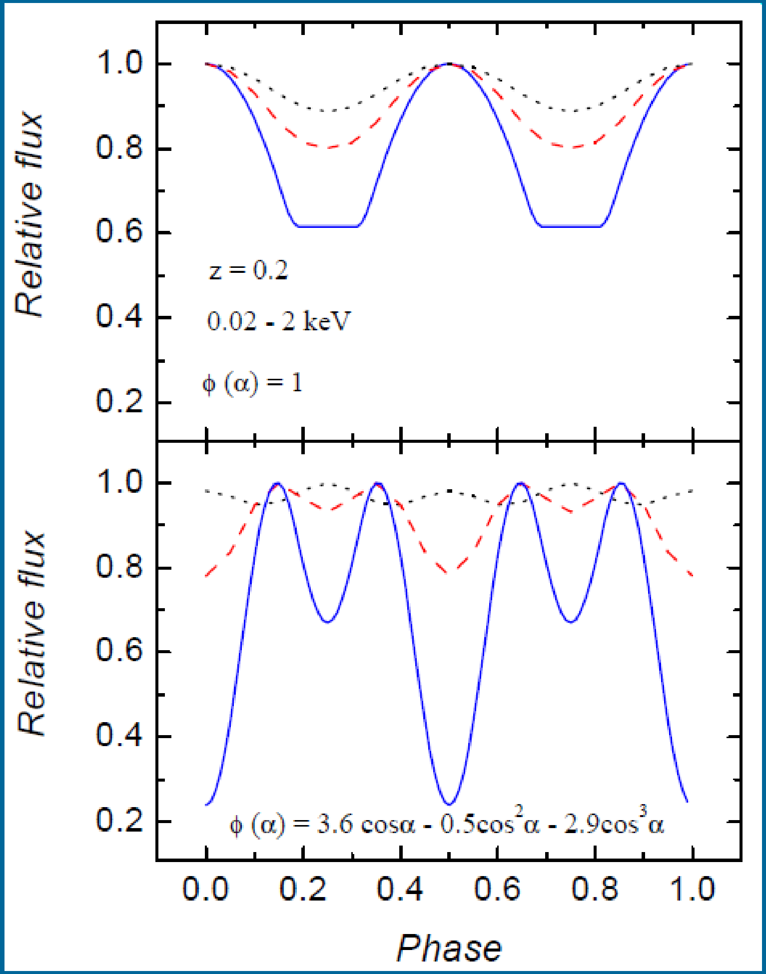
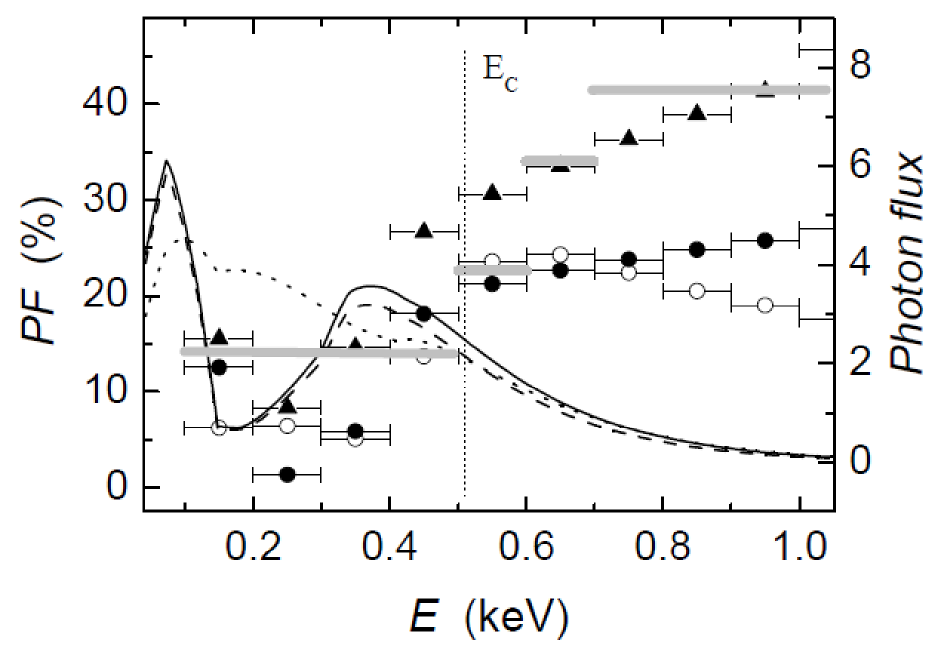
Light curves and pulsed fraction



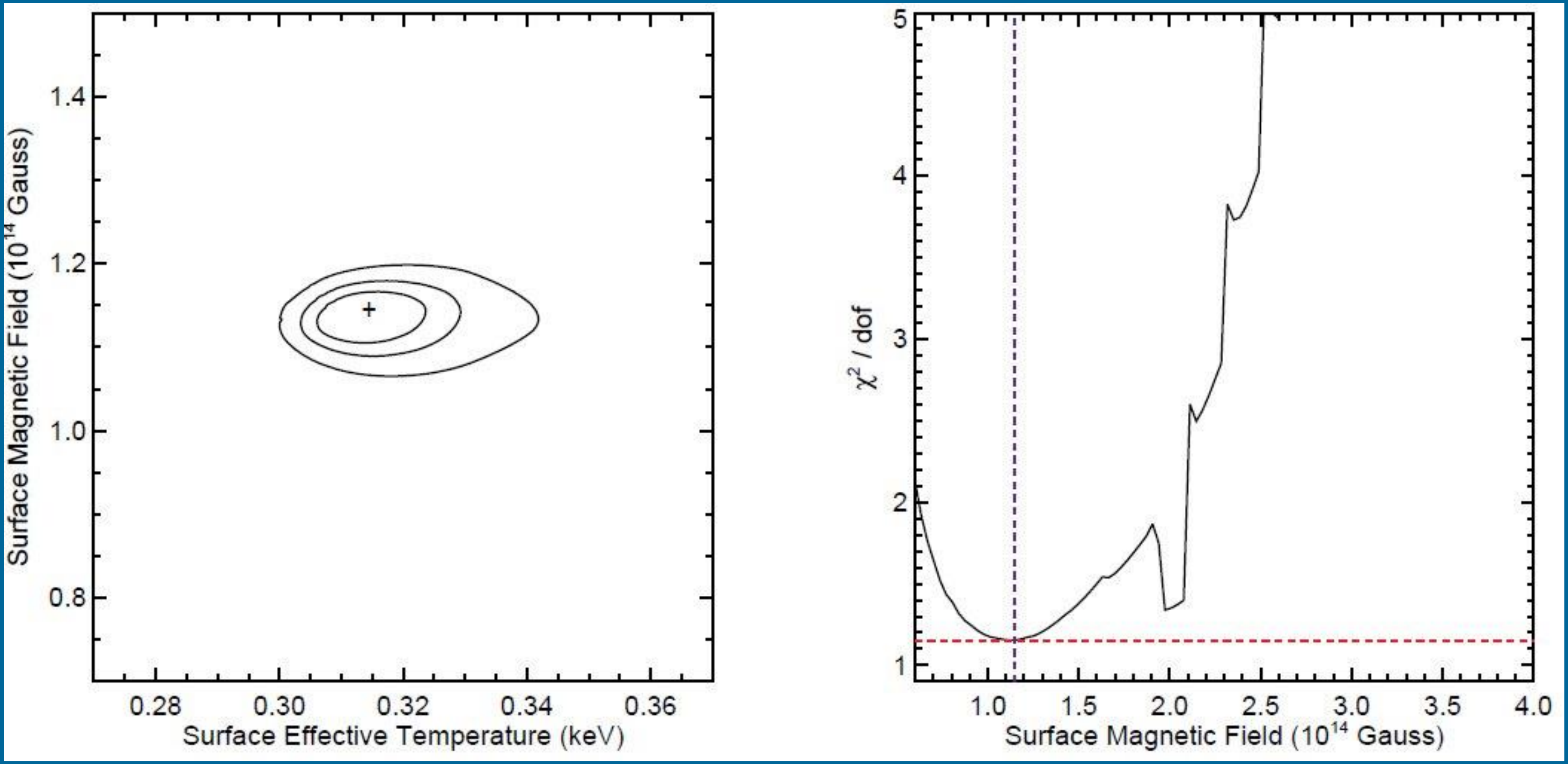


1010.0125

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.

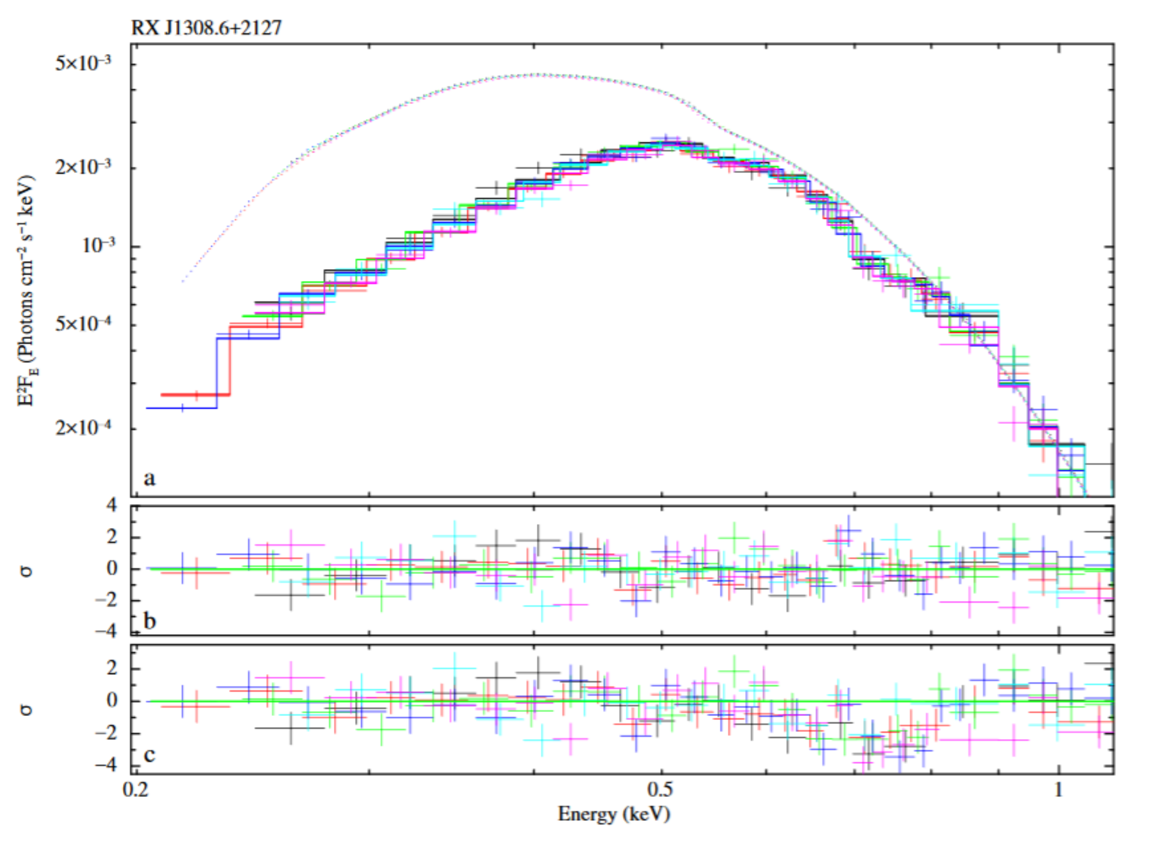


1103.3024

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

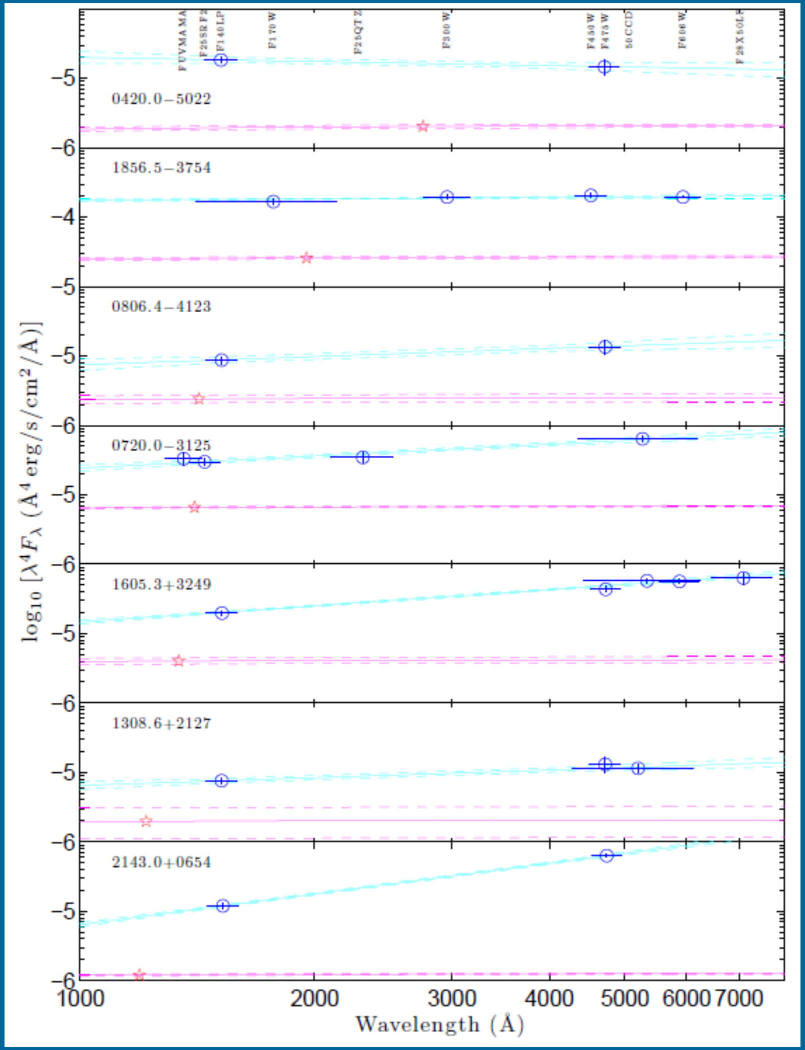
- astro-ph/0702426 ←
- arXiv: 0801.1143
  or astro-ph/0609066 } Reviews on the M7
- astro-ph/0206025 ←
- arXiv: 0905.3276
- arXiv: 1006.3292 } Recent calculations of spectra from magnetized atmos.
- arXiv: 1210.0916 - review

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

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

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

Does the atmosphere keep the star surface temperature ?