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Cyclotron line / flux correlation in Her X-1

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Based on repeated *RXTE* observations of Her X-1 between 1996 and 2005, Staubert et al. (2007) had reported a *positive* correlation between the energy of the Cyclotron Resonance Scattering Feature (CRSF) and the maximum X-ray flux of the respective 35 d Main-On, as determined from the *RXTE*/ASM. This dependence is opposite to the *negative* correlation observed in bright, super Eddington transient pulsars. Here we address the question whether the ASM flux used in that work can really be taken as a measure of the bolometric luminosity of the source. We repeated the spectral analysis of the same 35 d cycles used in the original work by using data from both instruments (PCA and HEXTE) and re-determined the energy of the cyclotron line, as well as the 5–60 keV bolometric flux from those spectra. This flux is then scaled to represent the 35 d maximum flux. We confirm the result of the original analysis: the cyclotron line energy changes by $\sim$6...7% for a change in flux by a factor of two.

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1. Introduction

Her X-1 is one of the most observed and best studied accreting binary X-ray pulsars and it was the first of this class of objects for which a cyclotron line was discovered (Trümper et al., 1978). This feature is now referred to as a Cyclotron Resonant Scattering Feature (CRSF) and seems to be quite common in accreting X-ray pulsars (Coburn et al., 2002). The discovery of this line-like feature played a key-role in the measurement of the magnetic field of this source, giving a direct way to estimate it through the following formula: B_{12} = (1+z) E_{cyc}/11.6 keV, where B_{12} is the magnetic field strength in units of 10^{12} Gauss, z is the gravitational redshift and E_{cyc} is the energy of the cyclotron line.

Staubert et al. (2007) reported results of repeated measurements of E_{cyc} with *RXTE* and *INTEGRAL* in the X-ray spectrum of Her X-1, having found a *positive* correlation between the cyclotron line energy and the maximum Main-On flux as measured by the *RXTE*/ASM. In Fig. 1 this correlation between the cyclotron line energy and the maximum 35 d Main-On X-ray flux (2–10 keV) is reproduced (Staubert et al., 2007).

In the original analysis the ASM maximum Main-On flux was taken as a measure of the true current accretion state of the source in the respective 35 d cycle as compared to the local flux which is influenced by the presence of the variable absorbing material in the accretion disk. The found correlation is opposite to the *negative* correlation observed in transient pulsars such as V0332+53 and 4U 0115+63 (Mihara et al., 1998; Mowlavi et al., 2006; Nakajima et al., 2006; Tsygankov et al., 2006), in which the energy of the cyclotron line is reduced when the X-ray luminosity increases.

Here we report on a re-analysis of the *RXTE* observations of the same 35 d cycles as used in the original analysis (Staubert et al., 2007). Using data from both instruments (PCA and HEXTE) we re-determine the cyclotron line energy and measure the 5–60 keV bolometric X-ray flux for the individual spectra. These fluxes are then scaled to represent the flux at the maximum of the respective 35 d cycle, such that they can be compared to the corresponding ASM fluxes used in the original analysis. The questions to be answered are:

1. Can the ASM flux really be taken as a measure of the bolometric luminosity?
2. Is the positive correlation between the cyclotron line energy and the maximum 35 d flux confirmed?

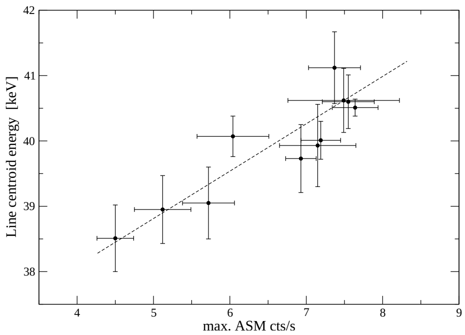

Figure 1: The centroid cyclotron line energy of Her X-1 versus the maximum flux during the corresponding 35 d Main-On as observed by the RXTE/ASM (Staubert et al., 2007).

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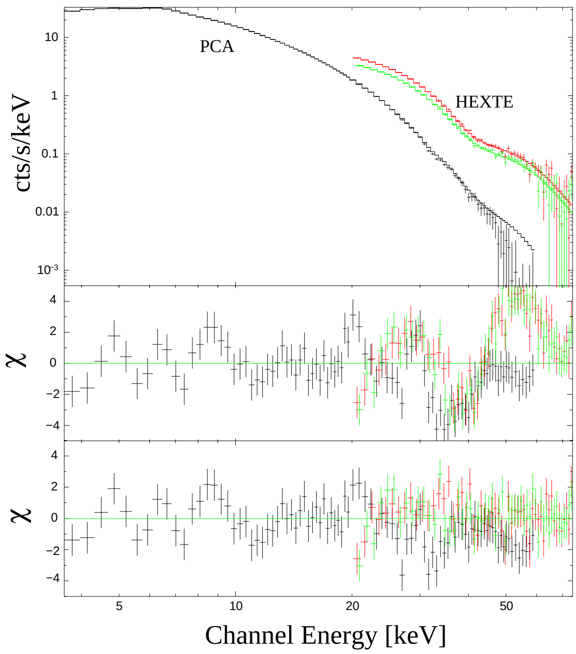

Figure 2: Example of a spectral fit of an *RXTE* observation of Her X-1 in July 1996 (cycle no. 257). The observation is centered at MJD 52599.36 and the integration time is 36 ks for PCA and 12 ks for each of the two HEXTE clusters. Black: PCA, red: HEXTE-A, and green: HEXTE-B, respectively; *top*: count rate spectra; *middle*: residuals with respect to a fit of a continuum model; *bottom*: residuals with respect to a fit which includes a cyclotron line.

2. Observations and results

In Table 1 we summarize the observation dates and the results of this re-analysis in comparison to those of the original work by Staubert et al. (2007). In our re-analysis we have used the data from both *RXTE* instruments: PCA (PCU2 only): 3.5 – 60 keV, and HEXTE: 20 – 75 keV. Note that in the original analysis PCA data were only used up to 25 keV (to define the continuum at lower energies). We have found that the PCA can indeed be used up to 60 keV, thereby contributing information about the cyclotron line around 40 keV. For the spectral analysis XSPEC (12.6.0) was used with the `highecut` model which is based on a power law continuum with an exponential cut-off. The cyclotron line is modeled by a *Gaussian* absorption line. In Fig. 2 we show an example of a spectral fit combining PCA and HEXTE data. In order to have a uniform data set, we used *RXTE* data only. Overall, we find a very good agreement between the new values for E_{cyc} and those from the original analysis.

In Fig. 3 (left) we plot the newly determined cyclotron line energies against those from the original analysis. There are small differences, as is expected, since in the original analysis PCA data were only used up to 25 keV and in this re-analysis we used an added systematic uncertainty of 0.5%, while the original analysis used 1%.

The 5–60 keV bolometric flux of the observations of a particular Main-On is found through the spectral analysis with XSPEC (summing essentially all available data). The X-ray flux of Her X-

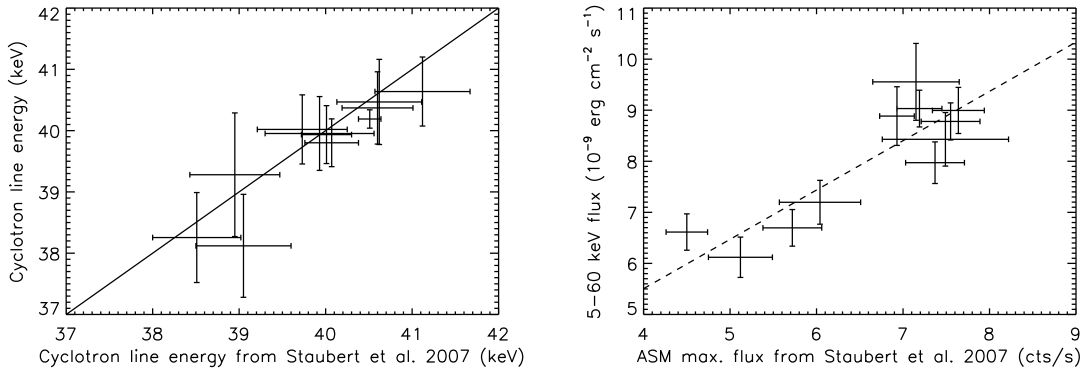

Figure 3: Left: E_{cyc} from the spectral re-analysis versus E_{cyc} from the original analysis (Staubert et al., 2007). Right: Scaled maximum 5–60 keV flux (in units of 10^{-9} ergs/cm^2 s) from the spectral re-analysis versus the maximum 2–10 keV ASM flux (in units of cts/s) from the original analysis.

1, however, varies as a function of phase of the 35 d modulation due to variable shading by the accretion disk, and observations are done at various phases. The variation of flux from one 35 d cycle to the next, on the other hand, is small, such that the maximum observed flux of one 35 d Main-On can be considered a good measure of the luminosity of the source during this particular cycle. This is why the maximum ASM flux was used as a reference in the original analysis by

Observation month/year	35d Main-On cycle number	Cyclotron line energy [keV]	Max. flux ASM [cts/s]	Cyclotron line energy [keV]	Max flux 5-60 keV [$10^{-9} erg/cm^2$ s]
July 96	257	41.12±0.55	7.37±0.34	40.63±0.56	7.97±0.41
Sep. 97	269	40.62±0.49	7.49±0.73	40.47±0.70	8.43±0.52
Dec. 00	303	40.07±0.31	6.04±0.47	39.80±0.39	7.20±0.43
Jan. 01	304	39.05±0.55	5.72±0.34	38.12±0.84	6.70±0.36
May 01	307	39.93±0.63	7.15±0.50	39.95±0.60	9.56±0.75
June 01	308	39.73±0.52	6.93±0.20	40.02±0.56	8.89±0.57
Aug. 02	320	40.01±0.29	7.19±0.26	39.94±0.47	9.03±0.34
Nov. 02	323	40.51±0.13	7.64±0.30	40.19±0.15	9.00±0.45
Dec. 02	324	40.60±0.41	7.55±0.34	40.37±0.59	8.78±0.36
Oct. 04	343	38.51±0.51	4.50±0.24	38.26±0.73	6.61±0.36
July 05	351	38.95±0.52	5.12±0.37	39.28±1.01	6.12±0.39

Table 1: Summary of observations and results. Columns 1 & 2: Date and Cycle Number. Columns 3 & 4: Cyclotron line energy and ASM maximum flux reproduced from Staubert et al. (2007). Columns 5 & 6: Cyclotron line energy and the 5–60 keV flux as obtained from the spectral re-analysis. The flux in column 6 is scaled to represent the 35 d maximum flux in the 5–60 keV range (see text). Note that for 35 d cycle numbers 303 and larger the corresponding numbers in Staubert et al. (2007) are larger by 1. This reflects the observation that there must have been an extra cycle during the long *anomalous low* before cycle 303. However, using the numbers as given here allows to use them in an ephemeris for a rough prediction of the 35 d turn-ons using a mean period of 35.88 d. We do not doubt the physical reality of the extra cycle found by Staubert et al. (2009).

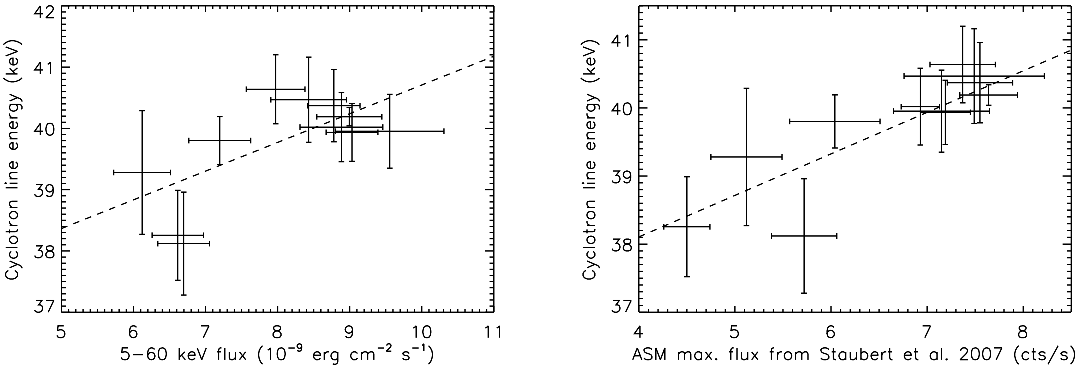

Figure 4: Left: E_{cyc} from the spectral re-analysis versus the scaled maximum 5–60 keV flux (in units of 10^{-9} ergs/cm^2 s). Right: E_{cyc} from the spectral re-analysis versus the maximum 2–10 keV ASM flux (in units of cts/s) from the original analysis.

Staubert et al. (2007). In order to find comparable bolometric flux values in the 5–60 keV range which represent the maximum flux for the particular cycle, it was necessary to scale the fluxes found in the individual spectra to the maximum flux. This was done with the help of a template for the mean 35 d Main-On modulation, the shape of which was taken from an overlay of many 35 d light curves observed by *RXTE*/ASM (see e.g. Klochkov et al., 2006). The 5–60 keV flux values of the various spectral fits from one 35 d Main-On were then fitted by this template with the flux amplitude as a free fitting parameter. The flux from this procedure is then taken as *the scaled 5–60 keV maximum Main-On flux* for this particular 35 cycle. These flux values are comparable to the corresponding *maximum ASM flux* values.

In Fig. 3 (right) the 5–60 keV maximum bolometric fluxes are plotted against the corresponding ASM fluxes of the original analysis. There is a good linear relationship between the two fluxes, which demonstrates, that the maximum ASM flux can be taken as a good measure of the bolometric X-ray flux (and luminosity) of Her X-1 during this 35 d cycle.

The final correlation between the cyclotron line energy and the X-ray flux is given in Fig. 4 in two ways: we correlate E_{cyc} from the re-analysis against the *scaled 5–60 keV maximum Main-On flux* (Fig. 4 left) as well as against the *maximum ASM flux* (Fig. 4 right). The corresponding slopes of the linear fits to these data (taking the uncertainties of both variables into account) are (0.47$\pm$0.1) keV/(10^{-9} ergs/cm^2 s) and (0.61$\pm$0.1) keV/(cts/s), respectively.

3. Summary

We have re-analyzed observations of Her X-1 in its Main-On state by *RXTE* between 1996 and 2005 with respect to its X-ray spectrum. Using data from both instruments (PCA and HEXTE) we performed a spectral analysis of observations of several Main-Ons and determined the cyclotron line energy E_{cyc} and the 5–60 keV flux for each of those Main-Ons. This observed flux was then scaled to a flux representing the maximum flux of the particular Main-On. The two questions asked are both answered by *yes*.

1. Yes, the ASM flux can indeed be taken as a measure of the bolometric luminosity. This is evident from Fig. 3 (right) which shows that there is a good linear relationship between the bolometric 5–60 keV flux with the 2–10 keV flux measured by *RXTE*/ASM (both fluxes refer to the *maximum 35 d Main-On flux*).

2. Yes, the positive correlation between the cyclotron line energy and the maximum 35 d flux is confirmed. This is demonstrated in Figs. 4 (left and right). A direct comparison to the original analysis can be made for Fig. 4 (right): the slope of the linear best fit is determined to (0.61±0.1) keV/(cts/s) which is in good agreement with the (0.66±0.10) keV/(cts/s) found in the original analysis by Staubert et al. (2007). The final and confirmed result with respect to this correlation can then be stated as follows: The value of the cyclotron line energy E_{cyc} changes by ∼6...7% for a change in flux by a factor of 2.

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