PROCEEDINGS OF SCIENCE

Periodic variations of the pulse profiles in Her X-1 – a pulse profile template for the 35 d modulation

Rüdiger Staubert[∗†]
Institut für Astronomie und Astrophysik, Universität Tübingen (IAAT), Tübingen, Germany
E-mail: `staubert@astro.uni-tuebingen.de`

Dmitry Klochkov
Institut für Astronomie und Astrophysik, Universität Tübingen (IAAT), Tübingen, Germany
E-mail: `klochkov@astro.uni-tuebingen.de`

Davide Vasco
Institut für Astronomie und Astrophysik, Universität Tübingen (IAAT), Tübingen, Germany
E-mail: `vasco@astro.uni-tuebingen.de`

Jörn Wilms
Dr. Remeis-Sternwarte Bamberg and Erlangen Center for Astroparticle Physics, University of Erlangen-Nürnberg, Germany
E-mail: `wilms@sternwarte.uni-erlangen.de`

Using observations of Her X-1 by *RXTE*/PCA representing a coverage of one complete Main-On of a 35 day cycle, we have investigated the systematic variation of the shape of the 1.24 s pulse profile. Here we describe the construction of a template which provides a quantitative description of the systematic variations of the 9–13 keV pulse profile as a function of 35 day phase for a Main-On of Her X-1. Using observations of other Main-On cycles of Her X-1 by *RXTE, INTEGRAL, Ginga, Beppo-SAX, Suzaku* and other satellites over the last three decades, we find that these systematic variations are very stable and reproducible. The constructed template therefore allows to determine the 35 d phase for any observed Main-On pulse profile in the 9–13 keV range.

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∗Speaker.
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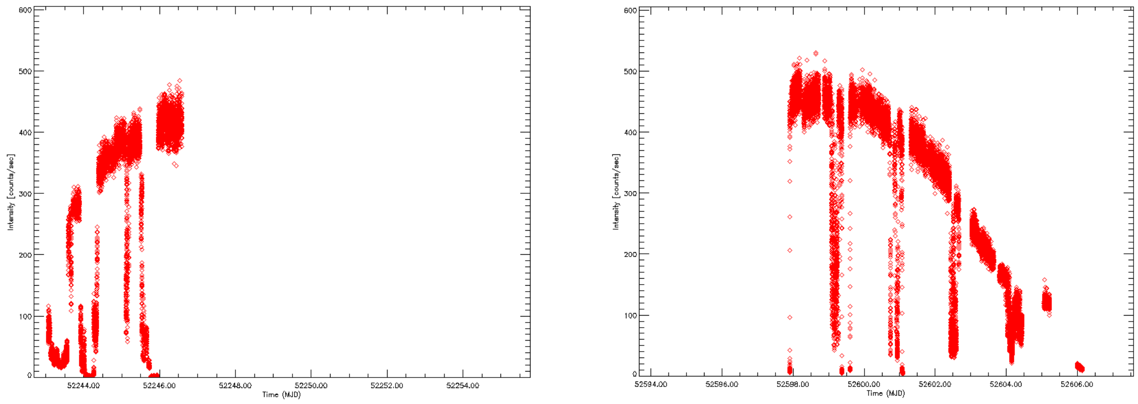

Figure 1: Main-On light curves of 35 d cycles in Dec 01 (cycle no. 313, left) and in Nov 02 (cycle no. 323, right) from *RXTE*/PCA, 3–20 keV.

1. Introduction

Her X-1 shows a regular modulation of its flux on a $\sim$ 35 d period, with a "Main-On" and a "Short-On", separated by two "Off" states. The 35 day modulation of the X-ray flux is generally explained by the precession of the accretion disk which regularly blocks the view to the X-ray emitting regions near the magnetic poles of the neutron star. Fig. 1 and Fig. 2 show light curves of two "Main-Ons" (cycles 313 and 323), as observed by *RXTE*/PCA in Dec 01 and Nov 02, respectively. Together they provide a continuous coverage of a complete "Main-On" of Her X-1. The shape of the observed 1.24 s pulse profiles varies with 35 d phase. We follow this systematic variation through the complete "Main-On" using pulse profiles in the energy range 9–13 keV and construct a pulse profile template. This template can then be used for comparison with any observed 9–13 keV profile and to predict its 35 d phase. In using scattered observations from various satellites we are then able to study the details of the "clock" behind the pulse profile variations and to possibly understand the physics causing these variations. One suggestion is that the variation of the shape of the X-ray pulse profiles is due to free precessing of the neutron star (Trümper et al., 1986, Shakura et al., 1999): the beamed emission from the accreting hot spot varies for a distant observer with the phase of the neutron star precession. Recent investigations show, that the "pulse profile clock" is just as irregular as the "turn-on clock" of the accretions disk - and, in fact, both clocks appear to be strongly coupled (Staubert et al., 2009a, 2010 and 2011).

2. Generation of the pulse profile template

The X-ray pulse profiles of the 1.24 s pulsation show systematic variations with phase of the 35 day modulation. Fig. 2 shows examples of pulse profiles for progressive 35 d phases for the Main-On cycles 313 and 323 (for a definition of pulse profile cycle counting see Staubert et al., 2009a). In this paper we describe the generation of a pulse profile template for the energy range 9–13 keV using the *RXTE*/PCA observations of Her X-1 of those two Main-Ons (Fig. 1).

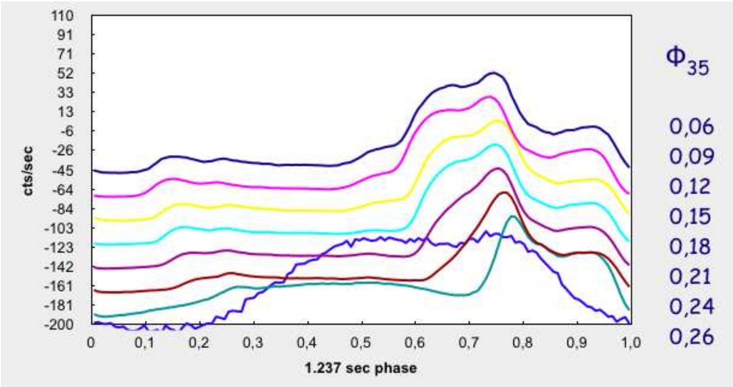

Figure 2: Pulse profiles of Her X-1 of 35 day cycles of Dec 01 (cycle no. 313) and Nov 02 (cycle no. 323) as a function of 35 day phase (RXTE, 9–13 keV).

For generating the template we proceeded through the following steps of analysis:

1. Generate pulse profiles with 128 phase bins by folding events from integration intervals of 0.035 days (0.01 in 35 d phase) with the predetermined best pulse period.

2. Normalize all profiles to a maximum of 100 cts/s.

3. If necessary, shift profiles such that the "sharp edges" all coincide. The sharp edges are defined by the fast decrease of flux after the right shoulder of the main peak into the eclipse-like trough (see Staubert et al., 2009b).

4. Record the 35 d phase for each profile.

5. Insert all profiles (each profile is one *line*) into the template matrix according to the corresponding 35 d phase (along *columns*).

6. Perform cubic best fits of the 35 d phase dependence (along the *columns*) for each pulse profile bin.

The template is then represented by of a 128 x 28 matrix of normalized count rate values: each of the 128 lines contains an observed normalized pulse profile (with 128 bins) corresponding to 35 d phases ranging from -0.05 to 0.22 in steps of 0.01. A graphical 3D-representation of the 9–13 keV template constructed from the data of 35 d cycles 313 and 323 is shown in Fig. 3.

In order to produce a smoothed analytical representation of the observed pulse profile template, cubic fits were performed of the normalized count rate values in each of the 128 columns: normalized flux (cts/s) = A + B*(ph-0.1) + C*(ph-0.1)^2 + D*(ph-0.1)^3, with ph being the 35 d phase (zero phase is *turn-on*). Fig. 4 shows the evolution of the four fit parameters (note: the reference 35 d phase is 0.1). Using these fit parameters, a new 128 x 28 matrix was produced which is then used for comparison with other observed profiles.

Any (9–13 keV) profile observed during a 35 d Main-On can be compared to this template and the 35 d phase can be determined (by χ^2_{min} fitting). For the *RXTE* data we find that this generally possible to an accuracy of ±0.02 in phase.

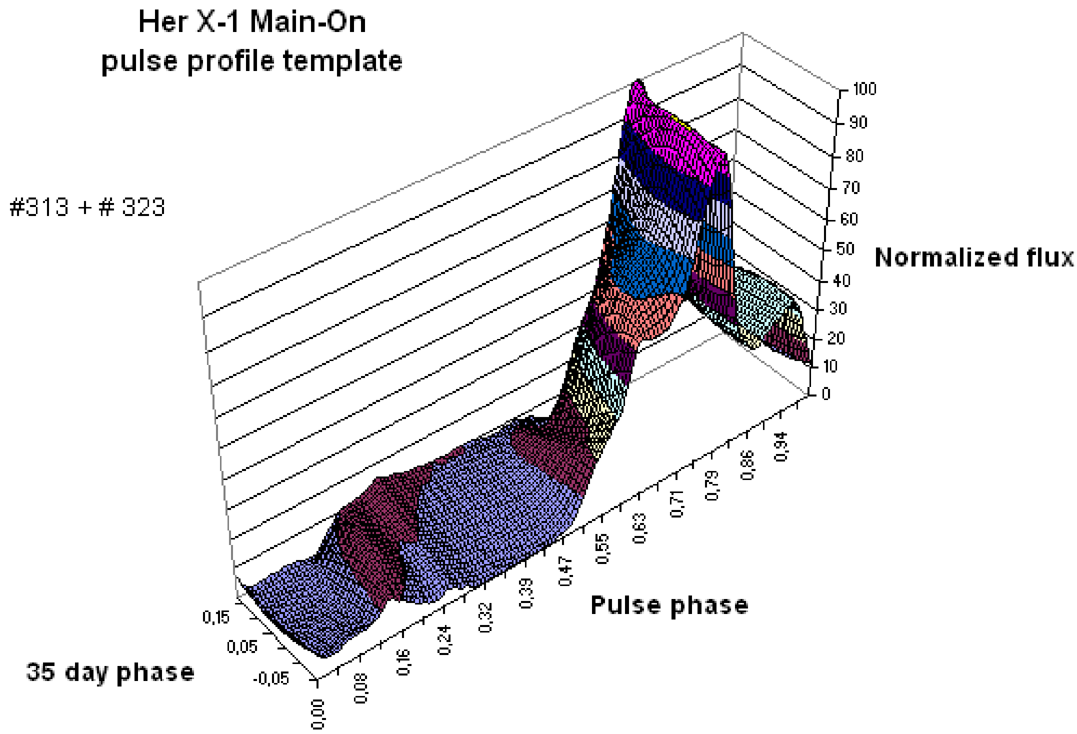

Figure 3: 3D pulse profile template for the Her X-1 Main-On (35 d phase -0.05 to 0.22) of cycles 313 and 323 in the energy range 9–13 keV. The resolution is: 128 bins in pulse phase and 28 bins in 35 d phase.

3. "Pulse profile phase-zero" and "accretion disk phase-zero" (turn-on)

In Fig. 5 (left) we give an example of how "pulse profile phase-zero" is found for observations of a particular Main-On. We demonstrate the case for the Main-On of cycle 257 (July 1996) as observed by *RXTE*/PCA: six different integration intervals were defined for which pulse profiles were generated. The normalized profiles were then compared with the analytical template and for each of them the 35 d phases were determined. These phase values are plotted against the observing time and a linear fit with a constant slope corresponding to a repetition period of 34.85 d is performed. For cycle 257 the time of "pulse profile phase-zero" was found to be MJD 50285.46. This method works with any number of observed pulse profiles per Main-On, even with only one profile.

We have collected observational data of Main-On states of Her X-1 in the 9–13 keV range from *Ginga* (1989), *RXTE* (1997–2005) and *INTEGRAL* (2005–2007) and determined the "pulse profile phase-zero" values for all of those Main-Ons. It was found, that the clock behind the pulse profile variations is quite variable, as demonstrated in Fig. 5 (right) (mangenta points) where an (O-C) diagram is shown ("Observed" phase-zero minus "Calculated" phase-zero, assuming a constant repetition period of 34.85 d). The other 35 d variation is the modulation in flux, and the green points (and green connecting curve) in Fig. 5 (right) represents the (O-C) diagram for all observed turn-ons since the discovery of the source.

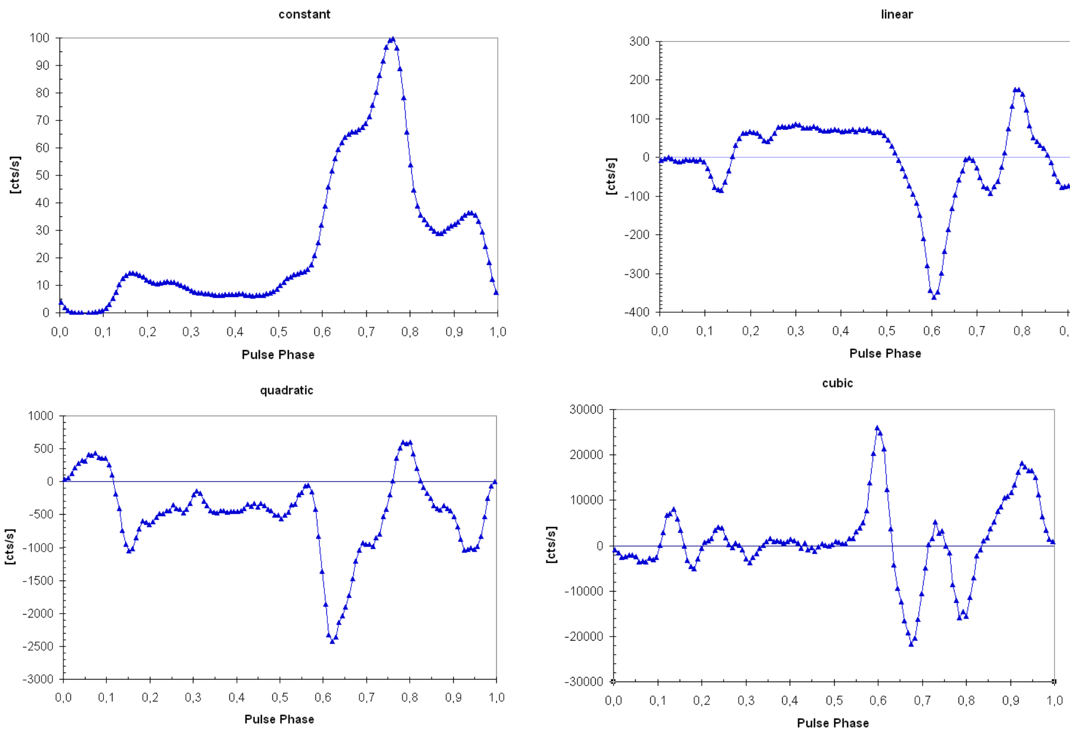

Figure 4: Best fit parameters for cubic fits to the evolution of the count rate of normalized pulse profiles for the used 128 pulse phase bins. The reference 35 d phase is 0.1. Constant A (upper left), linear B (upper right), quadratic C (lower left), cubic D (lower right).

4. Summary

1. The shape of the pulse profile varies reproducibly, repeating every ~ 35 days. A description of the variation during the Main-On for profiles in the 9–13 keV range is provided by a pulse profile template, constructed from two Main-Ons (cycles 313 and 223) observed by *RXTE.*

2. The clock behind the pulse profile variations is irregular.

3. The 35 d flux modulation, thought to be due to variable shadowing by the precessing accretion disk, has been known for some time to have a quite irregular timing behavior, see e.g. Staubert et al. (2006, 2009a), as well as green curve and green points in Fig. 5, right.

4. The (O-C) diagrams of the "pulse profile phase-zero" values and the "accretion disk phase-zero" (the turn-ons) track each other very tightly.

5. The physical implications of the application of the constructed pulse profile template to pulse profiles of Her X-1 observed over many years by several satellites (e.g. *RXTE, INTEGRAL, Ginga, Beppo-SAX, Suzaku* and others) are discussed in Staubert et al. (2009a, 2010, 2011). If the variation of the pulse profiles is due to (free) precession of the neutron star, as suggested by Trümper et al. (1986) and Shakura et al. (1999), the neutron star must be able to change its precessional period on short time scales (a few 35 d cycles). This appears questionable and alternatives for the generation of variable pulse profiles should be considered.

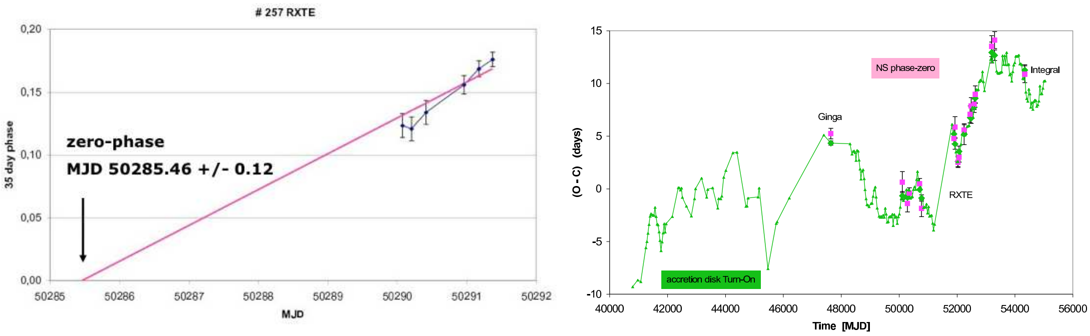

Figure 5: *Left*: Example for finding "pulse profile phase-zero" for the case of cycle 257 Main-On, as observed by *RXTE*/PCA in July 1996. *Right*: (O-C) values for all observed turn-ons (green) and for so far generated "pulse profile phase-zero" values from pulse profile fitting (mangenta).

Future work will extend the template to cover also the Short-On of the 35 d modulation of Her X-1 and to produce equivalent templates for other energy ranges.

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