Swift/BAT measurements of the cyclotron line energy decay in the accreting neutron star Hercules X-1: indication of an evolution of the magnetic field?

D. Klochkov[1], R. Staubert[1], K. Postnov[2], J. Wilms[3], R. E. Rothschild[4], and A. Santangelo[1]

[1] Institut für Astronomie und Astrophysik, Universität Tübingen (IAAT), Sand 1, 72076 Tübingen, Germany
  e-mail: klochkov@astro.uni-tuebingen.de
[2] Moscow M.V. Lomonosov State University, Faculty of Physics and Sternberg Astronomical Institute, 199992 Moscow, Russia
[3] Dr. Remeis-Sternwarte & ECAP, Astronomisches Institut der Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany
[4] Center for Astrophysics and Space Sciences, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0424, USA

ABSTRACT

Context. The magnetic field is a crucial ingredient of neutron stars. It governs the physics of accretion and of the resulting high-energy emission in accreting pulsars. Studies of the cyclotron resonant scattering features (CRSFs) seen as absorption lines in the X-ray spectra of the pulsars permit direct measurements of the field strength.
Aims. From an analysis of a number of pointed observations with different instruments, the energy of CRSF, E_{cyc}, has recently been found to decay in Her X-1 , which is one of the best-studied accreting pulsars. We present our analysis of a homogeneous and almost uninterrupted monitoring of the line energy with *Swift*/BAT.
Methods. We analyzed the archival *Swift*/BAT observations of Her X-1 from 2005 to 2014. The data were used to measure the CRSF energy averaged over several months.
Results. The analysis confirms the long-term decay of the line energy. The downward trend is highly significant and consistent with the trend measured with the pointed observations: $dE_{cyc}/dt \sim -0.3$ keV per year.
Conclusions. The decay of E_{cyc} either indicates a local evolution of the magnetic field structure in the polar regions of the neutron star or a geometrical displacement of the line-forming region due to long-term changes in the structure of the X-ray emitting region. The shortness of the observed timescale of the decay, $-E_{cyc}/\dot{E}_{cyc} \sim 100$ yr, suggests that trend reversals and/or jumps of the line energy might be observed in the future.

Key words. accretion, accretion disks – stars: neutron – stars: magnetic field

1. Introduction

Accreting magnetized neutron stars are among the brightest Galactic X-ray sources, with luminosities reaching 10^{38}–10^{39} erg s^{-1}. They are powered by the gravitational energy of matter that is supplied by the binary companion star and accreted by the compact neutron star (NS). The magnetic field of the NS is believed to have a roughly dipole configuration, with a field strength at the star surface of $B \sim 10^{12}$–10^{13} G. In the vicinity of the NS, the accretion flow consisting of heated ionized gas is channeled by the magnetic field lines toward the polar caps of the NS. In these regions, matter arrives at the stellar surface at a velocity of $\sim 0.5c$, causing energy release in form of X-rays. The rotation of the NS causes a periodic modulation of the observed flux – X-ray pulsations. The sources are therefore also referred to as X-ray binary pulsars (XBP) or accreting pulsars.

X-ray binary pulsars comprise the second most numerous observed population of NSs after radio pulsars: ~ 200 XBPs are currently known[1]. An important advantage of these objects is that their magnetic field strength can be measured through

observing cyclotron resonance scattering features (CRSFs). These features appear as absorption lines (cyclotron lines), caused by the resonant scattering of photons off the electrons in Landau levels (e.g., Trümper et al. 1978; Isenberg et al. 1998; Schönherr et al. 2007). The energy E_{cyc} of the fundamental line and the spacing between the harmonics are directly proportional to the field strength: $E_{cyc} \simeq 12B_{12}(1+z)^{-1}$ keV, where B_{12} is the magnetic field strength in units of 10^{12} G and z is the gravitational redshift at the region where the line is formed. The energies of the cyclotron lines in XBPs range from ~ 10 to ~ 100 keV (e.g., Caballero & Wilms 2012).

Her X-1 is the first XBP where a CRSF was discovered and interpreted as such almost forty years ago (Trümper et al. 1978). It is interesting to note that the feature was originally interpreted as an emission line at ~ 58 keV: part of the X-ray continuum on the high-energy side of the absorption feature was modeled with an emission component. The subsequent observations and analyses have shown, however, that the feature is an absorption line with a centroid energy of ~ 35 keV (e.g., Gruber et al. 2001, and references therein). Among more than a dozen confirmed CRSF sources, Her X-1 possesses one of the most prominent cyclotron lines whose characteristics can be reliably measured with shorter observations than in other XBPs at a similar flux level.

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[1] See, e.g., the on-line catalogue by M. Orlandini: http://www.iasfbo.inaf.it/~mauro/pulsar_list.html
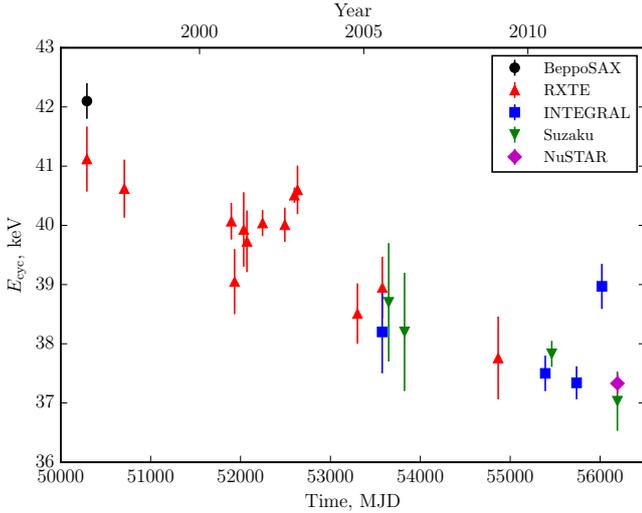
Fig. 1. Centroid energy E_{cyc} of the CRSF in Her X-1 measured with different instruments since 1995 (see Staubert et al. 2014, for details).

The source shows a regular pattern of on and off states repeating with a period of ∼35 d. One 35 d cycle includes two on states: the main-on characterized by a peak flux of up to 300 mCrab, and the short-on when the flux is about five times lower. The periodicity is believed to be caused by the warped accretion disk precessing with a ∼35 d period (e.g., Klochkov et al. 2006, and references therein). In most cases, only the data from main-ons have sufficient quality for the analysis of the cyclotron line. Thanks to its almost persistent nature and near regularity of the on-states, Her X-1 has repeatedly been observed with almost every hard X-ray instrument operated since the discovery of the source. As a result, an unprecedentedly long record of CRSF measurements in a single pulsar has been accumulated. For a detailed description of the observational data base of the cyclotron line measurements in Her X-1, we refer to the recent work by Staubert et al. 2014, hereafter, Paper I).

The CRSF centroid energy E_{cyc} in Her X-1 does not remain constant. In addition to the regular variability with the 1.24 s pulse phase of the NS, which is very common in XBPs, the cyclotron line energy in Her X-1 is found to depend on the source luminosity (Staubert et al. 2007; Klochkov et al. 2011). The luminosity L_X of Her X-1, which reflects the mass accretion rate $\dot{M}$, changes stochastically on a long timescale (from one 35 d cycle to the next) as well as on the timescale of individual 1.24 s pulse cycles (i.e., from one pulse cycle to the next, called pulse-to-pulse variability). By comparing the CRSF energies at different luminosities, it was found that E_{cyc} is directly proportional to the X-ray luminosity on both timescales.

In addition to and independently of the $E_{cyc}-L_X$ relation, it was demonstrated in Paper I that the line centroid energy has been significantly evolving with time since the beginning of the observations. Specifically, it is shown that E_{cyc} has been systematically decreasing since ∼1995 from ∼41 to ∼37 keV, that is, by ∼10% in total. In Fig. 1, we plot the line energy measured in pointed observations (all performed in main-on state of the source) as a function of time since 1995. See Paper I for a discussion of the E_{cyc} measurements obtained before 1995 for which the original data are no longer available for re-analysis.

A significant downward trend of the CRSF energy with time can be clearly seen in Fig. 1. The X-ray luminosity L_X of Her X-1 (characterized by the maximum flux during a main-on) changes stochastically between the observations without

showing any long-term trend. Since E_{cyc} is proportional to L_X, the measured energies of the cyclotron line are affected by the varying luminosity of the source. To take this dependence into account, in Paper I we modeled the measured CRSF energy by a linear function of both time and luminosity $E_{cyc} = F(t, L_X)$. The time dependence of the line energy was found to be characterized by the time derivative $dE_{cyc}/dt = -0.26 \pm 0.01$ keV/yr, indicating a significant trend.

In this work, we make use of the publicly available archival data taken with the Burst Alert Telescope (BAT, Barthelmy et al. 2005) – a hard X-ray detector onboard the *Swift* orbital observatory (Gehrels et al. 2004). The BAT instrument has a huge field of view of 1.4 steradian and is designed to provide triggers and accurate positions for gamma-ray bursts. While searching for bursts and other transient sources, BAT points at different locations in the sky, thus performing an all-sky monitoring in hard X-rays (see, e.g., Krimm et al. 2013). Here, we analyze the BAT data taken on Her X-1 since the launch of the mission, from 2005 to the end of 2014. The BAT data have some important advantages compared to the available data from the pointed observations. First, the regular visits of the source by the instrument provide a nearly homogeneously spaced set of data without long time gaps. Second, the measurements taken with the same instrument can be safely compared with each other. Third, in each single measurement of E_{cyc}, we summed the data from several main-ons (≳five). Thus, the variation of the cyclotron line energy due to stochastic variability of L_X from one main-on state to the next is expected to be mitigated (E_{cyc} is proportional to L_X, see above).

2. Reduction and analysis of the BAT survey data

The *Swift*/BAT data used in this work are available through HEASARC[2]. The BAT instrument is sensitive in the photon energy range ∼15–150 keV and is, therefore, well suited for the study of the ∼40 keV feature in Her X-1. Most of the BAT data are stored in the form of detector plane maps (histograms) accumulated over a five-minute exposure time. We collected such maps taken during the main-on states of Her X-1 (35 d phases ∼0.0–0.25, where phase zero corresponds to the time of X-ray turn-on – the sharp transition from the off- to the main-on state) when the source is in the BAT field of view starting from 2005 (start of *Swift* operation) to the end of 2014 (the time of the work on the publication). We then used the maps to construct the sky images with the help of the tools *batbinevt* and *batfftimage* from the HEASoft 6.16[3] package. For further analysis, we only took the data where Her X-1 is clearly detected in the image. One such image accumulated in an observation of about 1 ks is shown in Fig. 2.

Detector plane histograms of BAT also contain the spectral information of the detected X-rays with the photon energy binning determined by 80 pre-defined energy channels. We used this information to extract spectra of Her X-1 using the multipurpose task *batbinevt* mentioned above. To correct the BAT energy scale for the nonlinear behavior of the detector electronics and for the detector-dependent offsets not accounted for by the onboard calibration, we used the tool *baterebin* and the available data base of the gain/offset maps of the detector. The tool applies a detector-dependent energy shift to the data. According to the instrument team, the accuracy of the corrected energy scale
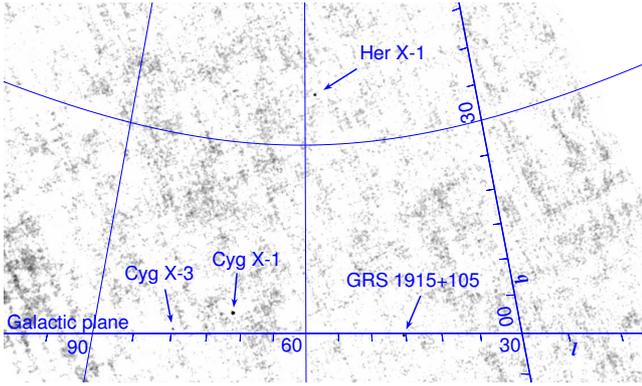
Fig. 2. Example of a sky image in Galactic coordinates taken with *Swift*/BAT in one observation (in this case, about one ks). Her X-1 and a few other detected hard X-ray sources are indicated.

is ±0.1 keV based on the spectrum of the on-board ^{241}Am calibration source[4]. To the resulting Her X-1 spectra we added an energy dependent systematic uncertainty of ≥4% using the tool *batphasyserr*, as suggested by the instrument team. An example of the extracted BAT spectrum of Her X-1 accumulated in an exposure time of ~15 ks is presented in Fig. 3. To model the obtained BAT spectra, we used the XSPEC *cutoffpl×gabs* model (power law with an exponential cutoff modified by an absorption line of a Gaussian optical depth profile). The power-law-cutoff model *cutoffpl* is the simplest continuum model of those that are commonly used to fit hard X-ray continua of XBPs. The Gaussian absorption line model *gabs* represents the cyclotron absorption line similarly to Paper I and to the most of the recent works on X-ray spectroscopy of Her X-1 (e.g., Staubert et al. 2007; Klochkov et al. 2008; Fürst et al. 2013). The solid line in the top panel of Fig. 3 shows the best fit of the spectrum with the described spectral model. The model provides stable fits with all our BAT spectra and results in line energies that are consistent with those measured in the pointed observations using other instruments, as shown in the next section.

To achieve a data quality sufficient for measuring the CRSF centroid energy with uncertainties similar to those of the pointed observations (Fig. 1), we summed BAT spectra of the source from four to ten adjacent main-on states. Although the BAT data coverage of a particular source is roughly homogeneous on a timescale of several hundred days, a significant clustering occurs on shorter timescales. We therefore used such a variable (adaptive) size of the time bins to maintain approximately the same accuracy for each measurement and to use as many BAT datasets useful for the spectral extraction as possible. Each of our BAT measurements of E_{cyc} thus corresponds to a time span of a few months. The CRSF centroid energies measured in this way using the data from the beginning of the *Swift* operation are provided in Table 1.

3. Secular decay of the CRSF energy

The presented cyclotron line energies measured with *Swift*/BAT demonstrate a clear downward trend very similar to that indicated by the pointed observations. In Fig. 4, the *Swift*/BAT measurements presented in Table 1 are plotted as red filled circles together with the measurements from the pointed observations (rest of the data points, identical to Fig. 1). To demonstrate that the BAT values generally follow the trend indicated by the
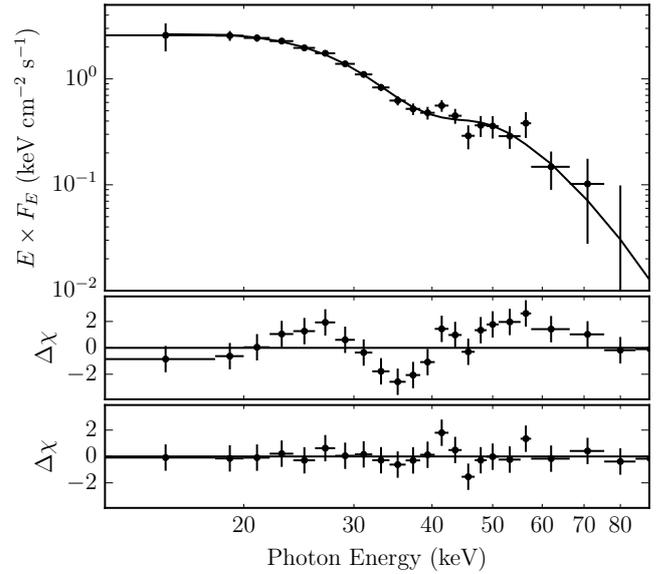
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[4] http://swift.gsfc.nasa.gov/analysis/bat_digest.html

Fig. 3. Example of a *Swift*/BAT spectrum of Her X-1 accumulated during an observation of about15 ks fitted with a power-law-cutoff model with a Gaussian absorption line representing the CRSF (*top*) and the residuals after fitting the spectrum without the Gaussian line (*middle*) and including the line (*bottom*).

Table 1. CRSF centroid energy E_{cyc} measured with *Swift*/BAT in Her X-1 since the beginning of the *Swift* operation.

MJD start	MJD end	E_{cyc} [keV]
53 440	53 580	$39.37^{+0.36}_{-0.38}$
53 610	53 750	$39.53^{+0.89}_{-0.88}$
53 790	54 030	$39.62^{+0.19}_{-0.19}$
54 070	54 210	$39.26^{+0.43}_{-0.46}$
54 240	54 450	$38.80^{+0.30}_{-0.30}$
54 480	54 590	$37.73^{+0.49}_{-0.35}$
54 620	54 970	$38.57^{+0.68}_{-0.63}$
55 010	55 150	$38.71^{+0.26}_{-0.54}$
55 180	55 320	$38.33^{+0.25}_{-0.42}$
55 360	55 530	$36.84^{+0.43}_{-0.40}$
55 570	55 740	$37.00^{+0.59}_{-0.54}$
55 780	55 920	$36.89^{+0.25}_{-0.24}$
55 950	56 090	$36.32^{+0.46}_{-0.44}$
56 120	56 260	$36.35^{+0.42}_{-0.40}$
56 300	56 470	$37.80^{+0.63}_{-0.60}$
56 510	56 610	$37.45^{+0.34}_{-0.33}$
56 650	56 790	$36.87^{+0.58}_{-0.55}$
56 820	57 030	$37.09^{+0.23}_{-0.23}$

Notes. The quoted uncertainties are at 1σ confidence level.

pointed observations, we added a linear fit to the pointed observations alone shown by the dotted line. Some deviations between the BAT and the pointed measurements reaching a few standard deviations are present and might be due to unknown BAT systematics and/or due to imperfect cross-calibration of the BAT spectral response with respect to the other instruments. The variability of E_{cyc} on a timescale of months due to the $E_{cyc} - L_X$ dependence might also contribute to the deviations because the
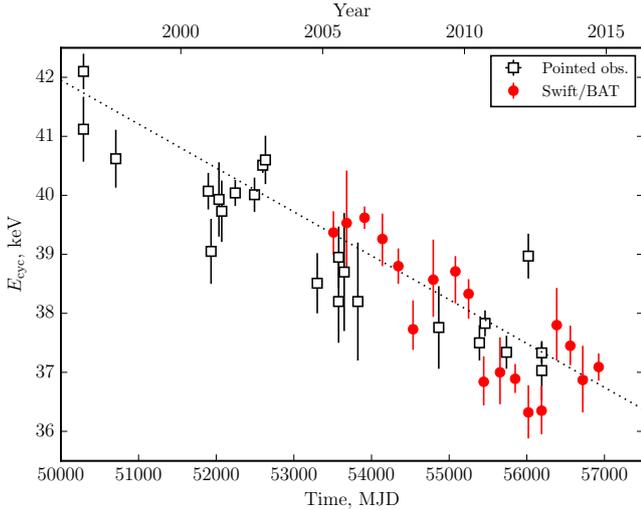
Fig. 4. CRSF centroid energy E_{cyc} in Her X-1 measured with pointed observations (black squares, same as in Fig. 1) and our *Swift*/BAT measurements (red circles). The dotted line indicates a linear fit to the data from only the pointed observations. The error bars in all cases indicate the uncertainties at 1σ confidence level.

BAT measurements cover much longer time spans than the pointed observations.

Despite the deviations, the long-term evolution of E_{cyc} indicated by the BAT data is consistent with that exhibited by the pointed observations. To demonstrate this quantitatively, we calculated the slope of the $E_{cyc}(t)$ dependence from a linear fit to the data. A fit to the BAT data alone yields $dE_{cyc}/dt = -0.32(3)$ keV/yr, which is consistent (within $\sim 2\sigma$) with the values $-0.26(1)$ and $-0.28(1)$ keV/yr reported in Paper I for the pointed observation with and without taking the $E_{cyc}-L_X$ dependence into account, respectively. The significance of the linear trend in the BAT data alone from a linear correlation analysis is characterized by a two-sided null hypothesis probability (to obtain the correlation/trend by chance) of $\sim 10^{-5}$.

4. Summary and discussion

The analyzed *Swift*/BAT observations of Her X-1 clearly confirm the long-term decrease of the cyclotron line centroid energy E_{cyc} with a rate of ~ 0.3 keV per year reported in Paper I based on the pointed observations with different instruments. The BAT data set provides a more continuous and homogeneous although less accurate and somewhat shorter (starting only from 2005) monitoring of the line energy than do the available pointed observations. As mentioned in the introduction, each BAT data point corresponds to measurements over several adjacent on-states of the source such that E_{cyc} variations from one on-state to the next (related to the variation of the luminosity) is partially averaged out. The data also provide an extension of the monitoring after the latest available pointed observations. We plan to continue our analysis of the upcoming BAT data and follow the evolution of the line energy in the future, also with more pointed observations.

In Paper I, we discussed a number of physical effects that might cause the observed decay of the CRSF energy. They are mostly related either to a possible local evolution of the *B*-field structure in/around the polar regions of the NS driven by the accumulation and re-distribution of the accreted plasma or to the long-term changes in the physical dimensions of the emitting

region, leading to a geometric displacement of the line-forming region in the inhomogeneous magnetic field. As Staubert (2014) has pointed out, the observed effect may be due to a slight imbalance between the rate on which matter is accreted (gained) and the rate at which matter is lost from the accretion mound – either by leaking to larger areas of the NS surface or by incorporation into the NS crust.

The evolution of the global dipole magnetic field of the neutron star, generally assumed to take place in accreting pulsars, must be characterized by the timescales of $\gtrsim 10^6$ yr (e.g., Bhattacharya et al. 1992), that is, much longer than that of the observed variation. Such a global evolution thus cannot explain the observed decay of E_{cyc}, whose characteristic time scale is $-E_{cyc}/\dot{E}_{cyc} \sim 100$ yr.

The local changes of the magnetic field, that are for instance due to accumulation and spreading of accreted matter in the magnetically confined accretion mound, can indeed occur on much shorter timescales. In Paper I, we argued that the timescale for the Ohmic decay $\tau_{Ohmic} = 4\pi R^2 \sigma/c^2$ for a small region like an NS polar cap with $R \lesssim 1$ km can be as short as $\sim 10^2$ yr. If the field evolution is driven by the crustal Hall effect, the characteristic timescale should be $\tau_{Hall} \sim 5\times10^8 (R_5^2/B_{12})(\rho/\rho_{nuc})$ yr (e.g., Goldreich & Reisenegger 1992), which for a characteristic size of the polar cap $R \sim 1$ km and a crustal density $\rho \sim 10^{11}$ g cm^{-3} gives $\sim 10^5$ yr – much too long for the observed changes. If we assume, however, that the footprint of the accretion stream on the NS surface has a shape of thin arcs (e.g., Postnov et al. 2013) with characteristic widths $R < 100$ m, τ_{Hall} falls below 1000 yr and approaches the observed timescale of the cyclotron line energy decay. On the other hand, the detailed calculations by Payne & Melatos (2004), although neglecting the Hall effect and elastic stresses, have shown that the NS needs to accumulate $\sim 10^{-5}$ $M_{\odot}$ for the magnetic field to be significantly reduced. For Her X-1 accreting at a rate $\dot{M} \sim 10^{-9}$ $M_{\odot}$ yr^{-1}, this leads to a corresponding timescale of $\sim 10^4$ yr, two orders of magnitude longer than the observed one. We note that a relatively short timescale of 100–1000 yr for the *B*-field evolution depending on the equation of state of the NS crust has recently been obtained by Priymak et al. (2014), who ignored the Hall drift and Ohmic diffusion, however. It is clear that more sophisticated MHD calculations are necessary to investigate the details of the *B*-field evolution in accreting pulsars on the observed timescale. At the current stage, we can only argue that the observed temporal decay of the CRSF energy in Her X-1 is most likely associated with a local effect in the vicinity of the NS polar cap. If this is true, it is expected that the decay should stop after some time, probably with an abrupt jump of the local magnetic field back to the unperturbed value. As discussed in Paper I, such a jump might have indeed been observed in the early 1990 s. However, the relatively sparse time coverage of Her X-1 by X-ray observations did not allow following the event in detail.

The spreading of accreted matter and the associated evolution of the local *B*-field might lead to a complicated configuration of the magnetic field in the polar regions of the NS with higher multipole components. Indeed, such a configuration seems to be indicated by complex emitting regions necessary to model the pulse profile evolution over the 35 d period of the source (Postnov et al. 2013).

We conclude that the long-term monitoring of accreting X-ray pulsars may give additional clues on the physical processes in the neutron star crusts through observations of time-dependent behavior of the CRSF energy.

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