Hercules X-1: variations of the cyclotron line energy with flux, with phase and with time

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Her X-1 is one of the the most intensively studied Accreting X-ray Binary Pulsars (AXBPs). This is largely because it is a bright and persistent X-ray pulsar, showing the largest variety of observable phenomena, partly due to the favorable geometry in observing the binary nearly edge-on. Her X-1 is the binary X-ray pulsar in which the first cyclotron line (or Cyclotron Resonant Scattering Feature - CRSF) was detected in 1976. Since then, we have made an effort to observe the source and the CRSF around 40 keV as often as possible, using those X-ray satellites which cover the high energy X-ray range. Extended contributions are from the *Rossi X-ray Timing Explorer* (RXTE), *INTEGRAL*, *Suzaku* and *Swift*. The most recent contribution with a new degree of quality is from the high energy imaging telescope on *NuStar*. We have found that the CRSF is variable with flux, with phase (both pulsational and precessional phase) and with time. The historical evolution of the pulse phase averaged CRSF centroid energy E_{cyc} since its discovery is characterized by an initial value around 35 keV, an abrupt jump upwards to beyond ~ 40 keV between 1990 and 1994 and an apparent secular decay thereafter. Much of this decay, however, was found to be due to an artifact, namely a correlation between E_{cyc} and the X-ray luminosity L_x discovered in 2007, amounting to a change of $\sim 7\%$ in energy for a factor of two in luminosity. In observations since 2007, however, we now find a statistically significant trend of a true secular decrease of the cyclotron line energy. In addition, we discuss recent results of pulse phase spectroscopy and evidence for the suspected variation in E_{cyc} with phase of the 35 d precessional period (which is observed both in the modulation of the X-ray flux and in the systematic variation in shape of the 1.24 s pulse profile).

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Table 1: Details of recent observations of Her X-1 by *INTEGRAL*, *RXTE Suzaku* and *NuStar*.

Observatory	Date of observation	Center MJD	Obs ID	Exposure [ksec]
INTEGRAL	2007 Sep 03-08	54348.86	Rev. 597/598	414.72
RXTE	2009 Feb 04/05	54866.95	P 80015	22.19
Suzaku	2010 Sep 22	55461.63	405058010/20	41.66
Suzaku	2010 Sep 29	55468.51	405058030/40	45.66
INTEGRAL	2010 July 10-18	55391.43	Rev. 945-947	621.03
Suzaku	2012 Sep 19-25	56192.23	4070510-10,20,30	~ 70
NuStar	2012 Sep 19-25	56192.23	3000200600-2,3,5,7	72.9

1. Introduction

The X-ray spectrum of the accreting binary pulsar Her X-1 is characterized by a power law continuum with exponential cut-off and an apparent line-like feature, which was discovered in 1975 (Trümper et al. 1978). This feature is now generally accepted as an absorption feature around 40 keV due to resonant scattering of photons off electrons on quantized energy levels (Landau levels) in the Teragauss magnetic field at the polar cap of the neutron star. The feature is therefore often referred to as a Cyclotron Resonant Scattering Feature (CRSF). The energy spacing between the Landau levels is given by $E_{cyc} = \hbar eB/m_e c = 11.6\,\text{keV}\,B_{12}$, where $B_{12} = B/10^{12}\,\text{G}$, providing a direct method of measuring the magnetic field strength at the site of the generation of the X-ray spectrum. The observed line energy is subject to gravitational redshift, z, such that the magnetic field may be estimated by $B_{12} = (1+z)\,E_{obs}/11.6\,\text{keV}$. The discovery of the cyclotron feature in the spectrum of Her X-1 provided the first ever 'direct measurement' of the magnetic field strength of a neutron star, in the sense that no other model assumptions are needed. Originally considered an exception, cyclotron features are now known to be rather common in accreting X-ray pulsars, with more than a dozen binary pulsars being confirmed cyclotron line sources, with several objects showing multiple lines (up to four harmonics in 4U 0115+63). Reviews are given by e.g. Coburn et al. 2002, Staubert 2003, Heindl et al. 2004, Terada et al. 2007, Wilms 2012.

Here we summarize some results, including our most recent ones, about the variability in cyclotron line energy. The application of pulse phase spectroscopy techniques has demonstrated a very strong variation in E_{cyc} as function of pulse phase. Considering this pulse phase variation and the variation in pulse shape with 35 d phase, there must be a variation in the phase averaged E_{cyc} with 35 d phase. From a long-term study, we present the first statistically significant evidence for a true secular decrease of the phase averaged E_{cyc}. We speculate about the physics behind the secular decrease as being connected to changes in the configuration of the magnetic field structure at the polar caps of the accreting neutron star.

2. Data base and method of analysis

Her X-1 is probably the best observed accreting binary X-ray pulsar. Its X-ray spectrum and the cyclotron line (CRSF) has been measured by many instruments since the discovery of the CRSF

Table 2: Recent cyclotron line energy measurements in Her X-1 by *INTEGRAL*, *RXTE*, *Suzaku* and *NuStar*. Uncertainties are at the 68% level. The two *Suzaku* data points from 2005 and 2006 are from Enoto et al. (2008), adjusted to describing the cyclotron line by a Gaussian line profile (see text). The *NuStar* value, as provided by the *NuStar* team, is preliminary. 35 d cycle numbering is according to Staubert et al. (1983, 2009a).

Satellite	Observation month/year	35 d cycle	Center [MJD]	Cyclotron Line Energy [keV]	max. Flux [ASM cts/s][*]
RXTE	Feb 2009	388	54866.60	37.58 ± 0.65	5.94 ± 0.50
Suzaku	May 2005	353	53648.90	38.70 ± 1.00	4.80 ± 0.35
	Mar 2006	358	53823.90	38.10 ± 1.00	4.70 ± 0.35
	Sep 2010	405	55461.60	37.80 ± 0.34	7.56 ± 0.23
	Sep 2012	426	56192.23	not yet analysed	6.94 ± 0.20[*]
INTEGRAL	July/Aug 2007	373	54348.00	36.50 ± 0.60	4.50 ± 0.48
	July 2010	403	55389.30	38.00 ± 0.60	8.50 ± 0.24
	June 2011	413	55738.47	37.34 ± 0.28	7.00 ± 0.20
NuStar	Sep 2012	426	56192.23	37.30 ± 0.15	6.94 ± 0.20[*]

[*] The maximum *Main-On* flux was determined using the monitoring data of *RXTE*/ASM and *Swift*/BAT (since 2012 from BAT only); the conversion is: (2-10 keV ASM cts/s) = 90 * (15-50 keV BAT cts cm^{-2} s^{-1})

in 1975 (Trümper et al. 1978). The data base behind previously reported results are summarized in corresponding Tables of the following publications: Gruber et al. 2001, Coburn et al. 2002, Staubert et al. (2007, 2009a, 2013), Klochkov et al. (2008, 2011) and Vasco et al. (2011, 2013). Details about more recent observations (proposed by our group during the last five years) by *RXTE*, *INTEGRAL*, *Suzaku* and *NuStar* are given in Tables 1 and 2. Generally, Main-On state observations (35 day-phases < 0.22) were used. The spectral analysis was performed using the standard software appropriate for the respective satellites (see the publications cited above). Unless otherwise stated, the spectral model used was a power law with exponential cut-off (`highecut`, `cutoffpl`, `FermiDirac`) for the continuum and a multiplicative absorption line with a Gaussian optical depth profile for the cyclotron line. Details of the fitting procedure can be found in the papers cited above. Here we discuss results of the spectral analyses of pulse phase resolved and pulse phase averaged spectra, a dependence on 35 phase and on elapsed time.

3. Variation of the cyclotron line energy E_{cyc}

We will discuss the variability in the energy of the Cyclotron Resonant Scattering Feature (CRSF) in Her X-1 with regard to the following variables:

- Variation with the current X-ray **luminosity**, both on long and on short time scales

(the 35 d precessional period and the 1.24 s pulse period, respectively).

- Variation with **phase of the 1.24 s pulsation**.

- Variation with **phase of the 35 d precessional period**.

- Variation with **time**, that is a true **secular decay**.
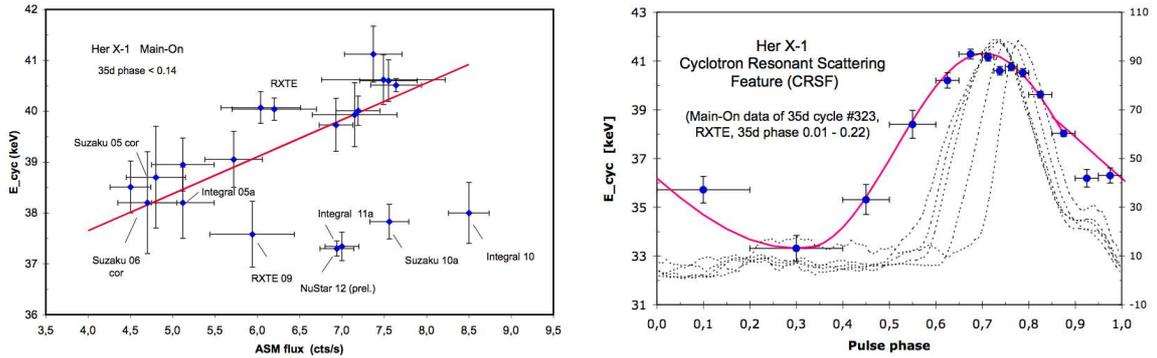
Figure 1: *Left*: The positive correlation between the cyclotron line energy and the maximum X-ray flux of the corresponding 35 day cycle as measured by *RXTE/ASM* (see Fig. 2 of Staubert et al., 2007) with eight added points: *INTEGRAL* 2005 (Klochkov et al. 2008), *Suzaku* of 2005 and 2006 (Enoto et al. 2008), *RXTE* 2009, *INTEGRAL* 2010, *Suzaku* 2010 and *NuStar* 2012 (preliminary). The solid red line is a linear fit, defining a slope of (0.47 ± 0.11) keV/(ASM cts/s). The *Suzaku* points of 2005/2006 have been 'corrected' upward by 2.8 keV, to account for the difference arising from the fact that in the analysis by Enoto et al. (2008) the Lorentzian profile was used, while for all others the Gaussian profile was used.
Right: Mean dependence of cyclotron line energy on pulse phase for the *Main-On* of 35 d cycle 323, as observed by *RXTE*/PCA in 2002 November. The solid red line represents a best fit function (a combination of two cosine components). The dotted lines are pulse profiles in the 30-45 keV range for five different 35 d phases: 0.048, 0.116, 0.166, 0.21 and 0.24. The main pulse is progressively moving to the right.

3.1 Variation of E_{cyc} with luminosity

For Her X-1 the dependence of the centroid energy of the phase averaged cyclotron line on X-ray flux was discovered by Staubert et al. (2007) while analyzing an extended set of observations from *RXTE*. As reference X-ray flux the maximum of the 2-10 keV flux of the respective 35 d cycle as measured by the All Sky Monitor (ASM) on *RXTE* was used. The correlation was found to be positive, that is the cyclotron line energy E_{cyc} increases with increasing X-ray luminosity L_x.

The opposite behavior, a negative correlation (a decrease of E_{cyc} with increasing L_x), had first been noted by Mihara (1995) in observations of a few high luminosity transient sources (4U 0115+63, Cep X-4, and V 0332+53) by *Ginga*. This negative correlation was associated with the high accretion rate during the X-ray outbursts, as due to a change in height of the shock (and emission) region above the surface of the neutron star with changing mass accretion rate, $\dot{M}$. In the model of Burnard et al. (1991), the height of the polar accretion structure is tied to $\dot{M}$. From this model one expects that an increase in accretion rate leads to an increase in the height of the scattering region above the neutron star surface, and therefore to a decrease in magnetic field strength and hence E_{cyc}. During the 2004/2005 outburst of V 0332+53 a clear anti-correlation of the line position with X-ray flux was observed (Tsygankov et al., 2006). The case of 4U 0115+63, however, is doubtful: while both Nakajima et al. (2006) and Tsygankov et al. (2007) had found a general anti-correlation between E_{cyc} and luminosity in *RXTE* data of the Feb–Apr 1999 outburst, Müller, S. et al. (2012), analyzing *RXTE* and *INTEGRAL* data from an outburst in March/April 2008, have found that the negative correlation for the fundamental cyclotron line is likely an artifact due to correlations between continuum and line parameters when using the NPEX continuum model.

The positive correlation in Her X-1 was secured by a re-analysis of the same *RXTE* data by Vasco et al. (2011), using the bolometric X-ray flux as reference. This analysis confirmed that the originally used 2-10 keV flux is a good measure of the bolometric luminosity. While the above discussed analysis tests the correlated variability of E_{cyc} and L_x on long time scales (35 d and longer), the "pulse-amplitude resolved" analysis of Klochkov et al. (2011) does so on short time scales (down to the pulse period of 1.24 s). Selecting pulses with amplitudes in certain ranges and producing mean spectra for each pulse amplitude range, showed that the cyclotron line energy scales positively with the mean pulse amplitude. In addition, it was found that the photon index Γ of the underlying power law continuum scales negatively with the pulse amplitude. The same behavior was seen in data of the transient A 0535+26. A recent pulse phase resolved analysis of A 0535+26 observations by *RXTE* and *INTEGRAL* showed that data of one of the two peaks (of the double peak pulse profile) displays the same trend while data of the other peak do not (Müller, D. et al., 2013). Applying the same "pulse-amplitude resolved" technique to data of V 0332+53 and 4U 0115+63, Klochkov et al. (2011) found the same behavior as originally detected in data sets that were selected on much longer time scales: E_{cyc} decreases and Γ increases with increasing L_x. Finally, we mention that a positive correlation of E_{cyc} with L_x was also seen by *INTEGRAL* in a flare of GX 304-1 (Klochkov et al., 2012).

Our current understanding of the physics behind these correlations assumes that we can distinguish between *two accretion regimes* in the accretion column above the polar cap of the neutron star: *super- and sub-Eddington accretion.* The former is responsible for the first detected negative correlation in high luminosity outbursts of transient X-ray sources: with increasing accretion rate $\dot{M}$, the shock and the scattering region move to larger height above the surface of the neutron star and consequently to weaker B-field (Burnard et al. 1991). Sub-Eddigton accretion, on the other hand, leads to the opposite behavior. In this regime an increasing $\dot{M}$ leads to an increased ram pressure on the scattering region and a resulting "squeezing" to smaller height and stronger B-field (Staubert et al., 2007). More detailed physical considerations have recently been presented by Becker et al. (2012). The persistent source Her X-1 is clearly a sub-Eddington source.

Fig. 1(left) reproduces the original correlation graph of Staubert et al. (2007) with new data points added (see Table 2). The E_{cyc} values measured later than 2007 are significantly lower than the earlier values, while they maintain a similar positive slope. It is these points that establish the secular decay of E_{cyc} which will be discussed below.

3.2 Variation of E_{cyc} with pulse phase

Recently, Vasco et al. (2013) have presented results of pulse phase resolved analysis of *RXTE* observations. Fig. 1(right) shows the mean dependence of the centroid cyclotron line energy on pulse phase for all *Main-On* data of cycle 323 (for 35 d phases between 0.1 and 0.22). It is the first time that for Her X-1 a phase profile of the centroid cyclotron line energy E_{cyc} is produced with such a high resolution and statistical accuracy (the four smallest bins around the peak of the pulse have a width of 1/80 of a phase). The shape of the modulation is nearly sinusoidal, but for a good fit, at least two sine functions are needed (solid red line). The peak to peak amplitude of the modulation is $\sim$ 21% of the mean energy. There is no 35 d dependence of the shape of this modulation. Generally, the E_{cyc} profile roughly follows the shape of the pulse profile, with its broad maximum close to the maximum of the main peak (pulse phases 0.7-0.8). The dashed curves

are 30-45 keV pulse profiles for five different 35 d phases: the main peak is progressively moving to the right with increasing 35 d phases.[1] The fact that the pulse moves, while the shape of the E_{cyc} profile stays constant, leads to the expectation for a variation in pulse phase averaged E_{cyc} with 35 d phase (see Section 3.3).

Pulse phase modulation in E_{cyc} is quite common among accreting X-ray pulsars and is generally believed to be due to the changing viewing angle under which the X-ray emitting regions are seen. If we adopt the idea, that peaks in the pulse profile can be associated with beamed radiation emitted from the accreting regions at the magnetic poles, then the observed pulse profiles are a representation of the emission characteristics. During a full neutron star rotation we may be seeing the beamed radiation of different emitting spots under changing angles. In addition, variable absorption and reflection at the inner edge of the precessing accretion disk and possibly a variable orientation due to precession of the neutron star (Postnov 2004) may contribute. The situation can be further complicated by gravitational bending. It is therefore not straightforward to interpret the observed pulse profiles and the variation in E_{cyc} in terms of accretion geometry and beaming characteristics. We note here, that also the photon index Γ of the power law continuum is dependent on pulse phase with a distinct minimum close to the pulse peak (Vasco et al., 2013).

3.3 Variation of E_{cyc} with precessional phase

A few measured low E_{cyc} values at late 35 d phases had led us to suspect that the pulse phase averaged cyclotron line energy may not be constant over the 35 d cycle. This has triggered proposals for repeated observations of Her X-1 at different 35 d phases by *INTEGRAL*, *Suzaku* and most recently *NuStar*. These observations are not yet fully analyzed, but using data from earlier *RXTE* observations (cycle 323), we have already clear indications, that there is a weak modulation of E_{cyc} over the *Main-On*. Vasco et al. (2013) had shown, that the shape of the (E_{cyc} vs pulse phase)-profile is not dependent on 35 d phase, while the pulse profile itself is. Fig. 1(right) demonstrates that the 30-45 keV pulse profiles (this is the energy range which includes most of the CRSF) clearly move to the right with increasing 35 d phase, which means that more and more photons are found at pulse phases where the cyclotron line energy is decreasing. So, a modulation of E_{cyc} with 35 d phase is inevitable. In order to quantitatively test this, we have performed a formal folding of 30-45 keV pulse profiles (for 10 different 35 d phases) with template (E_{cyc} vs pulse phase)-profiles at the same 35 d phases. These template profiles were constructed by inter- and extrapolation of the four individual profiles at different 35 d phases given in Fig. 3 and 4 of Vasco et al. (2013), taking into account that both the maximum value and the peak-to-peak amplitude are slightly 35 d phase dependent. By folding the pulse profile with the corresponding E_{cyc} profile, the expected pulse phase averaged E_{cyc} value can be calculated. In Fig. 2(left) these calculated values are shown as blue triangles (connected by the solid blue line): a slow increase up to phase ~ 0.19 is followed by a somewhat sharper decay. For comparison, we show the directly measured phase averaged E_{cyc} values (data points with uncertainties) for 13 small integration intervals covering the *Main-On* of cycle 323. The directly measured values are consistent with the calculated modulation. With the final analysis of additional data, more definite conclusions are expected. This new result

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[1]The definition of pulse phase zero is tied to the "sharp edge" at the decay of the right shoulder of the main peak (see Staubert et al., 2009b, 2013).
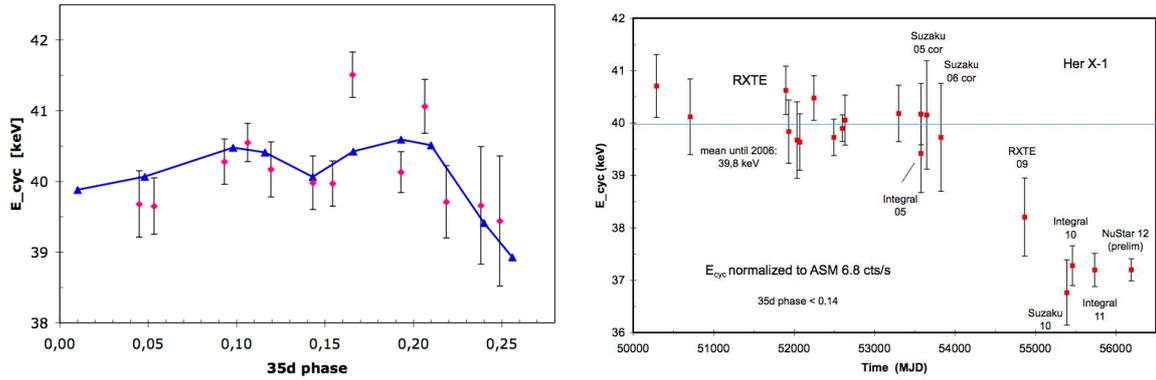
Figure 2: *Left*: Centroid pulse phase averaged cyclotron line energies at different 35 d phases of *Main-On* cycle 323. The data points with uncertainties are direct measurements for ten small integration intervals. The blue triangles connected by the solid blue line are values which are calculated by folding observed pulse profiles in the 30-45 keV range with template (E_{cyc} vs pulse phase)-profiles for the same 35 d phases. *Right*: Her X-1 pulse phase averaged cyclotron line energies E_{cyc}, normalized to a reference ASM count rate of 6.9 cts/s using the originally found correlation function. A break in E_{cyc} is apparent around MJD 54000. Note, that the four points measured last are all low, indicating a true secular variation.

adds another piece to the puzzle on the question about the physical nature of the 35 d modulation - precession of the accretion disk (and?) precession of the neutron star? - and the mechanism of generating the varying pulse profiles and the varying spectra - CRSF and continua (see discussion in Staubert et al., 2009a, 2013 and Vasco et al., 2013).

3.4 Variation of E_{cyc} with time - secular variation

In investigating the long-term behavior of the pulse phase averaged centroid cyclotron line energy, Staubert et al. (2007) had discovered that E_{cyc} depends on the X-ray flux of the source. Their Fig. 1 compiles the historical measurements until this time: after the initial measurements in the range 34–37 keV, a (so far unexplained) upward jump occurred, between 1991 and 1994, to beyond 42 keV, followed by an apparent decrease with time. This decrease had been noticed after the first observations with *RXTE* in 1996 and 1997 (in comparison to values from *CGRO*/BATSE and *Beppo*/SAX), and had served as an important argument to ask for more observations of Her X-1. But then, Staubert et al. (2007) showed that this decrease with time was largely an artifact due to the dependence of E_{cyc} on X-ray flux. Plotting E_{cyc} against the 2-10 keV X-ray flux, as measured by ASM on *RXTE* shows a clear positive correlation, with an increase in E_{cyc} by $\sim 7\%$ for a factor of two increase in flux (see Section 3.1). So, here nature had conspired such that later measurements were (on average) taken when the flux happened to be low (Her X-1 is known for varying its flux within a factor of two, on time scales of a few 35 d cycles).

Now, however, the situation has changed. Here, we report about the first statistically significant evidence for a *true secular decay of the phase averaged cyclotron line energy*. From Fig. 1(left), it is already evident that E_{cyc} values measured after 2008 are significantly lower, while maintaining a similar positive correlation within themselves (possibly less steep). In order to separate the dependence on time and the dependence on X-ray flux, we have normalized the measured E_{cyc} values to

a common X-ray flux (namely 6.8 ASM cts/s), using the slope as found in the original flux correlation. The result is shown in Fig 2(right). The normalized E_{cyc} values until 2006 are consistent with a constant value of 39.8 keV, a significant decrease occurs after that. This decrease is consistent with a linear decay with time between 2006 and 2012, but a more abrupt change can not be excluded. We note, that all measurements used for this plot are from observations corresponding to the *Main-On* of Her X-1 at 35 d phases less than 0.14 (for which the dependence on 35 d phase is very weak).

With regard to the physical implications of the now observed secular decrease of the cyclotron line energy, we speculate that the phenomenon could be connected to a restructuring of the polar magnetic field of the neutron star. This may be due to an adjustment of the field when coping with the continued accretion of plasma. Theoretically, such scenarios have been investigated e.g., by Brown and Bildsten (1998), Litwin et al. (2001), Mukherjee and Bhattacharya (2012) and Mukherjee et al. (2012).

References

[1] Becker P.A., Klochkov D., Schönherr G., Wilms J., Staubert R. et al. 2012, *A&A*, **544**, A123

[2] Brown E. F. and Bildsten L. 1998, *ApJ*, **496**, 915

[3] Burnard D. J., Arons J., Klein R. I. 1991, *ApJ*, **762**, 61

[4] Coburn W., Heindl W. A., Rothschild R. E., Gruber D. E., Kreykenbohm I. et al. 2002, *ApJ*, **580**, 394

[5] Enoto T., Makishima K., Terada Y., Mihara, T., Nakazawa, K. et al. 2008, *PASJ*, **60**, 57

[6] Heindl W., Rothschild R. E., Coburn W., Staubert R., Willms J. et al. 2004, in *Proc. "X-ray Timing 2003: Rossi and Beyond"*, AIP 714, p.323

[7] Klochkov D., Staubert R., Postnov K. A., Shakura N. I., Santangelo, A. et al. 2008, *A&A*, **482**, 907

[8] Klochkov D., Staubert R., Santangelo A., Rothschild R. E., Ferrigno C. 2011, *A&A*, **532**, A126

[9] Klochkov D., Doroshenko V., Santangelo A., Staubert R., Ferrigno C. et al. 2012, *A&A*, **542**, L28

[10] Litwin C., Brown E. F., and Rosner R. 2001, *ApJ*, **553**, 788

[11] Mihara T. 1995, *PhD Thesis*, Univ. of Tokyo

[12] Müller S., Ferrigno C., Kühnel M., Schönherr G. et al. 2012, *A&A*, in print, astro-ph.HE 1211.6298

[13] Müller D., Klochkov D., Caballero I., Staubert R., Santangelo A. 2013, *PoS(INTEGRAL12)*, this Vol.

[14] Mukherjee D. and Bhattacharya D. 2012, *MNRAS*, **420**, 720

[15] Mukherjee D., Bhattacharya D., Mignone A. 2012, *MNRAS*, in print, astro-ph.HE1212.3897

[16] Nakajima M., Mihara T., Makishima K., Niko, H. 2006, *ApJ*, **646**, 1125

[17] Postnov K. 2004, http://astro.uni-tuebingen.de/staubert65/talks/postnov.pdf

[18] Staubert R., Bezler M., Kendziorra E. 1983, *A&A*, **117**, 215

[19] Staubert R. 2003, in "Multifrequency behaviour of high energy cosmic sources", *ChJAA*, **3**, S270

[20] Staubert R., Shakura N. I., Postnov K., Wilms, J., Klochkov D. et al. 2007, *A&A*, **465**, L25

[21] Staubert R., Klochkov D., Postnov K., Shakura N., Willms J., Rothschild R. 2009a, *A&A* **494**, 1025

[22] Staubert R., Klochkov D., Wilms J. 2009b, *A&A*, **500**, 883

[23] Staubert R., Vasco, D., Klochkov D., Wilms J. 2013, *A&A*, **550**, A110 (astro-ph.HE 1212.5472)

[24] Terada Y. et al. 2007, in Adv. Space Res. 40, 1485

[25] Trümper J., Pietsch W., Reppin, C., Voges W., Staubert R., Kendziorra E. 1978, *ApJ* **219**, L105

[26] Tsygankov S. S., Lutovinov A. A., Churazov E. M., Sunyaev R. A. 2006, *MNRAS*, **371**, 19

[27] Tsygankov S. S., Lutovinov A. A., Churazov E. M., Sunyaev R. A. 2007, *Astr. Lett.*, **33**, 368

[28] Vasco D., Klochkov D., Staubert R. 2011, *A&A* **532**, A99

[29] Vasco D., Staubert, R., Klochkov D., Santangelo A. et al. 2013, *A&A*, **550**, A111

[30] Wilms J. 2012, in Proceed. 39th COSPAR Scientific Assembly, 14-22 July 2012, in Mysore, India: "Cyclotron Lines of Accreting Neutron Stars", Vol. 39, p. 2159