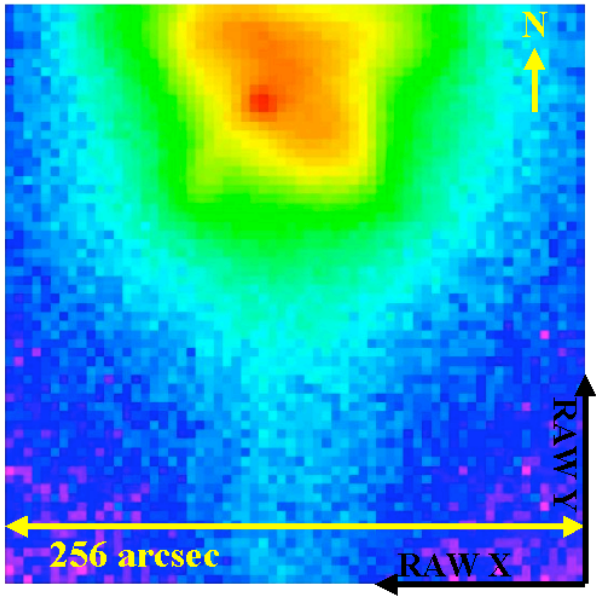
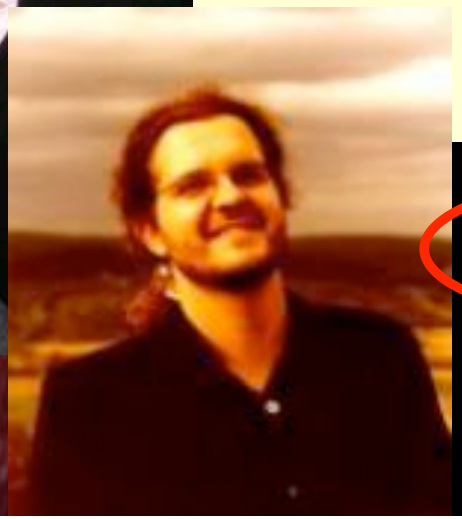
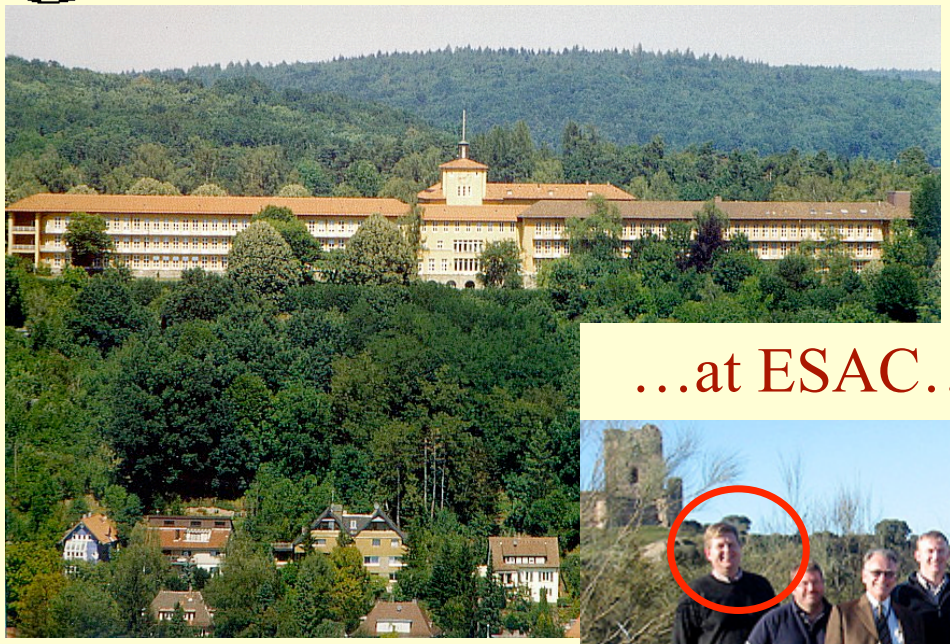
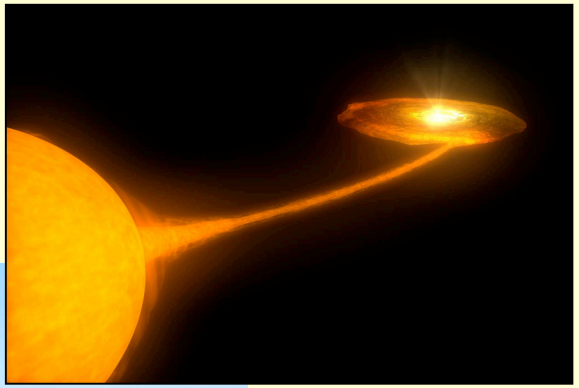
Trainee project 2004





PhD in Tübingen …



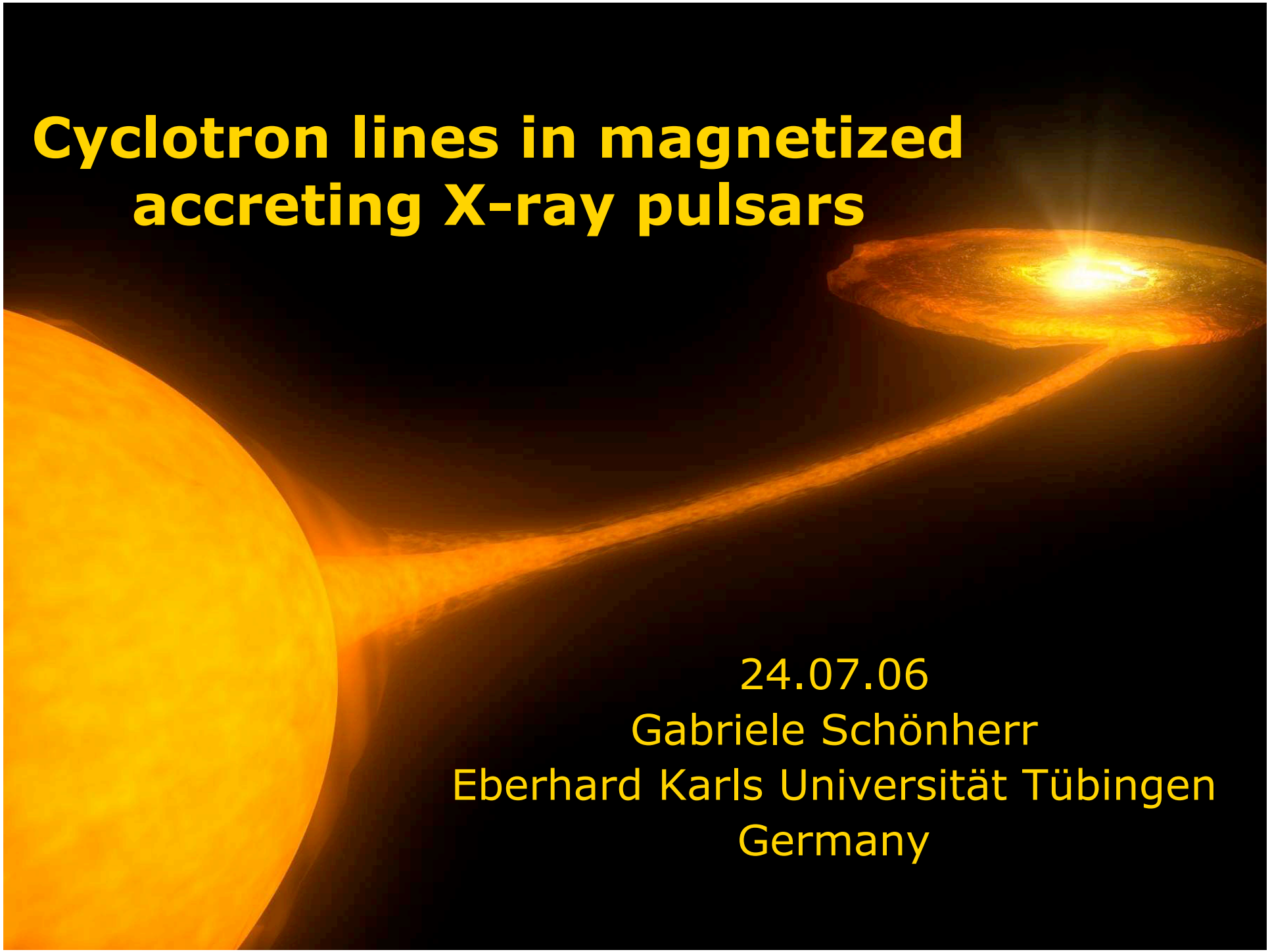


…at ESAC…

…and in Warwick

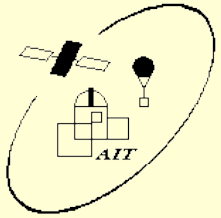
THE UNIVERSITY OF WARWICK

Cyclotron lines in magnetized accreting X-ray pulsars



24.07.06

Gabriele Schönherr
Eberhard Karls Universität Tübingen
Germany



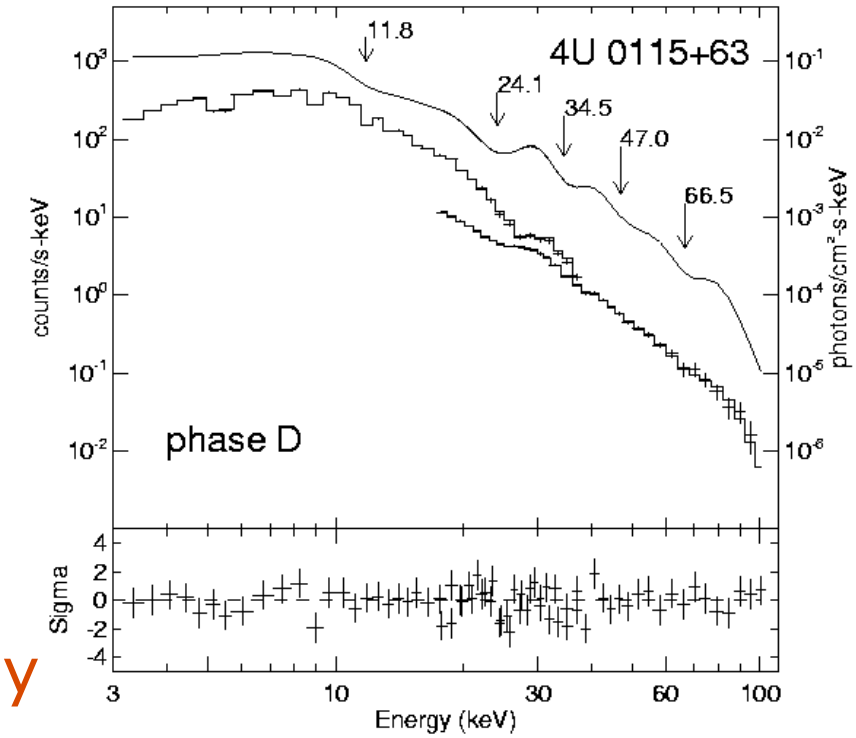
Outline

- Motivation
- Basic physics
  - Neutron Star characteristics
  - Accretion mechanisms & geometry
  - Cyclotron resonance scattering features
- Observations and Models
  - Observational data
  - Monte Carlo simulations
  - Comparison
- Summary and outlook

Eberhard Karls
Universität
Tübingen

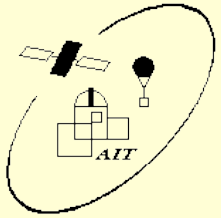
Detection of cyclotron lines

- First line seen in 1978 in Her X-1 spectrum (Trümper et al. 1978)
- Record holder until today: 4U 0115+63 (Heindl et al. 1999)



Line energies:
only method to directly measure B-field of an accreting neutron star!

Eberhard Karls Universität Tübingen



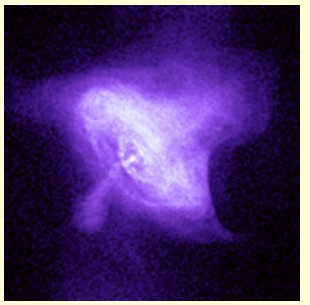
Diagnostic power

Line position and profile of cyclotron resonce scattering features (CRSF) depend on:

- B-field strength
- Physical conditions of the plasma (temperature, optical depth,...)
- Geometry of the accretion

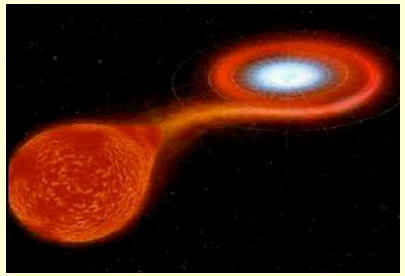
... HOW?

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

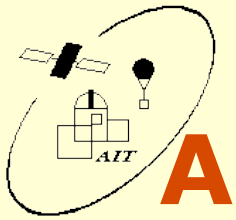


Neutron Stars

- Compact remnants from massive stars of ~25 $M_\odot$
- Extremly high densities (7×10^{14} g cm^{-3})
- Very strong magnetic fields (B~$10^{12\ldots14}$ G)
- Fast rotation (P ~ 1000s - 1ms)
- Strong gravitational fields
- Isolated NS ("radio pulsars") and accreting binary NS systems ("X-ray binaries")



Eberhard Karls
Universität
Tübingen



Accretion-powered emission

Accretion mechanisms

Roche overflow

Her X-1

• LMXB (companion<2.5$M_\odot$)

Accretion disk

Be mechanism

V0332+53

4U 0115+63

• HMXB transient systems

Accreting in periastron (disk?), X-ray outbursts,

wind accretion?

Stellar wind

Vela X-1

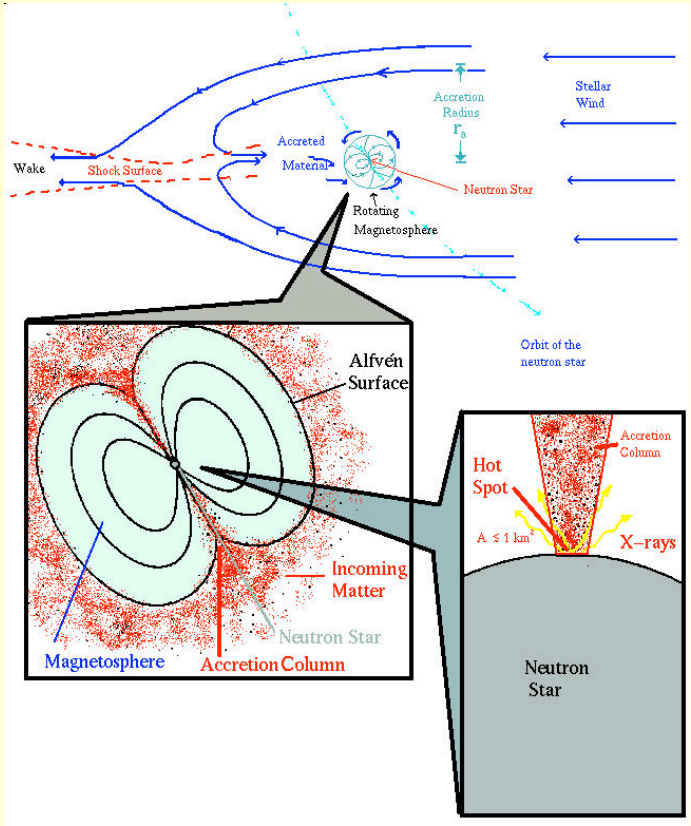
• HMXB (supergiant companion)

Direct accretion, accretion gas stream, accretion disk?

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Magnetosphere

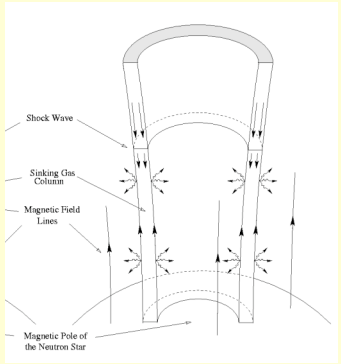
Accretion flow inside the magnetospheric radius



- Flow couples to magnetic field at Alfvén radius [Roche: disruption of disk]
- Channeling of material along field lines towards surface
- Formation of accretion columns at polar caps

Eberhard Karls Universität Tübingen

Accretion column



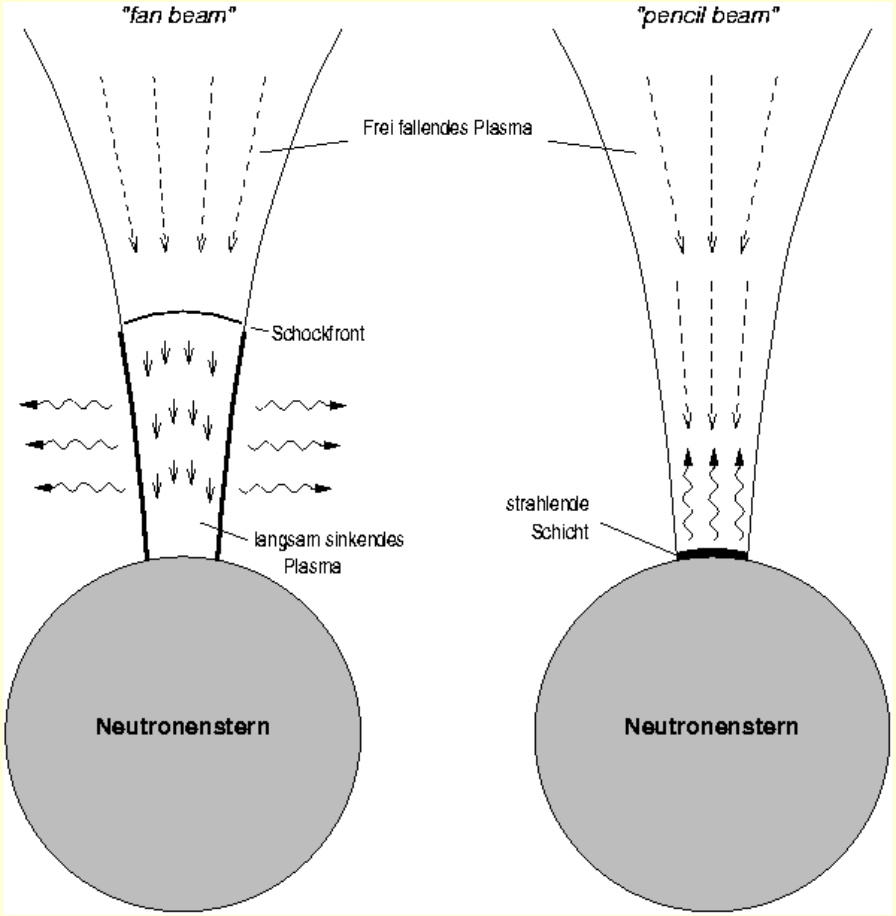


Fig. from Kretschmar (1996) after Harding (1994)

Hollow cylinder

- High $\dot{M}$ ->"fan beam": shock front decelerates infalling plasma, perpendicular photon emission
- Low $\dot{M}$ ->"pencil beam": no shock, direct fast infall, parallel photon emission

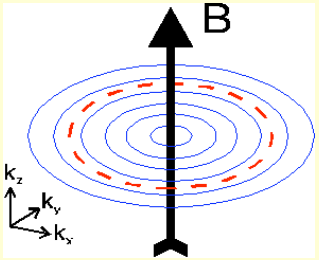
Limiting cases -> slab or cylinder geometry

Eberhard Karls Universität Tübingen

CRSF: theory

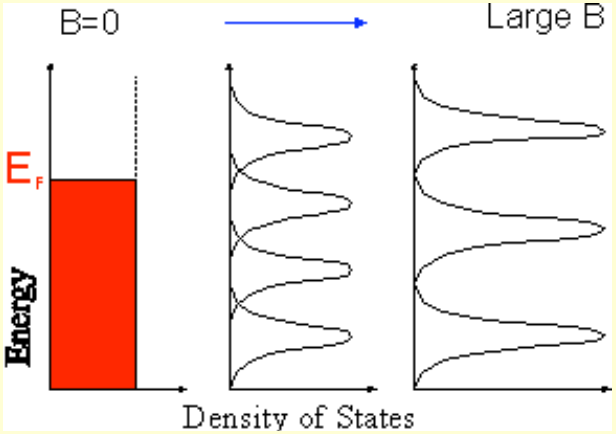
Classical: Spiraling motion of an electron in magnetic field

- $r = m\, v_z / e\, B$
- $\omega = e\, B / m$



Quantization of electron energy in Landau levels

if $r \sim \lambda_B = \hbar / mv$

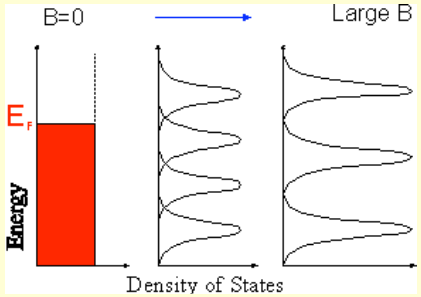


- $E_n = mc^2\sqrt{1+(p/mc)^2 + 2n(B/B_{crit})}$
- $B << B_{crit}$: $E_{n+1} - E_n = E_{cyc} = \hbar\omega$
  $= 11.6\ \text{keV}\ B_{12}$

(non – relativistic)

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

CRSF: theory



Lines form in "absorption":

- photon with n x E_{cyc} is absorbed by electron
- electron is excited to a n x higher Landau level
- lifetime of excited Landau level is very short; typical decay rate $\sim 10^{15}\, B_{12} s^{-1}$
- de-excitation of electron to ground state directly or via photon spawning under emission of one photon with n x E_{cyc} or n photons of E_{cyc}
- mean free path of photons of these energies is very short
- Quasi instantanous recapturing of the photon(s)

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

CRSF: theory

$$E_{n+1} - E_n = E_{cyc} = 11.6 \text{ keV } B_{12}$$

• scattering processes take place near the surface of the NS, gravitational redshift in observations

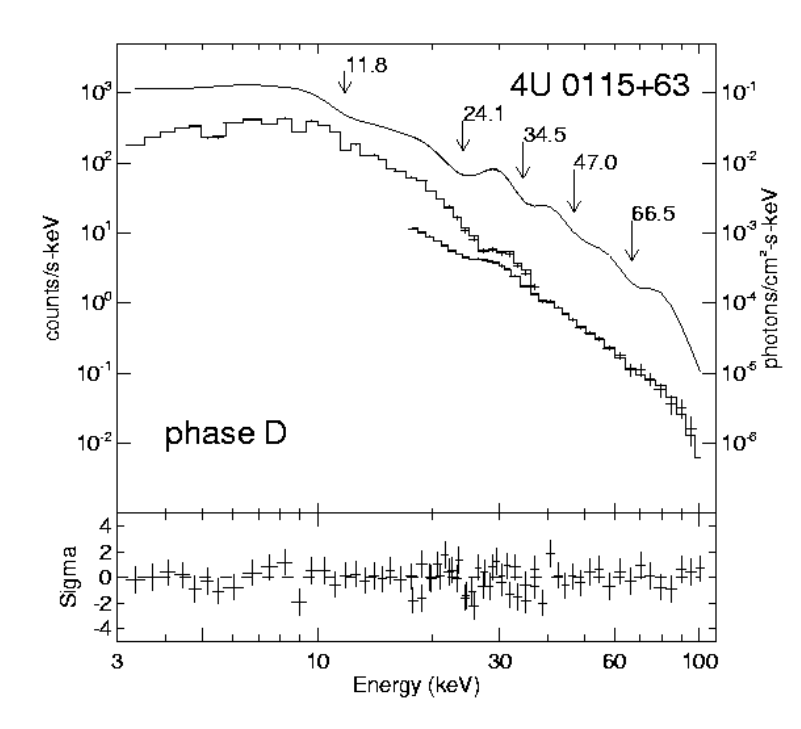
$$E_{cyc}^{(obs)} = (11.6 \text{ keV } B_{12}) / (1+z)$$

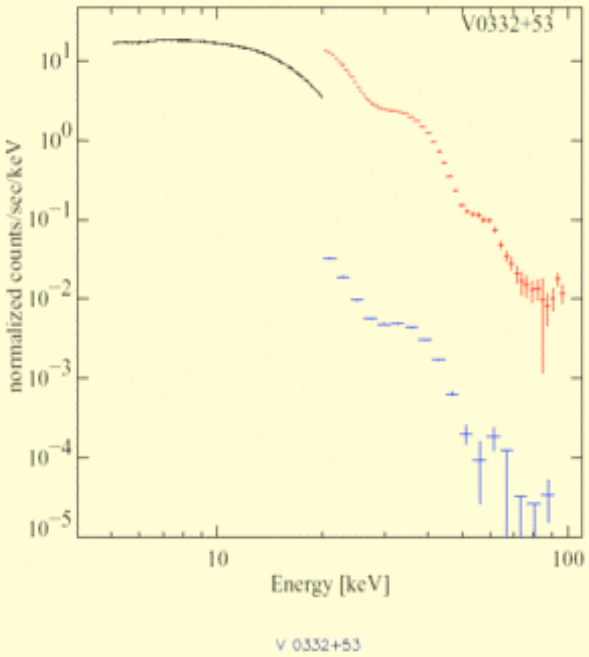
•For high magnetic fields near critical field strength relativistic, angle-dependent cross sections:

$$E_n = (m_e c^2/\sin^2\Theta)(\sqrt{1+2n(B/B_{crit})\sin^2\Theta} - 1)$$

→ Distribution of e-, orientation of magnetic field lines in plasma → geometry of formation region!

CRSF: Observed spectra





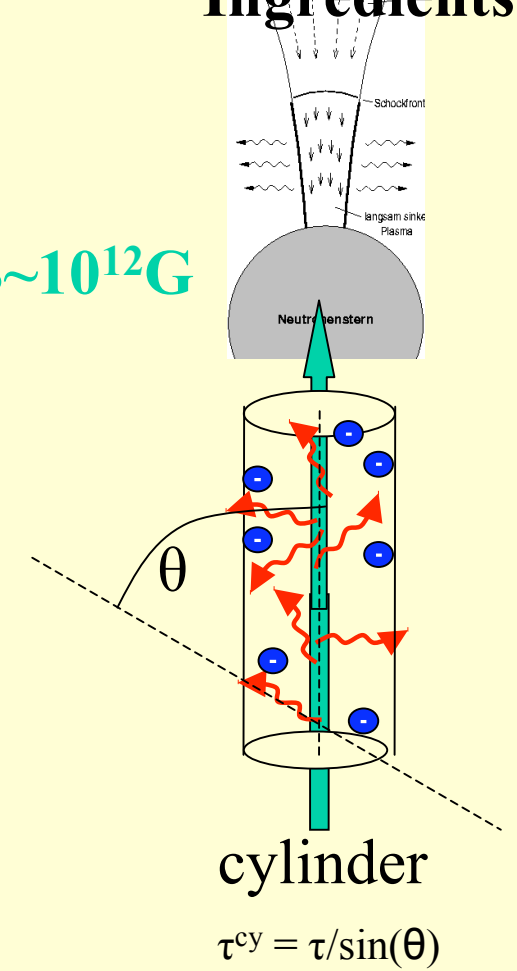
4U 0115+63 (Heindl et al. 1999, RXTE)
V 0332+53 (Kreykenbohm et al. 2005, INTEGRAL)

- Spectral absorption line features: 5 CRSF
- Clear line profiles
- Nearly harmonic spacing (E_{cyc})

Eberhard Karls Universität Tübingen

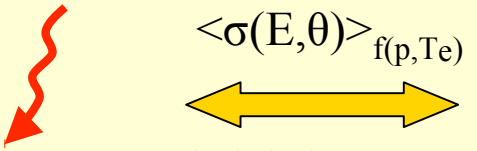
Monte Carlo Simulations

Ingredients: geometry, photons and electrons



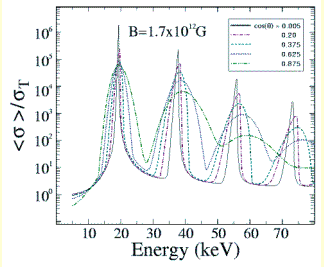
$B \sim 10^{12}$G

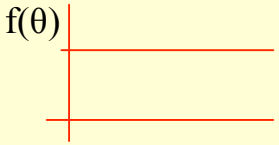
$\tau^{cy} = \tau/\sin(\theta)$



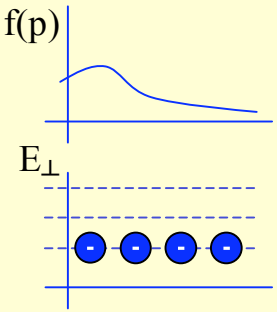
$\langle\sigma(E,\theta)\rangle_{f(p,Te)}$

QM relativistic cross sections





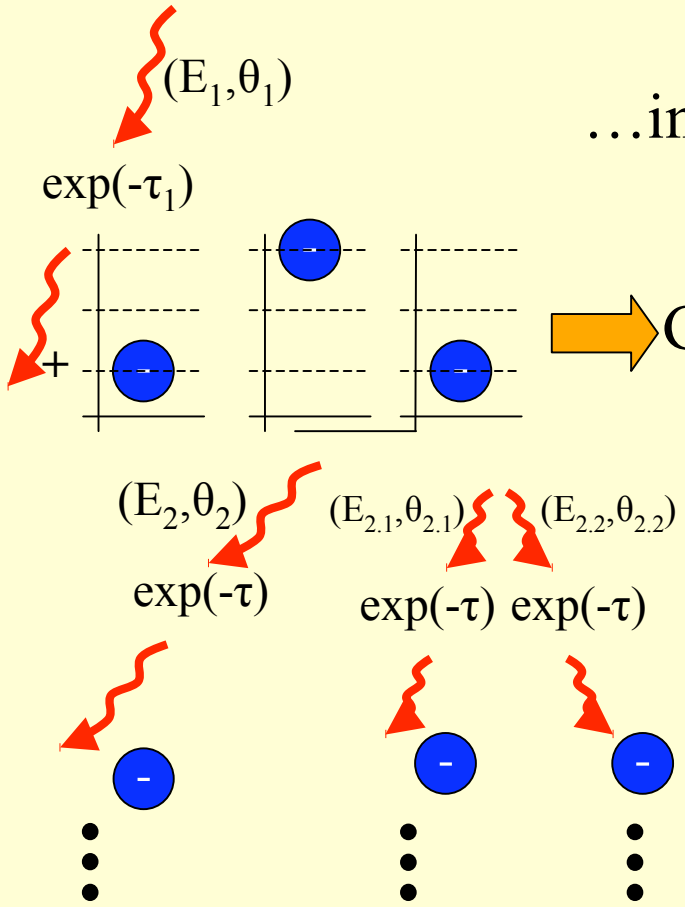
- isotropic injection
- internally irradiated plasma



- electron temperature T_e
- rel. Maxwellian distribution
- ground Landau state
- low-density plasma

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

MC Simulations II

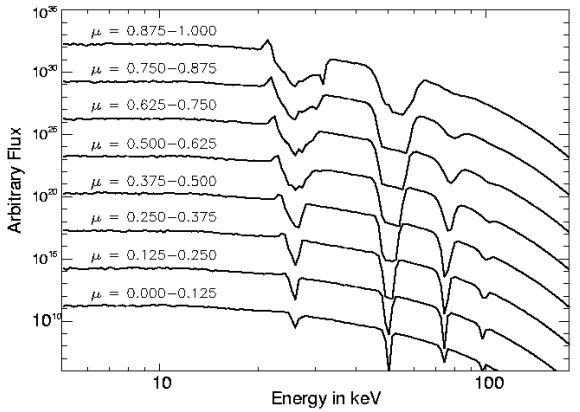


…inject 10,000 photons for each E_1...

$G(E,\theta \rightarrow E', \theta')$

Continuum spectrum

Folded spectra with cyclotron lines



Spectra for varying B, Te, geometry

Eberhard Karls Universität Tübingen

Variation of line profiles

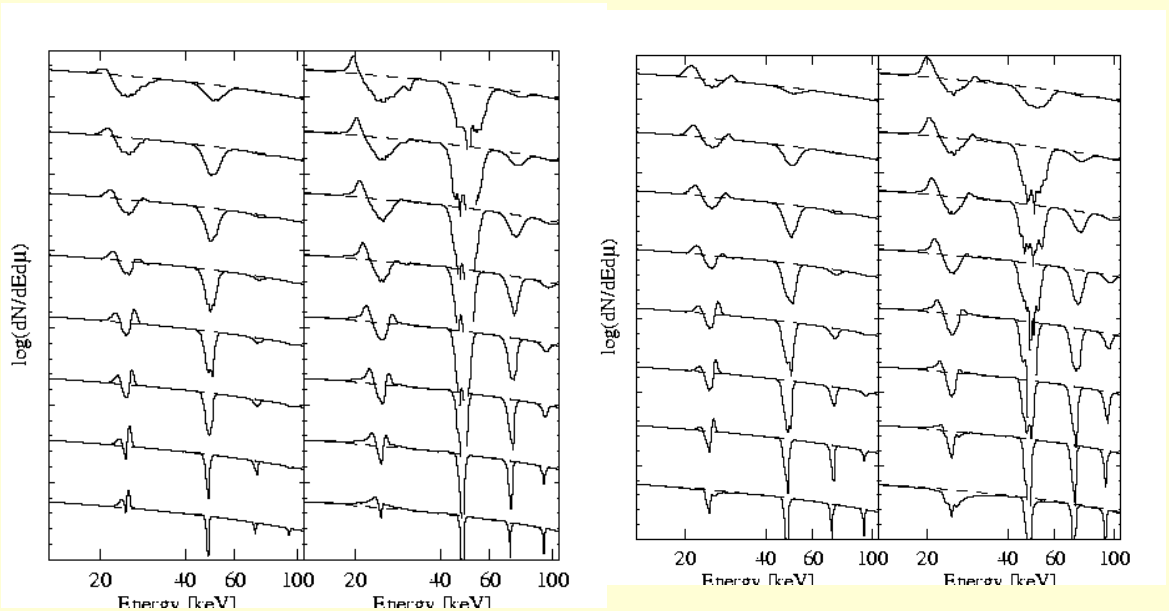
…with B

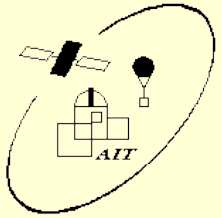
…with the continuum…

…with geometry…

…photon angle…

…and optical depth…





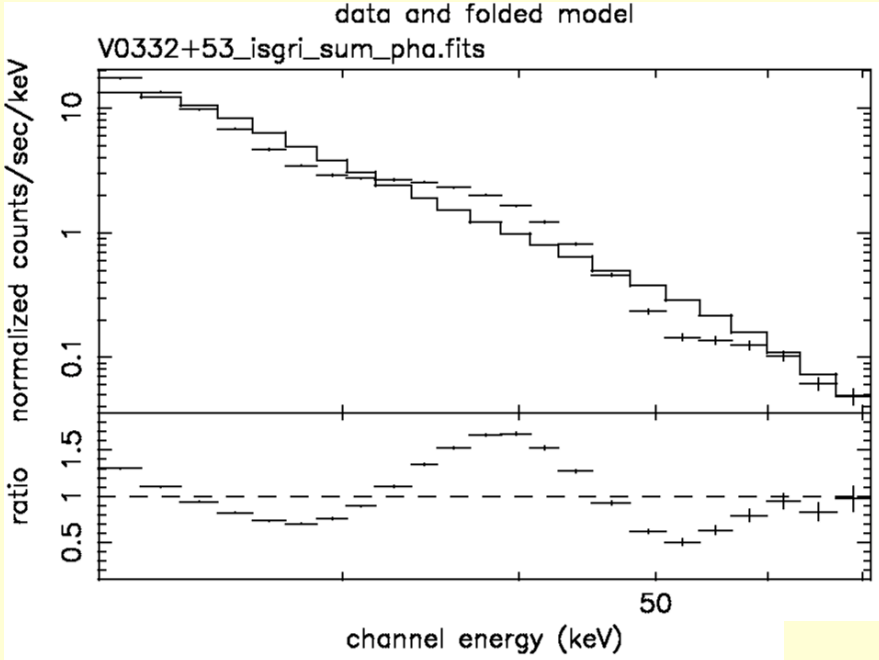
Observational material

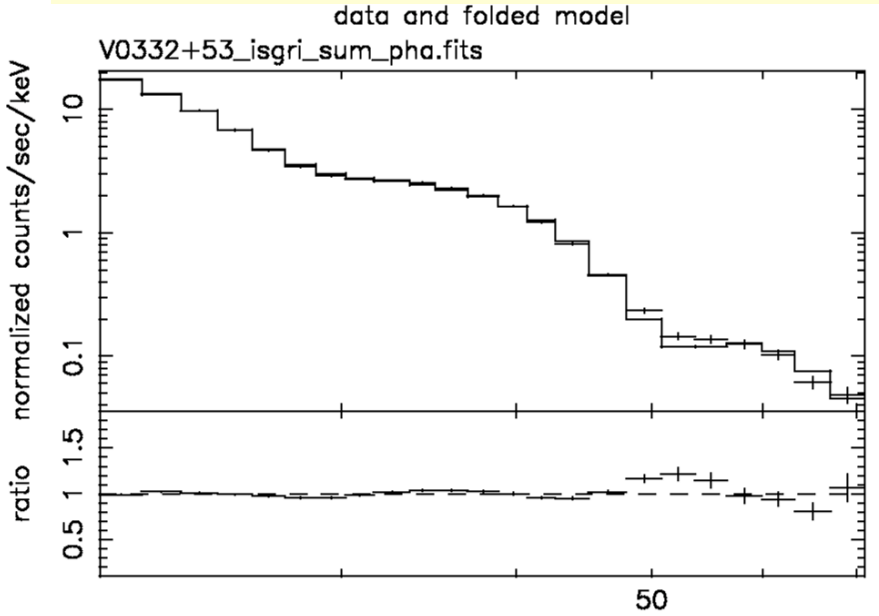
4U 0115+63	14,24,36,48,62	Wheaton et al.(1979, HEAO-1) Heindl et al. (1999, RXTE) al.(1999,SAX)
4U 1907+09	1	al.(1998,SAX)
4U 1538-52	2	990, Ginga)
Vela X-1	2	al(1992,Mir-Hexe) et al.(2002,RXTE)
V 0332+53	2	ashi (1990,Ginga)
Cep X-4	28	Mihara et al. (1991,Ginga)
Cen X-3	29	Santangelo et al. (1998 SAX) Heindl&Chakrabarty (1999, RXTE)
X Per	29	Coburn et al. (2001, RXTE)
MX 0656-072	35	Heindl et al. (2003,RXTE)
XTE J1946+274	36	Heindl et al. (2001, RXTE)
OAO 1657-415	36?	Orlandini et al. (1999, SAX)
4U 1626-67	37	Orlandini et al. (1998, SAX) Heindl & Chakrabarty (1999, RXTE)
GX 301-2	37	Mihara (1995, Ginga)
Her X-1	41	Trümper et al. (1998, Ballon-HEXE)
LMC X-4	100?	Barbera et al. (2001, SAX)

XSPEC model!!!

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

XSPEC model: `cyclomc´

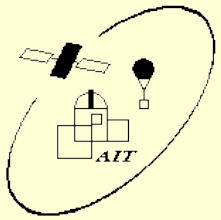




- complex line shapes
- simultanous fit of up to four lines
- independent of continuum shape

→B, T_e, θ, τ, cylinder

UNIVERSITÄT TÜBINGEN



Summary and outlook

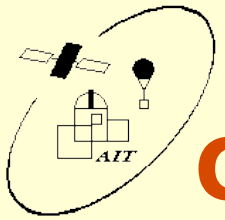
- Today's observations and insights require a new approach of modeling cyclotron lines
- Our preliminary model is a first step
- A thorough comparison of observational data and simulated spectra will be the next

Eberhard Karls
Universität
Tübingen


Thank you!


Thank you!


Thank you!

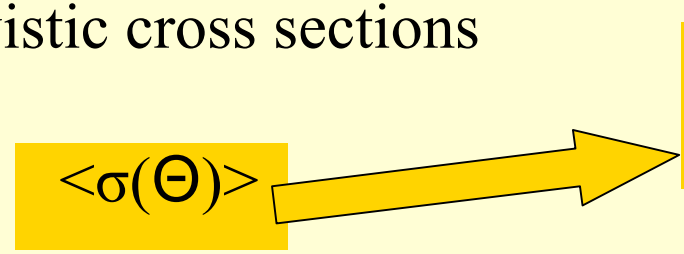


CRSF: Monte Carlo simulations

Araya&Harding (1999,2000)

- highly magnetized plasma with low density
- $B < B_{crit}$
- e^- initially in fundamental Landau state
- photon spawning from higher harmonics included

Calculation of magnetic relativistic cross sections

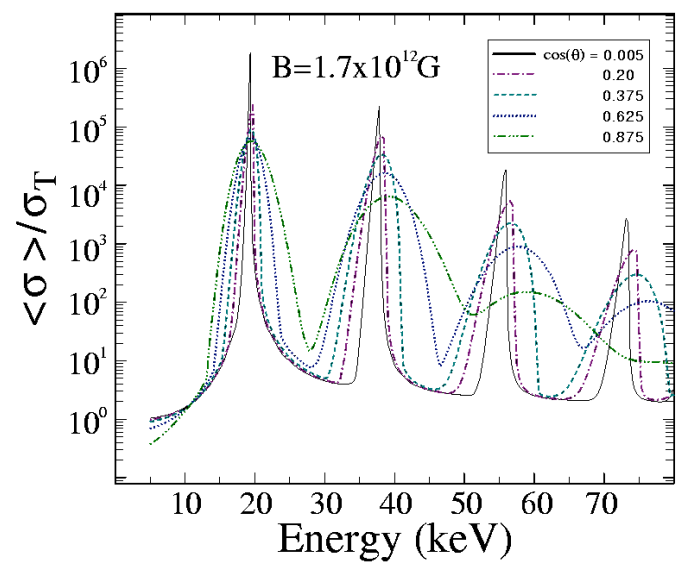


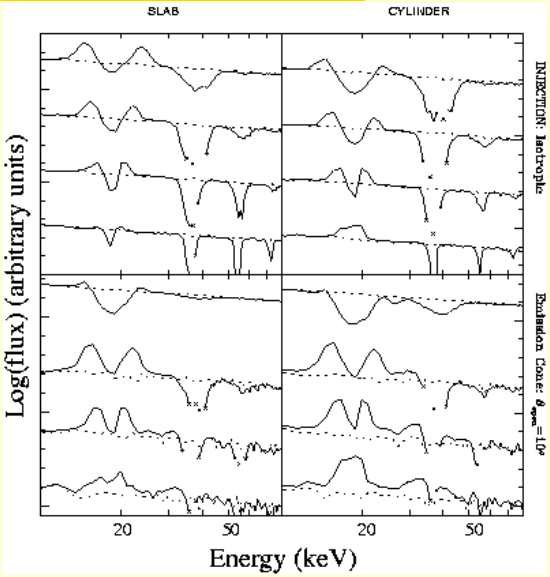
Monte Carlo program: calculation of spectrum

B, T_e, τ, α, geometry

CRSF: Monte Carlo simulations

Araya&Harding (1999,2000)





B_{12}=1.7

Calculation of magnetic relativistic cross sections

<σ(Θ)>

Monte Carlo program: calculation of spectrum

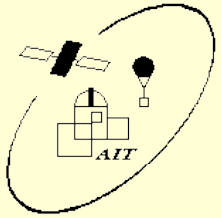
B, T_e, τ, α, geometry

The idea

Following an approach of Kretschmar et al. (2000) extensive simulations shall be performed on a finer parameter grid and a first large-scale comparison to observational data (mainly INTEGRAL) shall be performed

Changes in / Fine-tuning of Monte Carlo Code

Data analysis



MC code: first steps

- Documentation!!!!!!!!!!!
- Logical breakdown of code - ongoing
- Compilation of last cvs release successful
- Bugfix – ongoing
- Understanding the physics behind

Next…

- Restructuring the code
  - Facilitating parameter input
  - Optimizing time
- Reconsidering the physics behind

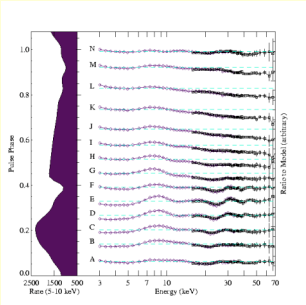
- Calculation on a finer parameter grid, large-scale comparison of models to observations

Eberhard Karls
Universität
Tübingen

Observations vs. models

Results:

- B-field strength (12-B-12 rule)
- Angle-dependent line shifts agree



Drawbacks:

- Anharmonic spacing
- Emission wings, vanishing of fundamental line in absorption

cannot be accounted for

(Kretschmar,Kreykenbohm…)

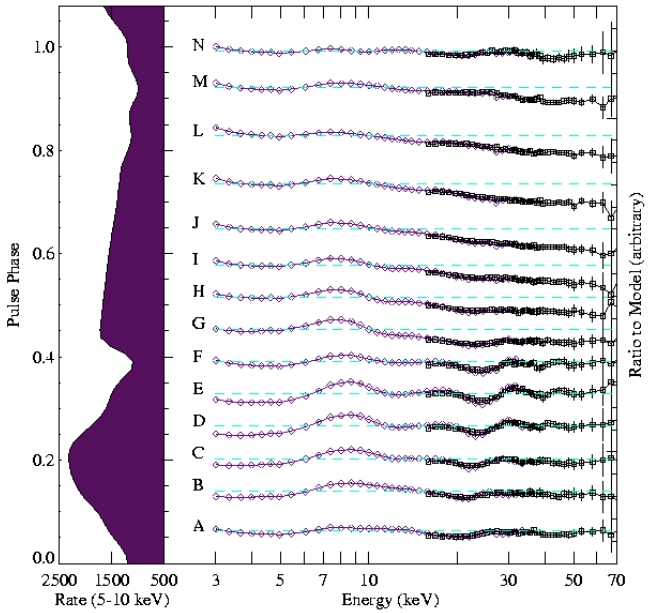
Current situation: CRSF are fitted mostly just with Gaussian/ Lorentzian profiles

Eberhard Karls Universität Tübingen

CRSF: Phase-resolved analysis

- Position and strength of lines differ with pulsation phase

- Line shifts seen with phase-resolved spectroscopy agree with angular dependence of relativistic cross section:



4U 0115+63, Heindl

$$E_n(\theta)=(m_e c^2/\sin^2\Theta)\left(\sqrt{1+2n(B/B_{crit})\sin^2\Theta}-1\right)$$

INTEGRAL observations

- 4U 0115+63
- 4U 1907+09
- 4U 1538-52
- Vela X-1
- V 0332+53
- Cep X-4
- Cen X-3
- X Per
- MX 0656-072
- XTE J1946+274
- OAO 1657-415
- 4U 1626-67
- GX 301-2
- Her X-1
- A0535+26
- (LMC X-4)

Eberhard Karls
Universität
Tübingen