VARIABLE CYCLOTRON LINE IN HER X-1

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ABSTRACT

We present new results on the cyclotron resonance scattering feature (CRSF) in the X-ray spectrum of the binary X-ray pulsar Her X-1 from repeated observations by *RXTE* between 2000 and 2005, together with earlier results from *RXTE* and historical data. The centroid line energy E_c in pulse phase averaged spectra shows considerable variation, both in the long-term historical development as well as during the time of the *RXTE* observations. Using *RXTE* data only, we find that the cyclotron line energy correlates with the observed maximum flux of the corresponding 35 day Main-On state, as measured by the *RXTE/ASM.* Contrary to what is observed in some high luminosity transient pulsars, the correlation found here is positive, with a change of $\sim$ 5% in E_c for a change of a factor of two in X-ray flux. We suggest that this behaviour is expected in the case of sub-Eddington accretion and present a calculation of a quantitative estimate.

Key words: X-ray binaries; X-ray pulsars; neutron stars; cyclotron lines.

1. INTRODUCTION

The X-ray spectrum of the accreting 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 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 cyclotron resonant scattering feature (CRSF). The energy spacing between the Landau levels is given by $E_{\text{cyc}} = \hbar eB/m_{\text{e}}c = 11.6\,\text{keV}\,B_{12}$, where $B_{12} = B/10^{12}\,\text{G}$, providing a direct method of measuring the magnetic field strength at the site of the X-ray emission. The observed line energy is subject to gravitational redshift, z, such that the magnetic field may be estimated by $B_{12} = (1+z)E_{\text{obs}}/11.6\,\text{keV}$. 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 were 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 Coburn et al. (2002). In several objects, multiple lines have been detected (up to four harmonics, see Staubert 2003, Heindl et al. 2004, Salvo et al. 2004 for reviews).

2. OBSERVATIONS

Her X-1 is probably the best observed accreting binary X-ray pulsar. Its X-ray spectrum, including the CRSF, has been measured by many instruments since its discovery in 1975 (Trümper et al. 1978). Fig. 1 displays the complete set of pulse phase averaged CRSF centroid energies available today.

Table 1. Cyclotron line energy measurements from *RXTE* and *INTEGRAL* (Klochkov et al. 2006). Uncertainties are at the 68% level.

Observations month/year	Center MJD	Line Energy keV	max. Flux ASM cts/s
RXTE	Gruber et al. (2001)		
02/96	50114.03	40.9(5)	—
07/96	50289.96	40.8(3)	7.83(54)
10/96	50361.13	39.4(7)	5.84(19)
09/97	50700.12	40.1(4)	7.60(41)
11/97	50762.90	40.0(6)	4.80(43)
RXTE	this work		
12/00–01/01	51915.67	39.92(30)	5.77(27)
05/01–06/01	52053.32	39.91(37)	6.96(31)
12/01–08/02	52369.02	40.04(20)	7.22(34)
11/02–12/02	52616.67	40.51(13)	7.49(22)
10/04–07/05	53439.15	38.74(47)	4.53(28)
Integral			
07/05	53576.00	38.50(70)	4.53(28)

uncertainties in parenthesis refer to the last digit(s)

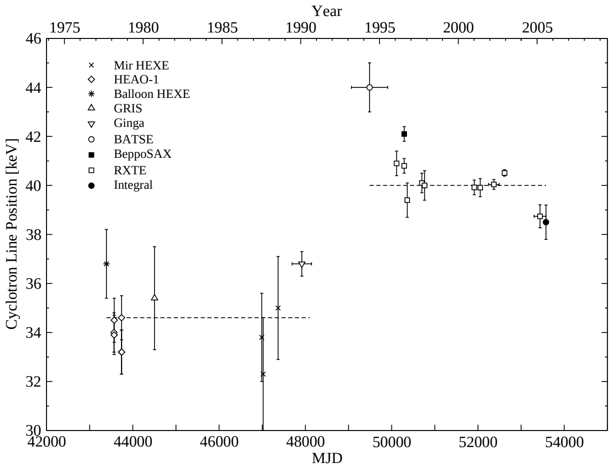

Figure 1. The centroid energy of the phase averaged cyclotron resonance line feature in Her X-1 since its discovery. Data from before 1997 were originally compiled by Gruber et al. (2001), where the original references can be found. The INTEGRAL point is from Klochkov et al. 2006.

Data points before MJD 53000 can be found in Gruber et al. (2001, their tables 2 and 3). The newly analysed data are given in Table 1. They constitute values obtained from combining two successive observations of different 35 day Main-On states. An analysis with higher time resolution is in preparation (Staubert et al. 2006). In Fig. 1 an apparent difference in the mean cyclotron line energy before and after 1992 is clearly visible. This was pointed out by Gruber et al. (2001) and is confirmed by the new data. While a comparison of measurements by different instruments is difficult because of systematic uncertainties due to calibration and analysis techniques, this difference may still be real (we will comment on this in the discussion).

3. RESULTS

Here we discuss results from spectral analysis of pulse phase averaged spectra only. Our main focus is on new results obtained between 2000 and 2006 from repeated observations by *RXTE*. These new measurements are of high quality and yield comparatively small uncertainties in the measured quantities. The joint spectral analysis of the *PCA* and *HEXTE* data was performed using the standard *XSPEC/FTOOLS* (6.0.4) software. For the spectral model we have chosen the 'high-E-cut' model which is based on a power law continuum with exponential cut-off, and the CRSF is modeled by an absorption line with a Gaussian optical depth profile. Details of the fitting procedure can be found in Coburn et al. (2002). Table 1 summarizes the observation dates, the CRSF centroid energies and the maximum X-ray fluxes for the corresponding 35 day Main-On states. Fig. 1 displays the measured CRSF centroid energies as a function of time. The new results are combined with historical measurements before MJD 51000, as taken from the compilation by Gruber et al. (2001, their tables 2 and 3), and the result of a 2005 observation by *INTEGRAL* (Klochkov et al. 2006).

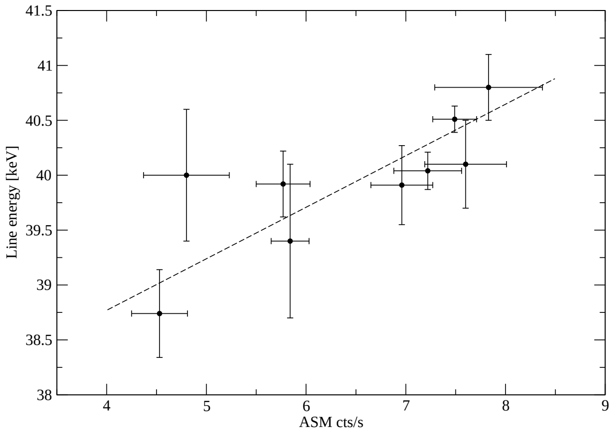

Figure 2. The centroid cyclotron line energy of Her X-1 versus the maximum flux during the corresponding 35 day Main-On as observed by the RXTE/ASM. A linear fit (taking uncertainties in both variables into account) defines a slope of 0.47 ± 0.11 *keV/(ASM cts/s).*

Here we concentrate on the *RXTE* results. Our new results on the CRSF in Her X-1 are the following:

- New measurements of the CRSF centroid energies E_c in Her X-1 were done in 2000–2006, as listed in Table 1, together with earlier *RXTE* values reproduced from Gruber et al. (2001).
- The mean CRSF centroid energy of all *RXTE* points is $\langle E_c \rangle = 40.3 \pm 0.1$ keV.
- Significant variability in E_c is observed. The reduced χ^2 for the *RXTE* values in Fig. 1 with respect to the mean is 2.7 for 9 d.o.f..
- A positive correlation between E_c and the maximum flux of the respective 35 day Main-On state (as measured by *RXTE/ASM*) is observed (Fig. 2): a factor of two change in flux corresponds to a $\sim$ 5% change in E_c.

4. VARIATIONS IN CYCLOTRON LINES

Apart from variations with pulse phase, shifts of line positions have been seen in phase averaged spectra in correlation with changing X-ray luminosity. Mihara et al. (1998) have interpreted those for for 4U0115+63, Cep X-4, and V0332+53, as due to the change of height of the shock and the 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 strongly 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 NS surface, and therfore to a decrease in the CRSF energy E_c. During the 2004/2005 outburst of V0332+53 a clear anti-correlation of the line position with X-ray flux was observed (Kreykenbohm et al. 2005; Tsygankov et al. 2006a; Mowlavi et al. 2006). Analysing *RXTE* data of the Feb–Apr 1999 outburst of 4U 0115+63, both Nakajima et al. (2006) and Tsygankov et al. (2006a) find a general anti-correlation between E_c and luminosity. There seems to be steep dependence in a limited luminosity range (2...5$10^{37}$ erg/s) with regions of near independence between the two quantities at lower and higher luminosities. At the lowest luminosity the data are even consistent with a reversal of the dependence (albeit with low statistical significance).

For Her X-1, however, so far no clear relation between the cyclotron line energy E_c and X-ray flux of any kind had been found (see e.g. Mihara et al. 1998; Gruber et al. 2001). Here we report the first detection of a positive correlation of E_c with X-ray luminosity. As a measure of the luminosity we take the maximum X-ray flux of the corresponding 35 day Main-On state as measured by the *RXTE/ASM* (formally determined by fitting the flux history of the respective Main-On by a template function derived from the mean of many Main-On cycles). This maximum flux provides a better information on the accretion state of the source than the locally measured flux since the latter is subject to modulation by variable absorption/shading by the accretion disk.

5. PHYSICS IN THE SUB-EDDINGTON ACCRETION REGIME

In the following we suggest a physical explanation of our finding and attempt a quantitative estimate of the expected effect. Since the pioneering paper by Basko & Sunyaev (1976), it has been known that the structure of the accretion column near the neutron star surface in X-ray pulsars differs for high-luminosity ($L > L_c$) and low-luminosity ($L < L_c$) regimes, where the critical luminosity L_c is given by the local Eddington luminosity L_E (Nelson et al. 1993)

$$L_E = \frac{2\pi \mathrm{GMcm_p}}{\sigma_T}\left(\frac{\sigma_T}{\sigma_m}\right)\theta_c^2$$

$$\simeq 10^{36}\ \text{erg/s}\ \left(\frac{\sigma_T}{\sigma_m}\right)\left(\frac{\theta_c}{0.1}\right)^2 \qquad (1)$$

Here M is the NS mass (assumed to be 1.4 $M_\odot$ in the numerical estimation), σ_m is the photon-electron scattering cross-section in the magnetic field, σ_T is the Thomson cross-section, and θ_c is the half-opening angle of the polar cap magnetic field lines. In the radiation-dominated super-Eddington regime the height of the accretion column increases with luminosity (Burnard et al. 1991). As discussed above, this explains the observed anti-correlation between the CRSF energy in spectra of bright transient X-ray pulsars with luminosity (Mihara et al. 1998; Tsygankov et al. 2006a,b; Nakajima et al. 2006), as the magnetic field value decreases with the height above the NS surface.

In the low-luminosity, sub-Eddington regime of accretion, however, we can expect a different behaviour of the CRSF centroid energy when the luminosity changes, turning even to the opposite to what is observed in high-luminosity X-ray pulsars. For the set of *RXTE* observations of Her X-1 we have a case of sub-Eddington accretion in this X-ray pulsar. With the cyclotron line energy E_c of about 40 keV, the cross-section of photon–electron scattering in the direction along the magnetic field lines (which is of interest for the radiation pressure against the infalling material) decreases $\propto (E/E_c)^2$ (Harding & Lai 2006, and references therein). At low energies where most of the photons are produced in the case of Her X-1, $(\sigma_m/\sigma_T) \ll 1$, and for an X-ray luminosity of a few times 10^{37} erg/s the source is in the sub-Eddington regime.

The physical picture of magnetic accretion in low-luminosity X-ray pulsars was discussed by Nelson et al. (1993). Accreting protons lose their kinetic energy in an electron-proton atmosphere formed at the surface due to the Coulomb drag and collective plasma effects. The characteristic braking length for protons can be identified with their mean free path $l_* \sim 1/n_e\sigma$, where σ is the effective interaction cross-section. A change in the observed cyclotron line energy can be associated with a change in the height of the emission region above the neutron star surface. We write the observed cyclotron energy as

$$E_c = \left(\frac{\hbar eB}{m_e c}\right) g_{00}^{1/2} \qquad (2)$$

where B is the polar magnetic field strength, $g_{00}^{1/2} = \sqrt{1 - R_g/r} = 1/(1+z)$ is the Schwarzschild metric coefficient determining the gravitational redshift z. $R_g = 2GM/c^2$ is the gravitational radius. Identifying the characteristic length l_* with the height of the scattering region above the surface of the NS, we define $r = R + l_*$ (with R being the radius of the NS). Then the fractional change of the cyclotron line energy is

$$\frac{\Delta E_c}{E_c} = \frac{\Delta B}{B} + \frac{1}{2}\frac{\Delta g_{00}}{g_{00}} \qquad (3)$$

Assuming a pure dipole field ($B \propto r^{-3}$) we obtain

$$\frac{\Delta E_c}{E_c} = -3\frac{\Delta r}{R} + \frac{1}{2}\frac{R_g}{R}\frac{\Delta r/R}{g_{00}} \qquad (4)$$

The redshift term can be neglected as long as $R_g/R < 1/2$ (which is fulfilled for a standard neutron star). Making the identification $\Delta r/l_* = -\Delta n_e/n_e$, we arrive at

$$\frac{\Delta E_c}{E_c} = 3\frac{l_*}{R}\frac{\Delta n_e}{n_e} \qquad (5)$$

Now we need to find how the density in the region of energy release and line formation is related to the luminosity. There is no simple estimate of this, but we can use the approach by Nelson et al. (1993) to find the structure of the accretion mound. In addition to the hydrostatic term considered by Nelson et al. (1993), we add the dynamical pressure of infalling protons so that the total pressure is

$$P = 2n_e kT = gy + (\rho_0 v_0^2 - \rho v^2) \qquad (6)$$

Here y is the mass column density, T is the temperature, ρ_0 and v_0 are the density and velocity of the infalling matter at the beginning of the braking region. It is of course not a self-consistent treatment of the problem, but a step forward to account for dynamical pressure of accreting protons inside the braking region. For the free fall acceleration near the NS surface $g = GM/R^2 \simeq 2 \times 10^{14}\,\mathrm{cm\,s^{-2}}$ and $y \simeq 20\,\mathrm{g\,cm^{-2}}$ (Miller et al. 1987), the hydrostatic term is not higher than 4×10^{15} dyn cm^{-2}. The dynamical term can be expressed using the solution found by Nelson et al. (1993) and the continuity equation $\dot{M} = \rho v A$ (A is the accretion area for one pole) in the form

$$\rho_0 v_0^2 - \rho v^2 = \left(\frac{\dot{M}}{A}\right) v_0 (1 - (1 - \tau/\tau_*)^{1/4}) \qquad (7)$$

where τ is the Thompson optical depth and τ_* is the proton stopping depth. Clearly, the dynamical term vanishes at the base of the accretion column (i.e. at $\tau = \tau_*$) where the bulk kinetic energy of the protons are transformed into their thermal motion. It dominates, however, at the beginning of the deceleration region (for small y and small τ, and for typical values like $\dot{M} = 10^{17}$ g s^{-1}, $A = 1/400$ of the NS surface area and $v_0 = 10^{10}\,\mathrm{cm\,s^{-1}}$). As the stopping depth is $\tau_* \sim 50$ for magnetic accretion (Nelson et al. 1993), we find for $\tau \ll \tau_*$ (from where the emission escapes)

$$n_e \simeq \left(\frac{\dot{M}}{A}\right) \frac{v_0}{2kT} \frac{\tau}{4\tau_*} \qquad (8)$$

As long as $l_* \ll R$ we can neglect a variation in A (this is justified since the stopping length for $\tau_* \sim 50$ and $n_e \sim 10^{24}\,\mathrm{cm^{-3}}$ is very small), so the main parameter which determines the density inside the stopping region is $\dot{M}$. So we finally obtain:

$$\frac{\Delta E_c}{E_c} = 3\frac{l_*}{R}\frac{\Delta\dot{M}}{\dot{M}} = 3\frac{l_*}{R}\frac{\Delta L}{L} \qquad (9)$$

We see that in the sub-Eddington accretion regime the fractional change in cyclotron line energy can be directly proportional to the fractional change in luminosity. For example, for the observed luminosity variations in Her X-1 $\Delta L/L \sim 1$ (a change of a factor of two in the observed flux) the formula above gives $\Delta E_c/E_c \sim 3l_*/R$. The stopping length is $l_* = \tau_*/(n_e\sigma_T)$, the density estimation for $\dot{M} = 2\ 10^{17}\,\mathrm{g\,s^{-1}}$, $v_0 = 10^{10}\,\mathrm{cm\,s^{-1}}$, $kT = 10\,\mathrm{keV}$, and $\tau \sim 1$ yields $n_e \sim 10^{22}\,\mathrm{cm^{-3}}$, so $l_* \sim 10^4\,\mathrm{cm}$. So the expected fractional change in the cyclotron line energy is $\Delta E_c/E_c \simeq 0.03$, which is very close to the observed value of 5%. We note, however, that we used a fiducial value of $\tau_* = 50$ appropriate for a weak magnetic field (Nelson et al. 1993), but in strong magnetic fields this value can be higher, the electron density would decrease and l_* increase, accordingly. So we suggest that a measurement of $\Delta E_c/E_c$ can in fact be used to assess the stopping length of protons in the regime of sub-Eddington magnetic accretion onto neutron stars.

6. DISCUSSION

Using standard parameters the calculations above for the sub-Eddington accretion regime lead to an estimate which is close to the observed effect in Her X-1 ($\sim$ 5% in E_c for a factor of two in luminosity). The decisive parameter is the local Eddington rate at the neutron star. Its value depends on the area upon which accretion proceeds, so it is expected to vary from pulsar to pulsar. In transient pulsars, such as 4U 0115+63, we may already have evidence for a transition between the two regimes (Tsygankov et al. 2006b; Nakajima et al. 2006; Terada et al. 2006) at the decline of the outburst when the luminosity decreases below $\sim 5 \times 10^{37}$ erg/s. Note that abrupt changes in the structure of the accretion column can occur when transiting from the super-Eddington to the sub-Eddington regime, which could be associated with the sharp jump in the observed cyclotron line energy in 4U0115+63 as reported by Tsygankov et al. (2006b).

It is conceivable that long-term variations in the accretion rate exist also in the persistent X-ray pulsar Her X-1. If so, the long-term history of the cyclotron line measurements (Fig. 1) may be looked at from this point of view. We speculate that the abrupt jump in the cyclotron line energy in Her X-1 noticed in the early 1990s might be associated with a transition of this pulsar from super-Eddington to sub-Eddington accretion. We plan to have a close look at the historical data with respect to variations in absolute flux. As mentioned above, this is not an easy task because of the difficulties connected with the inter-calibration of different instruments. We also point out, that the apparent overall decrease of E_c with time after 1991 (see Fig. 1) is an artifact, due to the variation with luminosity and the way the data points happened to be taken. Despite strong short-term variability the *RXTE/ASM* light curve does not provide any indication for a long-term change of the mean luminosity.

Taking the binary X-ray pulsar A 0535+262 as an example, the absence of a strong luminosity dependence reported by (Terada et al. 2006) may indicate that this source stays always in the sub-Eddington regime (for example, because the value l_* increases with the magnetic field strength). If anything, a slight increase in E_c with luminosity can be seen in Fig. 4 of Terada et al. (2006). Another positive correlation between E_c and luminosity has been noticed by LaBarbera et al. (2005) in GX 301–2 (albeit only on the basis of two observations) and interpreted qualitatively in the same way as we do here.

Finally, we note that Her X-1 is the only highly magnetized accreting pulsar for which repeated observations over longer periods of time exist. We therefore urge that the source continues to be monitored regularly and that the theoretical models are developed further.

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