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Magnetic fields of accreting X-ray pulsars

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Abstract The status of the knowledge about magnetic fields of neutron stars in accreting X-ray binaries through the measurement of cyclotron lines (Cyclotron Resonance Scattering Features — CRSF) is reviewed. A systematic search for cyclotron lines through observations with the *Rossi X-ray Timing Explorer* (RXTE) and a uniform analysis have led to a list of 10 objects showing one or more line feature(s) in phase averaged spectra (Coburn 2001, Coburn et al. 2002a). Another 3 objects are known from observations by Ginga, HEXE and OSSE, but were not observed by RXTE. For 12 further objects upper limits have been set from RXTE observations (Coburn et al. 2002b). Four objects show more than one line, with 4U 0115+63 showing up to five lines. The range of magnetic fields in these objects is $\sim (1 \ldots 5)\, 10^{12}$ Gauss. There are a number of significant correlations between parameters describing the line and the continuum spectrum, as well as among the line parameters themselves. The physics of these correlations is not well understood.

Key words: stars: neutron stars, X-ray binaries – magnetic fields: super strong

1 INTRODUCTION

Accreting X-ray pulsars are believed to be highly magnetized neutron stars (NS) in binary systems (Rappaport & Joss 1977a, White et al. 1983, Nagase 1989, Bildsten et al. 1997). These objects are powered by gravitational energy which is released when material accreted from the companion falls down along the magnetic field lines into the deep potential well and is stopped near the surface of the neutron star, in a small area close to the magnetic poles. An accretion rate of the order of $10^{-9}\, M_{\rm solar}\, {\rm year}^{-1}$ leads to a luminosity of order $10^{37}\, {\rm erg\, s}^{-1}$. When the magnetic axis is inclined to the axis of rotation, regular modulation of the observed flux with rotational phase is produced, and a pulsar is observed. An X-ray continuum from bremsstrahlung and Comptonization is released from a plasma with a temperature of the order of 10^8 K. The strong magnetic field significantly affects the radiation transport from the inside of the accretion mound, leading to spectral features due to resonant cyclotron scattering – the cyclotron lines, or Cyclotron Resonant Scattering Features (CRSF). The accretion process leads to an exchange of angular momentum between the accreted material and the neutron star due to torques produced when the material couples to the neutron star magnetosphere (Gosh & Lamb 1979). As a result, changes of the pulsational (rotational) frequencies are observed

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in all of these objects. Both spin-up and spin-down (often changing on short time scales) are observed (White et al. 1983, Nagase 1989, Bildsten et al. 1997). Using accretion torque theory and the observed characteristics (X-ray luminosity, pulse period P and its derivative $\mathrm{d}P/\mathrm{d}t$) and assuming standard NS parameters ($R = 10^6$ cm), the magnetic field can be estimated: the values are found to be of the oder of a few times 10^{12} Gauss. Such indirectly inferred values are quite consistent with the direct measurements of the field strength provided by cyclotron line observations.

Taking the Milky Way and the LMC and SMC together, about 80 accreting pulsars are known (∼10% low mass systems, ∼40% persistent giant/supergiant systems and ∼50% transient high mass Be-systems, see e.g. Coburn 2001). The accretion process is by Roche lobe overflow, wind accretion or transiently through Be disks.

2 CYCLOTRON LINE OBJECTS

Table 1 gives a compilation of 13 objects which are believed to show clear evidence for the existence of cyclotron lines. Besides the name and type of the binary, we give the pulsational and orbital periods, whether the X-ray source is eclipsed or not, the position of the fundamental cyclotron line (in keV) and the instrument which performed the first detection. The first 10 objects in Table 1 have been observed with RXTE, the last three objects were not observed by RXTE (Coburn et al. 2002a). The first cyclotron line was found in Her X-1 by the MPE/AIT Balloon-HEXE in 1975 (see Fig. 1, Trümper et al. 1978). This feature was originally interpreted as an emission line, the data itself did not allow to make a distinction between an emission and an absorption feature. It became soon clear from theoretical models (e.g Nagel 1981, Meszaros & Nagel 1985a,b) that the feature must be due to resonant scattering leading to apparent absorption. Observationally, this was for the first time confirmed by high quality data from the Mir-HEXE experiment (Kunz 1996).

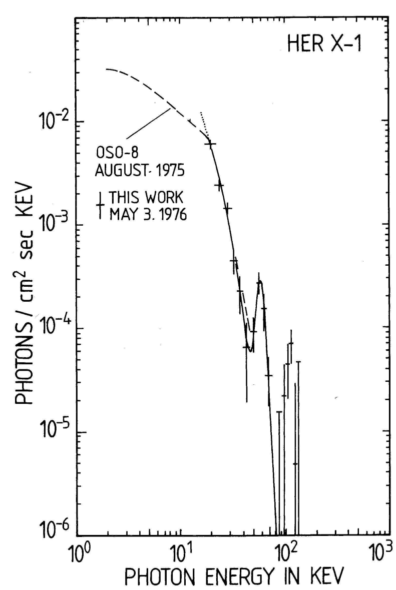

Fig. 1 The X-ray spectrum of Her X-1 as obtained in a balloon observation in 1975, constituting the first detection of a cyclotron line (from Trümper et al. 1978).

Table 1 Cyclotron Line Sources

System	Type	P_{spin} (s)	P_{orb} (days)	Ecl.	Line E. (keV)	Instr. of 1st Det.	Ref.
RXTE:							
Hercules X-1	LMXB[a]	1.2377	1.70	yes	41	Balloon	1
4U 0115+63	Be trans.	3.61	24.3	yes	12	HEAO-1	2
Centaurus X-3	HMXB[b]	4.82	2.09	yes	28	BeppoSAX	3
4U 1626−67	LMXB	7.67	0.0289	no	37	BeppoSAX	4
XTE J1946+274	Transient	15.83	–	no	36	RXTE	5
Vela X-1	HMXB	283.2	8.96	yes	25	HEXE	6
4U 1907+09	HMXB	440.4	8.38	nearly	18	Ginga	7
4U 1538−52	HMXB	528.8	3.73	yes	20	Ginga	8
GX 301−2	HMXB	681	41.5	nearly	37	Ginga	9
4U 0352+309	Be persist.	837.7	250.3	no	29	RXTE	10
non-RXTE:							
A 0535+26	Be trans.	103	111	no	50, 110	HEXE/OSSE	11/12
V 0332+53	Be trans.	4.4	34	no	28	Ginga	13
Cep X-4	Be trans.	66.2	(100?)	no	30	Ginga	14

[a] Low Mass X-ray Binary, [b] High Mass X-ray Binary.
Ref.: 1: Trümper et al. 1978; 2: Wheaton et al. 1979; 3: Santangelo et al. 1998; 4: Orlandini et al. 1998; 5: Heindl et al. 2001; 6: Kretschmar et al. 1996; 7: Makishima & Mihara 1992; 8: Clark et al. 1990; 9: Makishima & Mihara 1992; 10: Coburn et al. 2001; 11: Kendziorra et al. 1994; 12: Grove et al. 1995; 13: Makishima et al. 1990; 14: Mihara et al. 1991.

3 THEORY OF CYCLOTRON RESONANCE SCATTERING FEATURES (CRSF)

The general environment of the hot plasma at the magnetic poles of an accreting neutron star emitting an X-ray continuum spectrum with cyclotron features, may be described by Fig. 2 which shows a schematic representation of an accretion mound at the magnetized polar cap. The continuum photons produced inside the hot region by thermal bremsstrahlung and comptonization trying to escape through the surface have a finite probability of being resonantly scattered in the outer layers, thereby producing an apparent absorption line. The resonance occurs because of quantized energy states (Landau levels) of electrons with respect to their motion in circular orbits transverse to the magnetic field direction. The fundamental energy where the feature appears (corresponding to the energy difference between the ground state and the first excited state) is given by

$$E_{\mathrm{c}} = 11.6\,(\mathrm{keV})\frac{B}{10^{12}}(1+z)^{-1}\,, \tag{1}$$

where B is the magnetic field strength (in Gauss) in the scattering region, and z is the gravitational redshift. “Higher harmonics” appear at roughly equidistant levels $n \cdot E_{\mathrm{c}}$ ($n = 2, 3, \ldots$). Such higher harmonics are indeed observed in some sources (see below). At sufficiently high magnetic fields a deviation from the equidistant leveling occurs and the cyclotron line energies appear at

$$E_{\mathrm{c}} = m_{\mathrm{e}}c^2 \frac{\left(1 + 2nB' \sin^2\theta\right)^{1/2} - 1}{\sin^2\theta}\,, \tag{2}$$

where $B' = B\hbar e/(m_e^2 c^3)$ is the field scaled to the QED field scale, n is the harmonic number, and θ is the angle of propagation of the photon relative to the magnetic field. This means that the observed features will depend strongly on the spatial distribution of electrons and their flight paths.

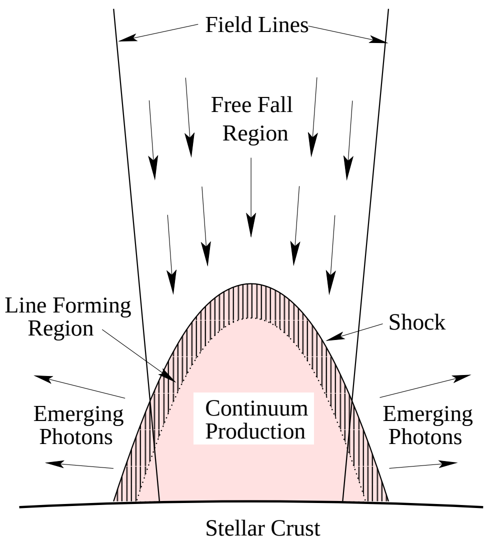

Fig. 2 Schematic representation of an accretion mound close to the surface at the magnetic pole of a neutron star.

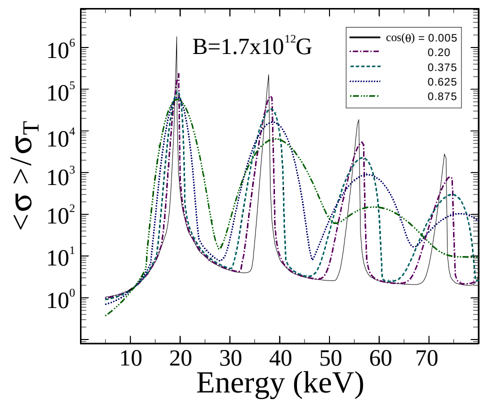

Fig. 3 Cyclotron scattering cross sections (in units of the Thomson cross section) (Araya & Harding 1999). θ is the angle between the magnetic field and the direction of photon propagation.

Monte Carlo calculations of the radiation transport in the emitting region by Araya & Harding (1999) and Isenberg, Lamb & Wang (1998a,b) have shown, that the shape of the fundamental and harmonics can be quite complex and very dependant on the details of the geometry and the physics (temperature, electron density, B field) in the emission region. Figure 3 (right) reproduces Fig. 2 from Araya & Harding (1999), showing the cyclotron scattering cross section (in units of the Thomson cross section) for a field with $B = 1.7 \times 10^{12}$ Gauss, where the dependence on the photon propagation angle θ is quite apparent (for $\cos\theta$ approaching unity – propagation nearly parallel to B – the cross sections get smeared out due to free thermal motion of the electrons along the field lines). Figure 4 gives the result of Monte Carlo calculations of cyclotron line spectra after Araya-Gochez & Harding (2000). In these calculations a power law continuum with photon index 1.0 (dotted lines) is injected into the magnetized plasma with $B = 1.7 \times 10^{12}$ Gauss under various geometries: it is distinguished between slab and cylinder geometry, in the upper panels (left and right) the injection of the input photons is isotropic, while in the lower panels the injection is in a cone pattern along the B-field (left) and as fan-beam perpendicular to the field (right). The resulting output spectra are given as solid lines, the individual spectra in each quadrant are for different viewing angles to the magnetic field (dividing 90° into 4 sections: going from near parallel to near perpendicular from top to bottom).

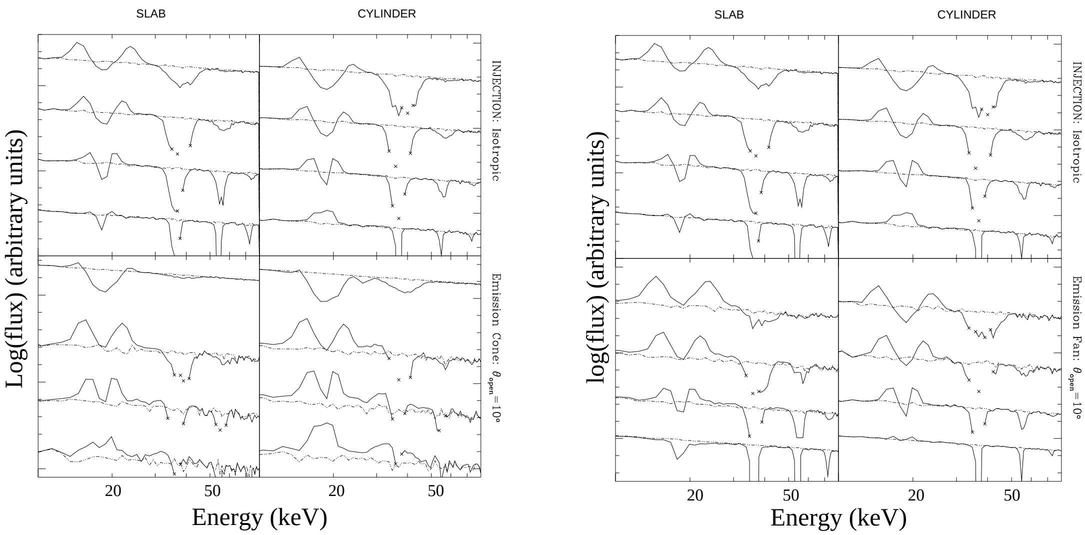

Fig. 4 Monte Carlo calculations of cyclotron line spectra after Araya-Gochez & Harding (2000). See text for explanation.

4 SOME EARLY RESULTS OF PULSE PHASE SPECTROSCOPY

The technique to accumulate spectra using photons which belong to well defined intervals of pulse phase is referred to as *pulse phase spectroscopy.* This technique was already applied to the first data leading to the detection of the cyclotron line in Her X-1 (Trümper et al. 1978) as a powerful means of background subtraction by e.g. taking the difference between spectra of the pulse region and spectra of the off-pulse region ("pulse-minus-off-pulse", POP), thereby avoiding systematic errors which do not depend on pulse phase. In the early balloon observations of Her X-1 (Voges et al. 1982) and those by HEAO-1 (Soong et al. 1990) it was already found that the observed X-ray spectra, particularly the cyclotron line parameters, vary with pulse phase. This had been confirmed by high quality data from Mir-HEXE. Figure 5 shows the mean pulse profile of Main-On data of Her X-1 (1987-1989) and spectra for certain phase intervals. The line position varies by about 25% and the line depth by at least a factor of five, both parameters are highest near the peak of the pulse (Kunz 1986). But also continuum parameters, such as the power law index and the cut-off energy have been found to vary.

A very special object is the transient 4U 0115+63 of which several outbursts have been observed. During the outburst in March 1999, *Beppo*SAX and RXTE discovered multiple cyclotron line features (Santangelo et al. 1999, Heindl et al. 1999a), making it the first X-ray pulsar with more than two lines (the fundamental and the first harmonic — as e.g. in Vela X-1, A 0535+26 and 4U 1907+09). Figure 6 shows the spectrum of 4U 0115+63 as observed by RXTE (Heindl et al. 1999a) for phase bin D (as defined in Fig. 7). The best fit to the spectrum requires 5 cyclotron lines, the positions of which are consistent with equidistant energy levels between 12 and 66 keV. Figure 7 shows the mean pulse profile of the 3.61 s pulsation, the definition of pulse phase bins (A through N) and the positions of the 1st and 2nd harmonic which clearly vary with pulse phase.

Pulse phase is equivalent to rotation phase of the NS and the observed variations are believed to be due to the different viewing angles under which the observer sees the emission region.

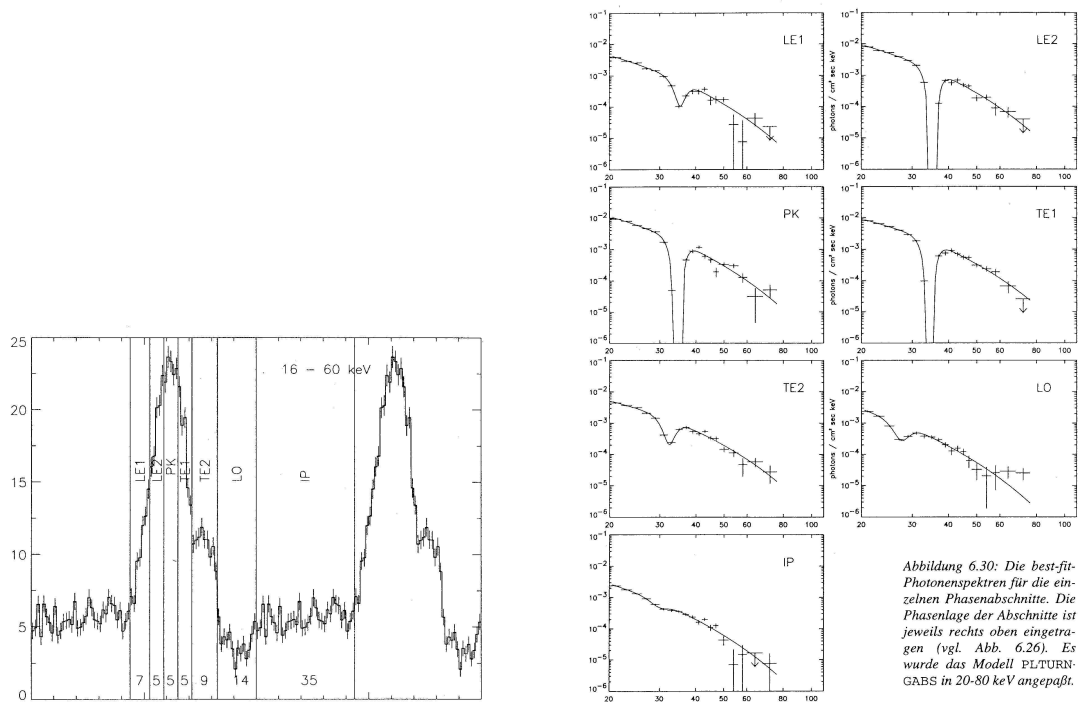

Fig. 5 Left: 1.24 sec pulse profile of Her X-1 as observed by Mir-HEXE (note the definitions of certain phase bins). Right: Cyclotron line spectra of Her X-1 (photon spectra) as observed by HEXE (coadded Main-On data of Juli 1987 to April 1989) for those pulse phase bins defined in the left panel (Kunz 1996).

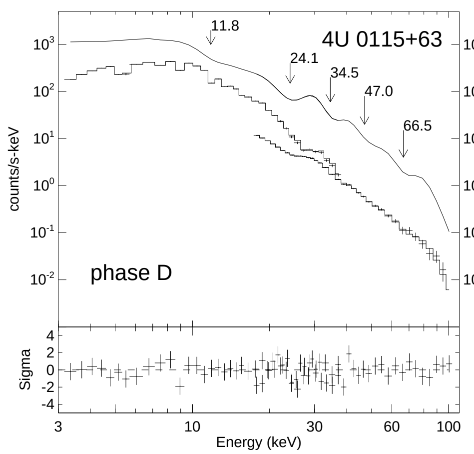

Fig. 6 Spectrum of 4U 0115+63 of phase bin D (definition see Fig. 7) from observations during the outburst in March 1999 (Heindl et al. 1999a).

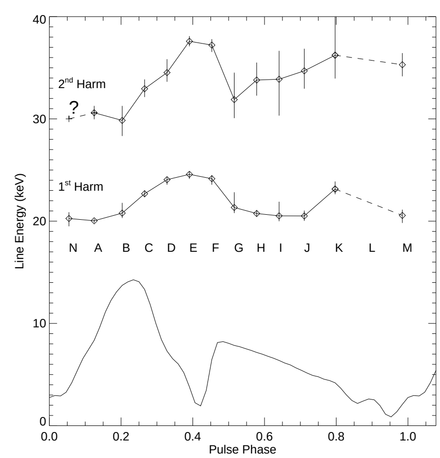

Fig. 7 Folded pulse profile of 4U 0115+63, definition of phase bins and the variation of the position of the 1st and 2nd cyclotron harmonic.

By performing high resolution pulse phase spectroscopy one studies the combined effects of the accretion flow geometry, the physics inside the accretion mound and radiation transport in the highly magnetized plasma - in a highly complex setup.

5 UNIFORM ANALYSIS OF RXTE DATA

Cyclotron line research was significantly advanced by the *Beppo*SAX and RXTE missions. Not only were several new cyclotron lines found (mostly in previously known sources, see Table 1 — confirming the notion that cyclotron lines may not be a rare but rather a common phenomenon in accreting X-ray binaries), but it has now become possible to do systematic and uniform analysis of such objects and to do a class study.

Even though it is evident that pulse phase resolved spectroscopy is the ultimate method to be chosen, it has not been applied to all known accreting X-ray binaries in a uniform way. However, a uniform analysis using pulse phase averaged spectra has recently been done on all RXTE observations of such objects which were suspected to possibly have one (ore more) cyclotron line(s) (altogether 25 objects, Coburn et al. 2002a,b). This analysis allows a unique class study and a meaningful comparison of different objects: the data were all taken with the same instruments (PCA and HEXTE on RXTE), the data were analyzed in the same uniform way, using the same analysis procedures, in particular the same fitting model.

For modeling the continuum, the widely applied power-law with high-energy cutoff (PLCUT, White, Swank & Holt 1983) was used:

$$\mathrm{PLCUT}(E) = AE^{-\Gamma} \times \begin{cases} 1 & \text{for } E < E_{\mathrm{cut}} \\ e^{-(E-E_{\mathrm{cut}})/E_{\mathrm{fold}}} & \text{for } E > E_{\mathrm{cut}}\,, \end{cases} \tag{3}$$

where Γ is the photon index, and E_{cut} and E_{fold} are the cutoff and folding energies, respectively. (The continuum was somewhat modified by a smoothing function to reduce the effect of the discontinuity at the cutoff energy, see Coburn et al. 2002a). The PLCUT function was chosen (despite the difficulty with the discontinuity) because of distinct advantages (see the detailed discussion in Coburn et al. 2002a) over alternative models such as the Fermi-Dirac cutoff model (FDCO, Tanaka 1986), or the dual power law cutoff model (NPEX, Mihara 1995). To model the cyclotron absorption line, the continuum $I_0(E)$ was modified to

$$I_0(E)e^{-\tau(E)}\,, \tag{4}$$

where $\tau(E) = \tau_{\mathrm{c}} \exp\left((E - E_{\mathrm{c}})^2/(2\sigma^2)\right)$ with E_{c} being the energy of the resonance, τ_{c} is the depth of the line at E_{c} and σ is the width of the line (with the FWHM roughly equal to 2.36σ).

The uniform analysis of RXTE observations of accreting X-ray pulsars has led to a number of conclusions (Coburn 2001, Coburn et al. 2002a,b): In 10 objects (the first 10 entries in Table 1) cyclotron lines were clearly detected (the last 3 known cyclotron line objects in Table 1 were not observed by RXTE). For additional 15 objects analyzed, only upper limits could be established (Coburn et al. 2002b). Even though pulse phase resolved spectroscopy is certainly the best way of investigating accreting pulsars, pulse phase averaged spectra allow to establish correlations between continuum and line parameters and among line parameters themselves.

Three correlations have emerged, two of which had been known from previous (non-uniform studies) and the third is a new one:

1. The continuum cut-off energy E_{cut} correlates with the cyclotron energy E_{c}.
2. The width of the cyclotron line σ correlates with the cyclotron energy E_{c}.
3. The relative width of the cyclotron line σ/E_{c} correlates with the optical depths τ_{c} of the line.

Figure 8 shows the first relation (E_{cut} versus E_{c}). Such a relation was first noticed by Makishima & Mihara (1992) and Makishima et al. (1999) and modeled by the non-linear function $E_{\mathrm{cut}}\ \alpha\ E_{\mathrm{c}}^{0.7}$. However, the parameters were then derived from observations with different

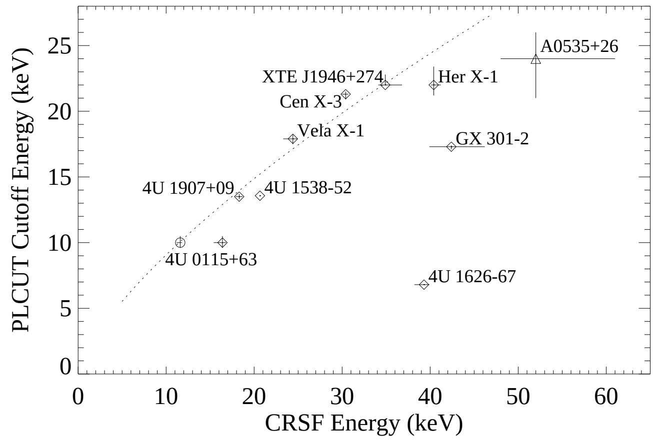

Fig. 8 The cut-off energy E_{cut} as found in fits using the PLCUT function versus the energy E_{c} of the fundamental cyclotron line.

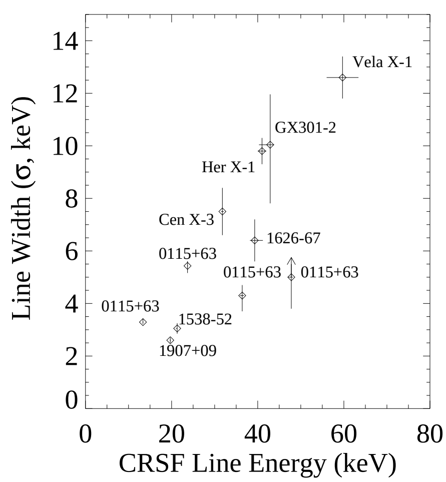

Fig. 9 Line width versus cyclotron energy.

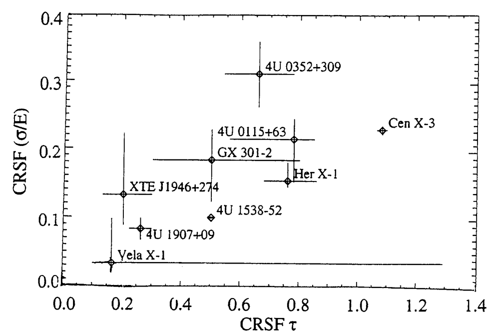

Fig. 10 Relative line width versus line optical depth.

instruments and in using different continuum models for the spectral fits. Now, this basic correlation is indeed confirmed by the uniform analysis of 10 accreting pulsars observed by RXTE. For 4U 1626-67, GX 301-2 and 4U 0352+309 (the data of which are not shown) arguments can be made that their pulse phase resolved spectra show unusually large variations of E_{cut} with pulse phase (Coburn et al. 2002a). Apart from these three objects the scatter around the mean correlation is rather narrow. The data for A 0535+26 (and possibly Her X-1) suggest that there may indeed be a non-linear relationship or a saturation in E_{cut} towards high E_{c}.

From this relation it appears, that also the continuum spectrum is somehow influenced by the strength of the B-field. This may in fact be through a fundamental physical parameter in the accretion region, namely the electron temperature kT_e. Not only have Lamb et al. (1990) shown that under conditions of isotropic injection into an optically thick plasma dominated by cyclotron line cooling and heating, kT_e is about $E_c/4$, but it may be such that the parameters in the accretion mound find natural equilibrium values which do not depend very much on the accretion rate (e.g. by the matter falling in on-top being balanced by the spreading at the base of the mound), thereby allowing kT_e to vary within a rather small range, even for large variations in accretion rate.

The second relation (σ versus E_c, Fig. 9) has also been found earlier from observations by RXTE (Heindl et al. 1999) and *Beppo*SAX (Dal Fiume et al. 2000), but is again strongly confirmed by the uniform analysis. The relation may simply be governed by the cyclotron line energy E_c and the electron temperature kT_e, Trümper et al. (1977) have already noted that Doppler broadening due to the free thermal motion of the electrons along the field lines leads to a cyclotron line width of $\sigma \; \alpha \; E_c \cos(\theta) \sqrt{kT_e}$, θ being again the viewing angle with respect to the magnetic field (see also Meszaros 1992).

This gives (together with the above mentioned relation between kT_e and E_c) a straight forward correlation as seen in Fig. 9. However, there is also the dependence on $cos(\theta)$: for any randomly selected group of objects the distribution of θ should be uniform between 0 and 90° and therefore should completely wash out the correlation. This is, however, not observed and one has to conclude that the objects in Fig. 9 do not constitute a random selection but have an observational bias towards a specific viewing angle θ. In inspecting the objects one finds that 6 out of the 10 CRSF systems are eclipsing systems. Together with the fact that the angular momentum transfer during the accretion process tends to align the NS spin with that of the binary, we appear to have a preferred offset angle between the dipole and spin axes in our sample objects. In turn, this might naturally explain why we do not see cyclotron lines in certain objects (like 2S 1417-624 and others), where there are no observational constraints (e.g. source brightness): our viewing angle may simply not be favorable.

The third relation, σ/E_c versus τ_c as shown in Fig. 10, is a new result of the uniform analysis. It states that the lines become deeper when they become broader (more precisely: when their relative width increases). So, there are particularly strong (wide plus deep) lines (as e.g. in Cen X-3 or 4U 0352+309) and particularly weak lines (as e.g. in Vela X-1, perhaps explaining the difficulties to detect the fundamental line in this source). With regard to a simple interpretation of resonance cross sections (see Fig. 3), the observed relation is the opposite of what one expects: small and deep lines or broad and shallow lines. It is is quite clear that a much more sophisticated interpretation is necessary, taking subtle effects (e.g. angular redistribution of photons and photon spawning) into account. Interestingly, the above correlation has now been found to also hold in a single source, GX 301-2, comparing spectra of different pulse phases (Kreykenbohm et al. 2003).

6 SUMMARY

Of the roughly 80 known accreting pulsars a substantial fraction show Cyclotron Resonant Scattering Features (CRSF) thereby allowing to measure the magnetic field strength (usually of the order of a few times 10^{12} Gauss) and to study the physics in the polar cap accretion mounds. There are 13 objects with confirmed features (Table 1). In most objects just one cyclotron line is seen, in three objects (Vela X-1, A 0535+26, 4U 1907+09) two lines are observed (assumed to be the fundamental and the first harmonic) and in one object (4U 0115+63) up to five lines have been identified. For 12 further objects upper limits have been set from RXTE observations (Coburn et al. 2002b). While some of these observations may have been not sensitive enough (e.g. too short observations), it cannot be excluded that there are objects that do not have cyclotron lines — at least not in pulse averaged spectra (e.g. due to unfavorable viewing directions).

The state of the art of cyclotron line research has received a boost by the *Beppo*SAX and RXTE missions. Through the detection of correlations between spectral parameters for the continuum and the lines in pulse averaged spectra, especially through the uniform analysis, we have been able to get a deeper understanding of the physics in accreting X-ray pulsars. However, there is a wide open field of unanswered questions. Some seemingly simple physical relations meet with difficulties when applied to observational data. It appears that three main efforts are needed for the further advancement of the field: 1) perform a systematic, uniform analysis of pulse resolved spectroscopy of all existing observational data from *Beppo*SAX and RXTE (as complete as the uniform pulse averaged study), 2) perform further Monte Carlo calculations under different assumed physical conditions, and 3) perform new observations of accreting X-ray pulsars, in particular with instruments of higher energy resolution (e.g. with the ISGRI and SPI instruments onboard of INTEGRAL) in order to widen the diagnostic power of the observational data.

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Addendum During the preparation of this contribution a new cyclotron source was discovered in observational data from RXTE: the 160.7 s transient X-ray pulsar MX 0656-072 (RXTE J0658-073) shows a strong cyclotron scattering feature at 35 keV (Heindl et al. 2003).

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