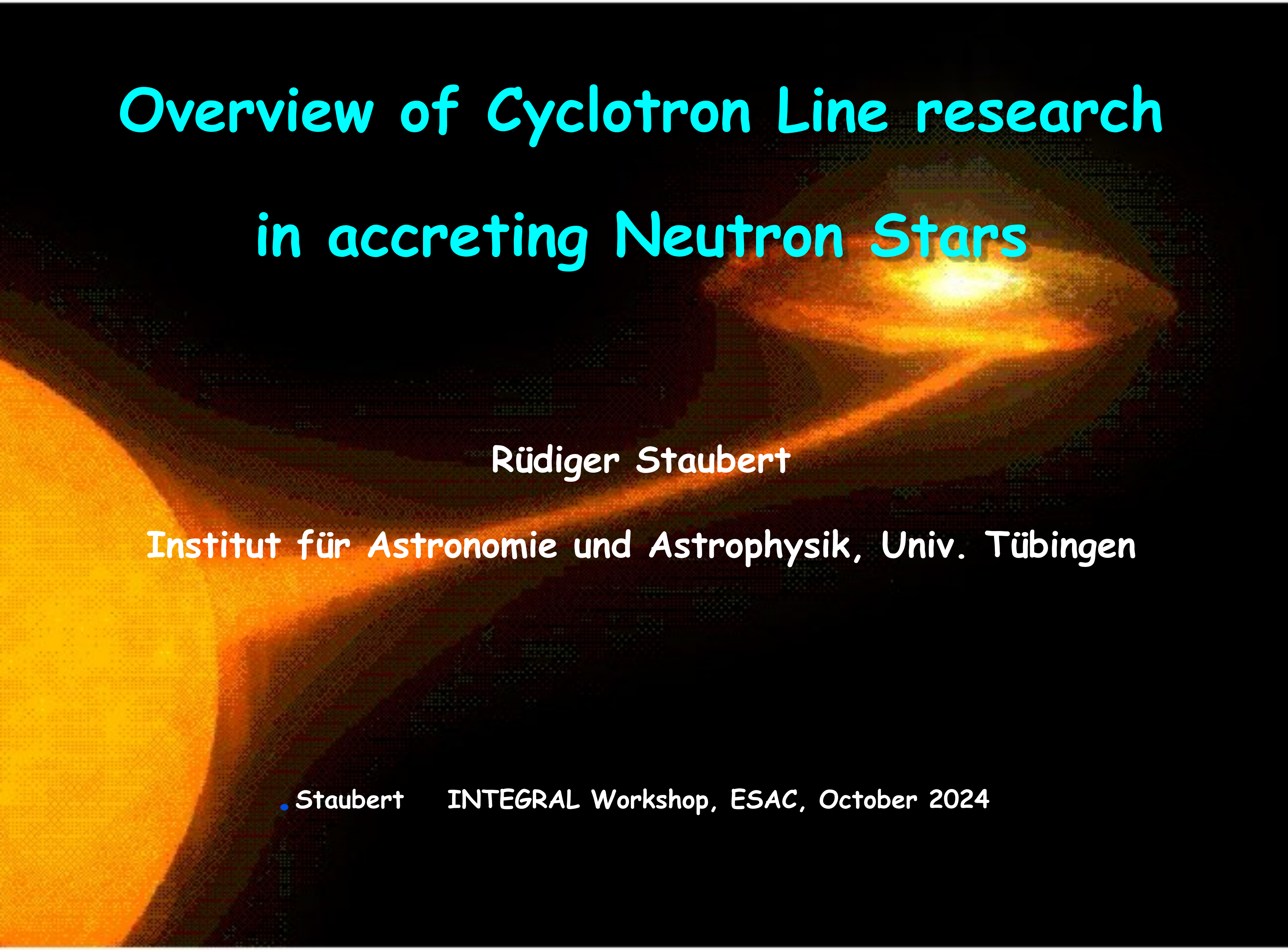


Overview of Cyclotron Line research in accreting Neutron Stars

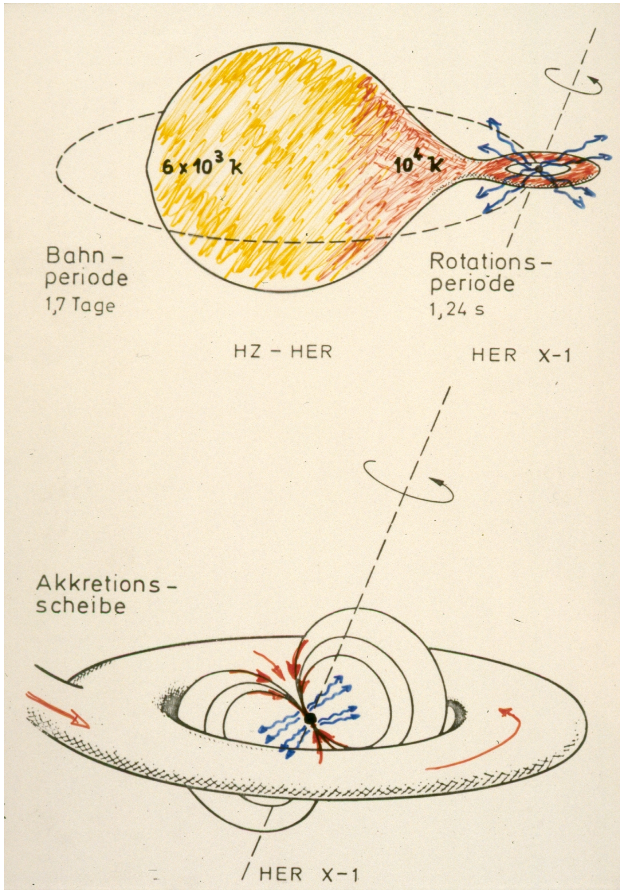
Rüdiger Staubert

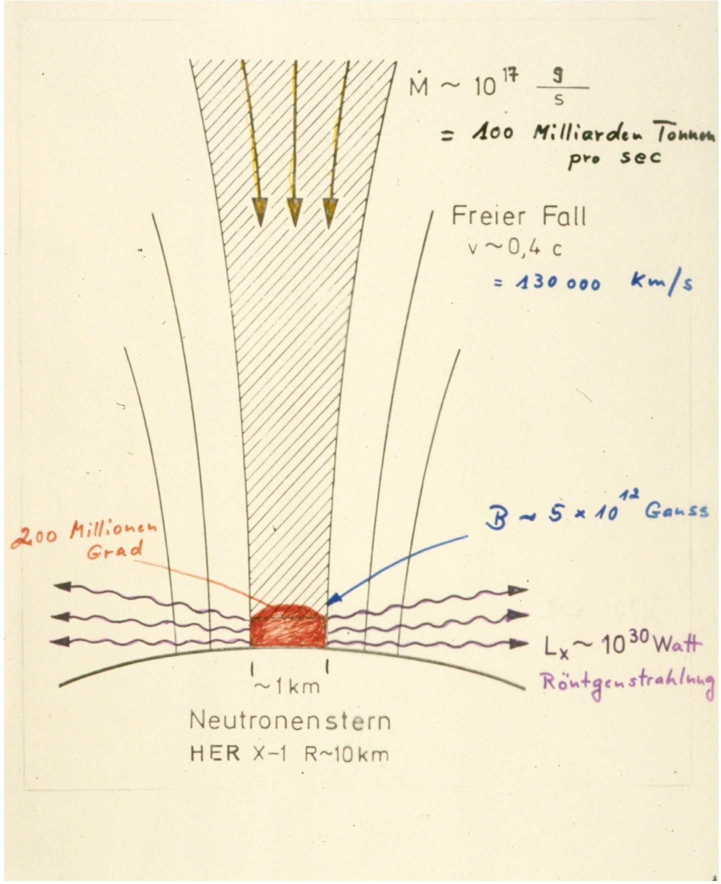
Institut für Astronomie und Astrophysik, Univ. Tübingen

Outline

- Cyclotron Resonant Scattering Feature (CRSF)
- Variability of the cyclotron line energy Ecyc
- CRSF sources observed by INTEGRAL
- „New“ CRSF sources (after Review of Staubert et al. 2019)
- A few comments
- The future of CRSF research

Accreting binary X-ray pulsar with Roche-lobe overflow





R. Staubert INTEGRAL Workshop, ESAC, October 2024

Discovery of the first Cyclotron Line

MPE /AIT

Balloon-HEXE observation

Texas, 3 May 1976

(Trümper et al. 1977, 1978)

first direct measurement of the field strength of a NS:

$B \sim 3 \times 10^{12}$ Gauß

EVIDENCE FOR STRONG CYCLOTRON LINE EMISSION IN THE HARD X-RAY SPECTRUM OF HERCULES X-1

J. Trümper, W. Pietsch, C. Reppin, and W. Voges
Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestrische Physik, Munich

and

R. Staubert and E. Kendziorra
Astronomisches Institut der Universität Tübingen

Received 1977 August 19; accepted 1977 October 12

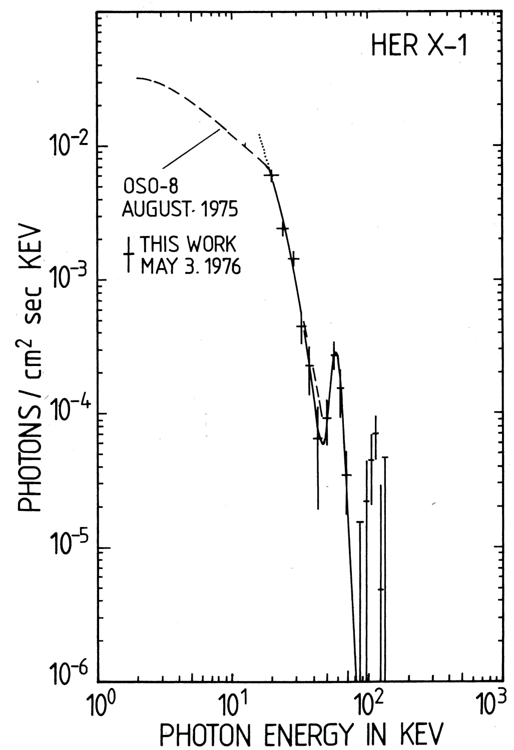


Fig. 2.—Deconvoluted X-ray spectrum of the Her X-1 *pulses*. *Solid line*, best-fitting exponential spectrum with a Gaussian line to the data points. The error bars are $\pm 1\ \sigma$; the upper limits are at $2\ \sigma$. For comparison, a *total* X-ray spectrum of Her X-1 observed by OSO-8 during the 1975 August on-state is shown (Becker *et al.* 1977).

The Astrophysical Journal, 219:L105–L110, 1978 February 1

ApJ 219 (1978) L105

R. Staubert INTEGRAL Workshop, ESAC, October 2024

Cyclotron Resonant Scattering Feature (CRSF)

$$E_{cyc} = n\ he/m_e c * B$$

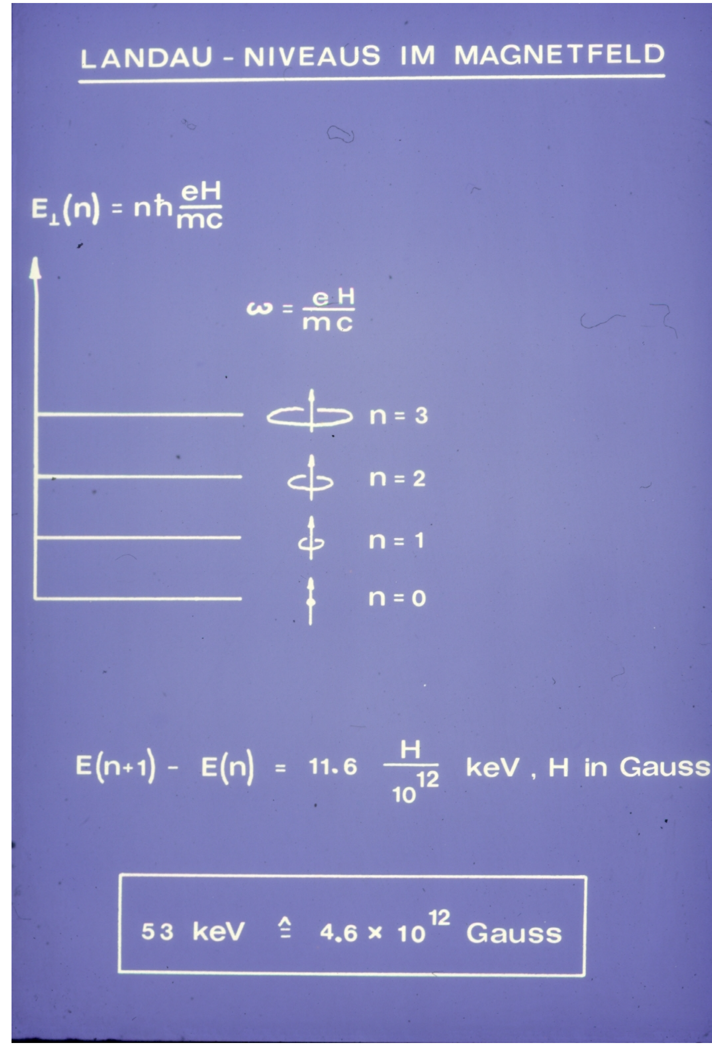
$$= n\ 11.6[\mathrm{keV}] * B[\mathrm{Gauß}]/10^{12}$$

(several lines possible)

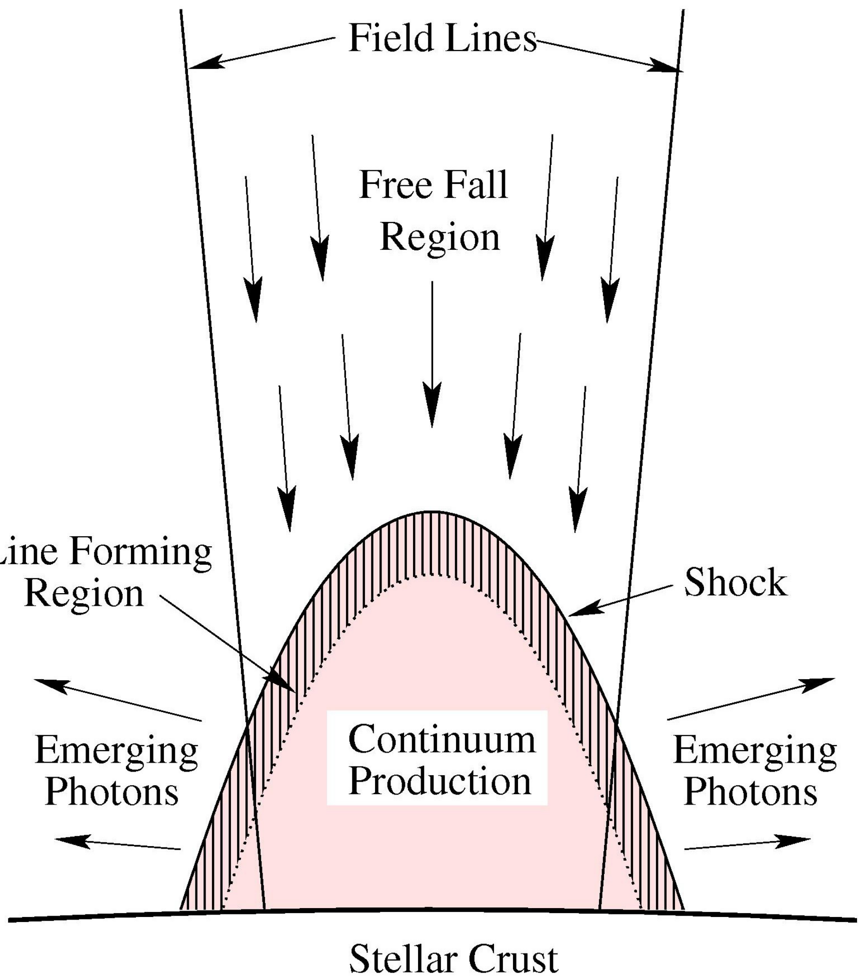
for n =1 (fundamental):

$$\boxed{B_{12} = (1+z)\ E_{obs}\ /\ 11.6\ \mathrm{keV}}$$

(z gravitational redshift)



Cyclotron Resonant Scattering Feature (CRSF)



drawing Biff Heindl

Accretion Mound

Continuum photons trying to escape from the hot mound are resonantly scattered by electrons at the cyclotron energy and are therefore missing in the observed spectrum

→ absorption line

List of Cyclotron line Sources

see Review of Staubert et al. 2019: Astron. & Astrophys. 2019, 622, A61

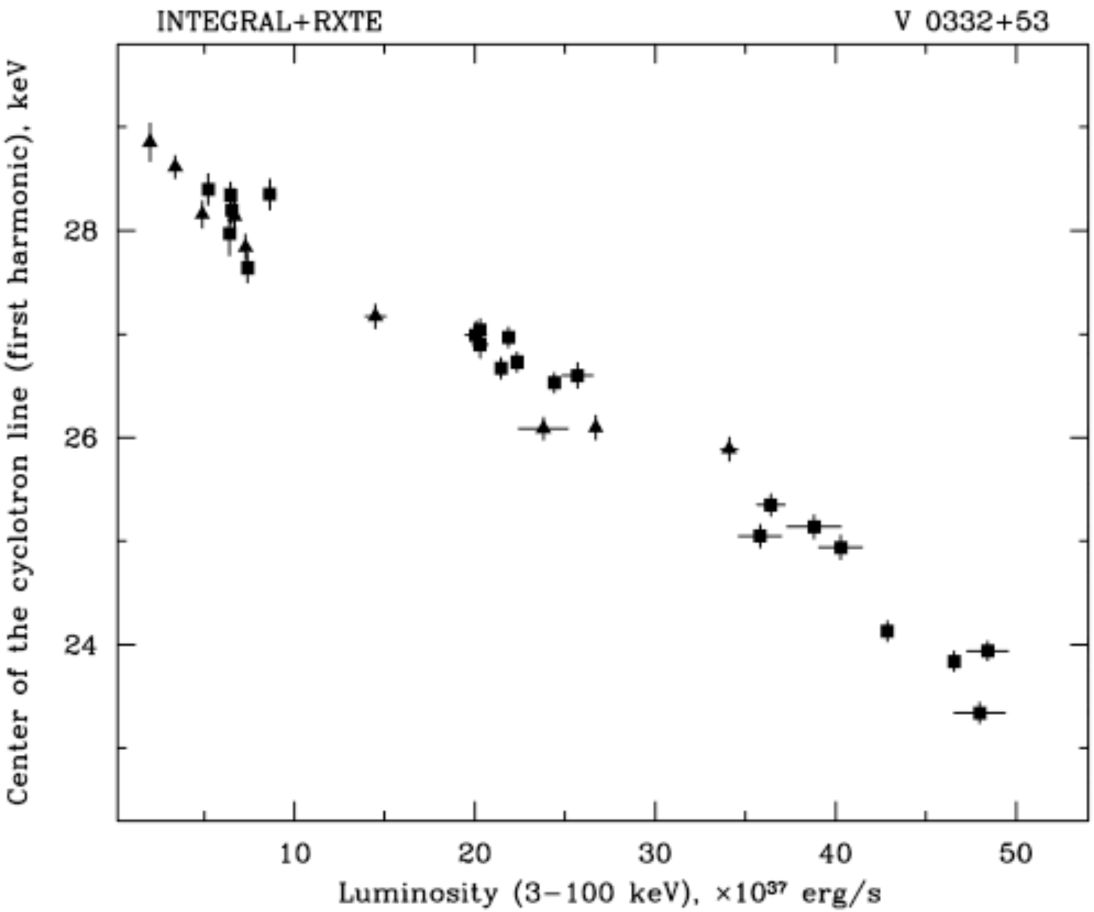
Variability of E_{cyc}

The cyclotron line Energy E_{cyc} varies with

- **pulse phase**
- **luminosity** <—— a few words
- **time** (secular / random)
- **35d phase**

R. Staubert INTEGRAL Workshop, ESAC, October 2024

Negative correlation of E_{cyc} with L_x



V 0332+53

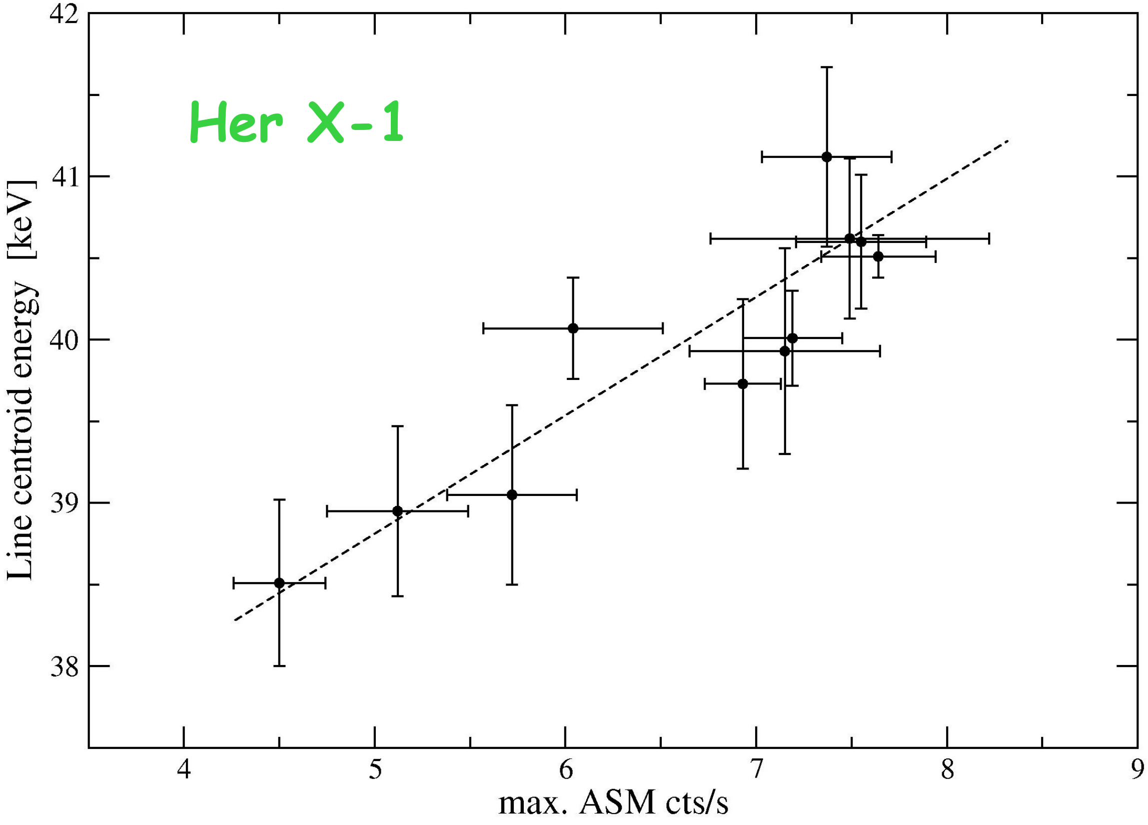
Tsygankov et al. 2006,

MNRAS 371, 19

E_{cyc} drops
by ~7% for a
factor of 2 increase
in L_x

Positive correlation of E_{cyc} with L_x

E_{cyc} [keV] = 40 + 0.66 (max. ASM cts/s - 6.8)



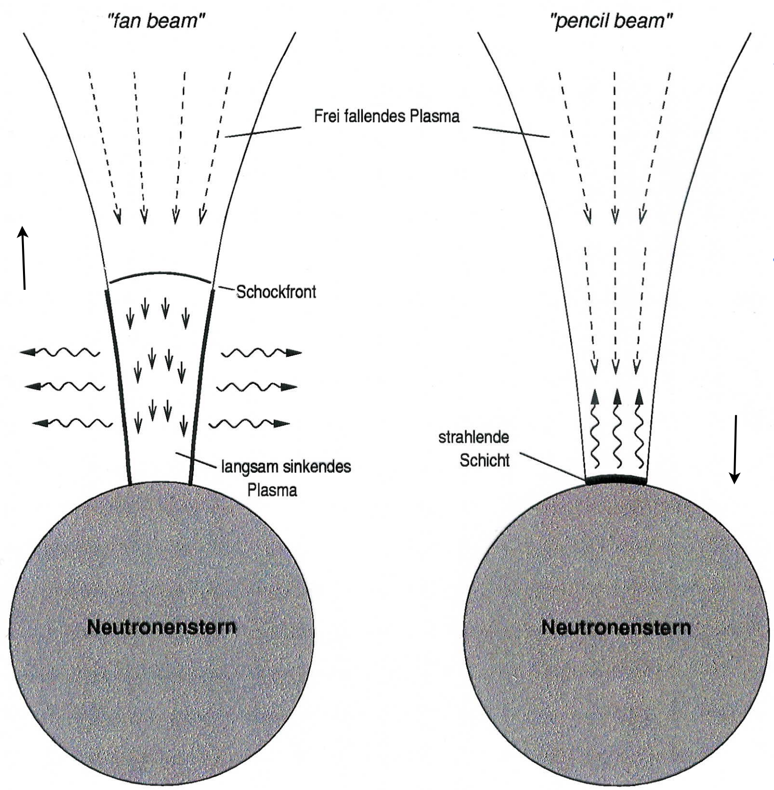
E_{cyc} increases by ~7% for a factor of 2 increase in L_x

Staubert et al. 2007, A&A 465, L25

Two accretion regimes

height increases

for increasing L_x



$L_X > L_{crit}$ $L_x < L_{crit}$

observations:

Staubert et al. 2007, A&A 465, L25

Klochkov et al. 2011, A&A 532, 126

theory:

Becker et al. 2012, A&A 544, 123

height decreases

for increasing Lx

L_{crit} ~ few 10^{37} erg/s

R. Staubert INTEGRAL Workshop, ESAC, October 2024

A&A 622, A61 (2019)
https://doi.org/10.1051/0004-6361/201834479

Astronomy & Astrophysics

Cyclotron lines in highly magnetized neutron stars

R. Staubert[1], J. Trümper[2], E. Kendziorra[1,⋆], D. Klochkov[1], K. Postnov[3], P. Kretschmar[4], K. Pottschmidt[5,6], F. Haberl[2], R. E. Rothschild[7], A. Santangelo[1], J. Wilms[8], I. Kreykenbohm[8], and F. Fürst[4]

Review: state of cyclotron line (CRSF) research

(~ 40 years after the discovery of the first line in Her X-1)

List of 35 CRSF sources + 16 candidates

(from a total of ~350 X-ray binary pulsars)

11 sources with multiple lines (7 with two, 3 with three, 1 with >3 lines)

7 sources with a positive E_{cyc} / L_x correlation

2 sources with a negative E_{cyc} / L_x correlation

2 sources with a long-term variation of E_{cyc}

R. Staubert INTEGRAL Workshop, ESAC, October 2024

Two points to make here:

1. What is INTEGRALs contribution to CRSF research?

2. What is the general progress in the last 5 years?
(since the 2019 review by Staubert et al.)

INTEGRAL and CRSF-sources

13
CRSF sources
observed
by INTEGRAL

Table 1. Cyclotron line sources with published results from INTEGRAL observations

System	E_{cyc} (keV) prev.	E_{cyc} (keV) INT.	INTEGRAL Flux dep. fundam.	harmonics	Pulse phase depend.	Key References of INTEGRAL results
GX 301-2	37/50	35,35-47[g]	—[c]	—	—[c]	Yu & Wei 2016, Astron. Res. and Technol. 13, 11
GX 304-1	54	50-58	pos.	—	—	Klochkov et al. 12, A&A 542, L28
Her X-1	37	38-42	pos.	—	yes	Staubert et al. 2012, PoS (INTEGRAL 2012) 010
Vela X-1	25, 53	22-27,52	—[a]	49-57	—[d]	Wang 2014, MNRAS 440, 1114[a]
4U 0115+63	12,24,36, 48,62	11,22,36, 47,60	—[b]	24/36[b]	no —	Müller et al. 13, A&A 551, A6, Boldin et al. 13, Astron. Lett. 39, 375
V 0332+53	28	25,51,72	neg.	51,72	little	Kreykenbohm 05, A&A 433, L45
A 0535+26	50 / 110	44-50	pos.[f]	99-107	—	Sartore et al. 15, ApJ 806, 193
4U1538-522	22,47	22[i] ,47	no[h]	47	—	Rodes-Roca 09, A&A 508, 395
IGR J18179-1621[l]	21	21	—	—	—	Li, J. et al. 12, MNRAS 426, L16
4U 1907+09	18,36	18,36	pos.	36	—	Hemphill et al. 13, ApJ 777, 61
4U 1946+274	36	25[k]	pos.[k]	—	—	Müller et al. 12, A&A 546, A125
Candidates:						
GX 1+4[l]	—	34	—	—	yes	Ferrigno et al. 2007, A&A 462, L16
RX J0440.9+4431[l]	32	32[e]	—	—	—	Tsygankov et al. 12, MNRAS421, 2407
EXO 2030+375[l]	11,36	(36?)[j]	—	63[j]	yes	Klochkov et al. 08, A&A 491, 833

——>
CRSF
detected
by
INTEGRAL

[a] Vela X-1: see NuSTAR: Fürst et al. 2014, ApJ 780, 133; Swift/BAT: La Parola 2016, MNRAS 463, 185: E_{cyc} pos. correlated to L_x
[b] 4U 0115+63: see NuSTAR: Roy et al. 2024, A&A 690, A50: two systems of CRSFs with fundamental lines at
.... 12 keV and 16 keV, and E_{cyc} pos. corr. to L_x
[c] GX 301-2: see HXMT: Ding et al. 2021, MNRAS 506, 2712: E_{cyc} pos. and neg. corr. to L_x
[d] Vela X-1: see HXMT: Liu et al. 2022, MNRAS 514, 2805: E_{cyc} prop. to L_x, and E_{cyc} is pulse phase dependent
[e] RX J0440.9+4431: see INTEGRAL: Salganik et al. 2023, MNRAS 524, 5213: no CRSF;
.... see Astrosat: Sharma et al. 2024, MNRAS 534, 1028: no CRSF
[f] A 0535+26: Kong et al. 2021, ApJ(Lett) 917, L38: E_{cyc} pos. and neg. correlated to L_x (sub-critical / super-critical accretion)
[g] GX 302-1: see NuSTAR: Fürst et al. 2018, A&A 620, A153: two CRSFs at 35 keV and 50 keV; E_{cyc} varies with pulse phase
[h] 4U 1538-522: see INTEGRAL: Hemphill et al. 2016, MNRAS 458, 2745: no E_{cyc}/L_x corr.; see NuSTAR:
[i] 4U 1538-522: see NuSTAR: Hemphill et al. 2024, MNRAS 527, 3164: E_{cyc} around 22 keV shows long-term variability
[j] EXO 2030+375: see INTEGRAL: in Pulse Phase Resolved spectral analysis: 63 keV, possibly first harmonic to 36 keV
[k] 4U 1946+274: see RXTE, Suzaku: E_{cyc} at 36 keV —> E_{cyc} pos. correlated to L_x!?
[l] detections by INTEGRAL

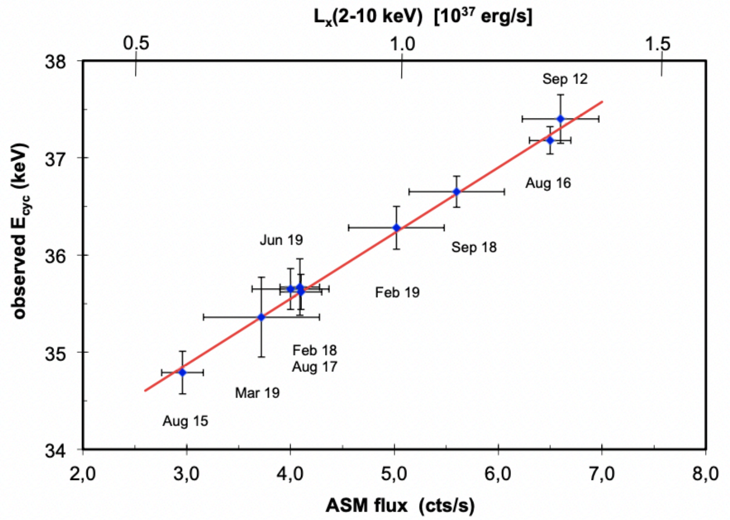
R. Staubert INTEGRAL Workshop, ESAC, October 2024

New CRSF-sources, after 2019 Review by Staubert et al.

System	Type	P_{spin} (s)	P_{orb} (d)	Ecl.	E_{cyc} (keV)	Instr. of 1st Det.	Dep. E_{cyc} / L_x	Ref. 1st Det.
0243.6+6124 (Swift)	Be/ULX	9.8	28	no	120-146	HXMT	—	Kong et al. 22, ApJ(Lett) 933, L3
06074+2205 (IGR)	BE XRB	373	?	no.	55	NuSTAR	—	Tobrej et al. 24, High En. Astroph. 42, 129
1626.6-5156 (Swift)	Be HMXB	15.3	133	no	10	RXTE	pos	DeCesar et al. 13, ApJ762, 61
(not new)					5	Nicer	pos	Rai et al. 24, J. Astrophys. Astron. 45, 7
	E_{cyc} (keV) =	4.9 /	8.6 /	12.6	/ 16.9	NuSTAR	—	Molkov et al. 21, ApJ(Lett) 915, L27
16320-4751 (IGR)	HMXB	1309	9	no	14	NuSTAR	pos	Bodaghee et al. 23, ApJ 951, 37
17407-2808 (IGR)	LMXB?	?	?	—	8.6 ?	NuSTAR	—	Ducci et al. 23, A&A 674, A100
1750-27 (GRO)	Be HMXB	4.5	29.8	no	43	NuSTAR	—	Malacaria et al. 22, ATEL 15241
1808.4-1754 (Swift)	Be XRB	910	?	no	21, 37?	Swift	—	Salganik et al. 22, MNRAS 514, 2707
2058+42 (GRO)	HMXB.	196	55	no	10/20/30	NuSTAR	—	Molkov et al. 19, ApJ(Lett) 883, L11

- note:
- Swift 0243.6+6124: E_{cyc} = 120 … 146 keV, highest ever measured! HXMT
- Swift 1626.6-5156: four CRSFs: 4.9 / 8.6 / 12.6 / 16.9 keV
- GRO 2058+42: three CRSFs: 10 / 20 / 30 keV
- Swift 1808.4-1754: two CRSFs: 21 / 37 keV
- In 2 of 7 new sources: E_{cyc} has positive correlation with Lx

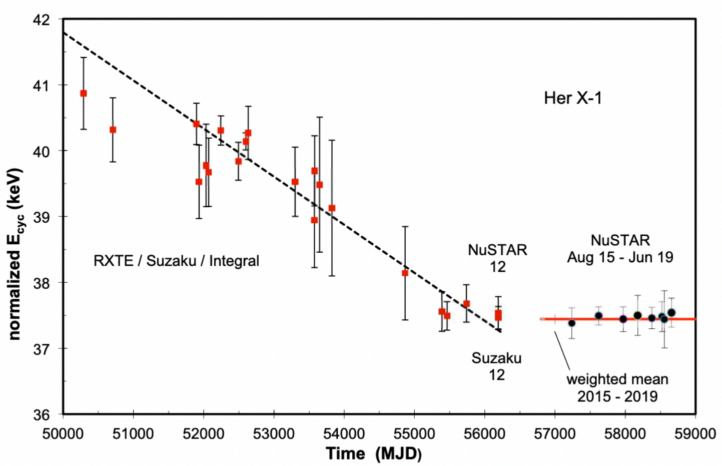
Her X-1 (Staubert et al. 2020, A&A 642, A196)



E_{cyc} increases by ~7% for a factor of 2 increase in L_x

(Staubert et al. 2007, A&A 465, L25)

today: about one dozen objects



E_{cyc} decayed by ~10% between 1996 and 2012

(originally: Staubert et al. 2014, A&A 572, A119)

today: two objects (Her X-1, Vela X-1

R. Staubert INTEGRAL Workshop, ESAC, October 2024

Progress (in the last 5 years - observationally)

7 new CRSF sources identified during the last 5 years

(~ 1.4 / year, compared to 51 in 42 yrs = ~1.2 / year [2019])

what else ?

several „non-confirmed“ CRSFs are now confirmed (some not)

several „candidate“ CRSFs can be considered secured (e.g. 4U 1700+37, GX1+4, 4U1901+03)

new CRSFs positively correlated to L_x (GX 301-2, Swift 1626.6-5156, IGR 17407-2808, …)

CRSFs with positive and negative correlation with L_x (GX 301-2, Cep X-4, SMC X-2, A 0535+26, …)

1 „very high“ CRSF finally discovered (Swift 0243.6+6124: E_{cyc}= 120 … 146 keV)

more sources with multiple CRSFs (Swift 1626.6-5156 [4], GRO 2058+42 [3], Cen X-3 [2], Swift 1808.4-175 [2], …)

some sources with „randomly“ variable CRSF at same flux (e.g. SMC X-2, …)

more sources with power law index correlated with L_x

Recent theoretical progress

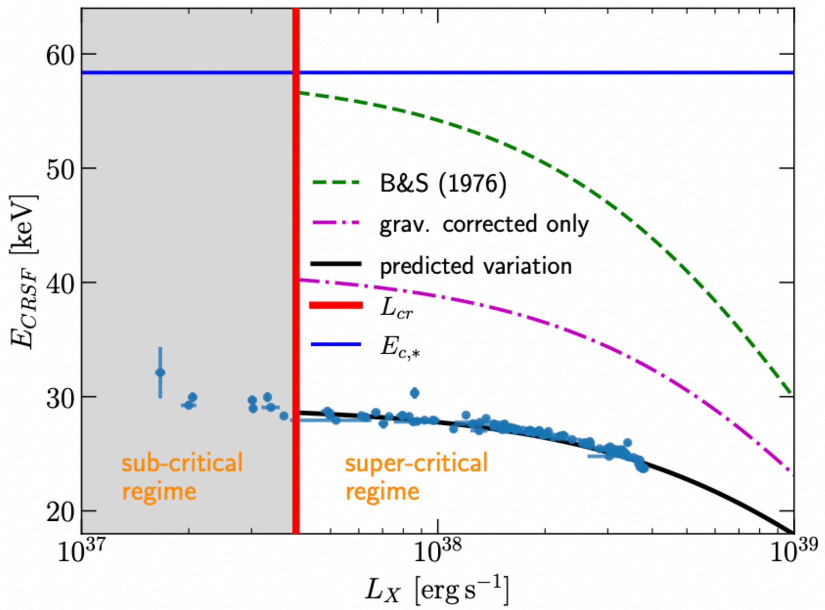


Fig. 2. Observed cyclotron-line energy variation of the source V0332+53 with luminosity. The blue points correspond to data reported in Tsygankov et al. (2010). The solid black line is the optimal fit to the data, using our theoretical prediction. The dashed green line is the expected variation only due to the magnetic-field strength (see Eq. (3) and Basko & Sunyaev 1976), using as $E_{c,*}$ and a the parameters obtained through the fit. The dash-dotted magenta line is the one accounting for the magnetic field variation and gravitational redshift, but not the Doppler effect (see Sect. 2.2.1). The vertical red line denotes the critical luminosity, and the horizontal blue line represents the cyclotron line energy on the NS's surface.

Laudas, Kylafis, Trümper, 2024,

A&A 689, A75

Analytical model to describe the dependence of E_{cyc} on L_x due to the increase of the height of the shock front above the neutron star surface because of increased accretion rate, including:

- change of B-field strength,
- gravitational redshift and
- relativistic boosting

Application to data of V 0332+53

The future of CRSF research

- More discoveries of new CRSF sources expected (rate: ~1 /year)
- Confirmation of more „uncertain“ lines (~20 candidates)
- Discoveries of more harmonics
- INTEGRAL will - unfortunately - not take part
- ——> need a new mission for high energy X-rays (2-200 keV)
-

Thank you for your attention