Understanding very faint X-ray binaries their x-ray light curves

Simon van Eeden

Anton Pannekoek Institute, University of Amsterdam

Abstract

TODO

Studentnumber	11870206
Supervisor	Nathalie Degenaar
Version	Draft

1 Introduction

TODO

2 Theory

2.1 XRT classification

The classification of X-ray transients is based on their peak luminosity.

Bright to very bright X-ray transients have peak X-ray luminosities of 10^{37-38} $erg\ s^{-1}$.

Faint X-ray transients have peak X-ray luminosities of 10^{36-37} $erg\ s^{-1}$. The faint outbursts occur usually in series separated by the orbital period. This can be explained by the companion star moving in a wide eccentric orbit and accretes only matter at minimal distance (Okazaki and Negueruela 2001). There are two main characteristic for the faint X-ray transients. The first one is that a large fraction contains neutron star accretors. The second one is that the faint X-rays are more concentrated towards the galactic center (Cornelisse et al. 2002a). But this might be an artifact of observations mainly focussing on this region [3].

Very Faint X-ray transients have peak X-ray luminosities of 10^{34-36} $erg\ s^{-1}$. It is most likely that this class contains accreting neutron stars and black holes because only one white dwarf with outburst above 10^{34} $erg\ s^{-1}$ has been observed (Watson et al. 1985). It is possible that for some very faint transients this low luminosity is caused by the inclination (e.g., Muno et al. 2005).
The characteristics of spectra and light curves have been studied in (Sakano et al. 2005; Muno et al. 2005a; Torii et al. 1998). These papers suggest that this is not a homogeneous class. Diferent characteristics are:

1. Slow pulsations: Indicating high mass donor star (e.g., Torii et al. 1998) or relatively close-by accreting magnetic white dwarfs

2.2 High mass transients

For the hight mass transients there are two possibilities. The first one is that the companion star has a stellar wind. The second one is that the companion star loses mass via a decretion disk. The most common type for this decreation proces are Be/X-ray transients. "The most common type are the so-called Be/X-ray transients in which matter is accreted from the circumstellar decretion disks around rapidly spinning B or sometimes late O-type stars. The physics behind the irregular outbursts observed for the bright high-mass transients are not yet fully understood but it has been suggested that these systems might be Be/X-ray binaries which have relatively low eccentricities (e.g., Okazaki Negueruela (2001))" [5]

2.3 Low mass transients

In low mass transients the mass is transfered via Roche Lobe overflow of the donor star. For the bright low mass transients the accepted description for the outbursts come from the disk instability model (e.g. Lasota (2001)).

3 Method

The x-ray light curves were obtained by two telescopes: the Rossi X-ray Timing Explorer (*RXTE*) and the Neil Gehrels Swift Observatory (*Swift*). The light curves from *RXTE*, exlcuding *XTE J1118*, are taken with the Proportional Counter Array (*PCA*) which has a energy range of 2-10keV. The light curve from *XTE J1118* is observed with the All Sky Monitor (*ASM*) which has the same energy range.

The Swift light curves include data from two observing modes, depending on the count rates. Most of the time our sources are observed with the Photon Counting (*PC*) mode. But when the count rates reach the maximum of the *PC* mode Swift switches to Window Timing (*WT*) mode. Data from both observing modes is included for data analysis.

3.1 Outburst detection

Before starting analysis on the light curves, for each light curve potential outbursts are identified. The identification is done by eye using 10 days meridian binned light curves.

3.2 Outburst duration τ_{dur}

Based on the symmetry of most outburst shapes, each outburst is fitted to a Gaussian using the `astropy` package [1]. From each Gaussian fit the standard deviation (*std*) is used to derive the duration of the outburst

$$t_{dur} = 6std \tag{1}$$

with τ_{dur} the outburst duration and *std* the standard deviation from the Gaussian fit. Before fitting the average count rate and the standard deviation of the background or quiescence is determined, purposing to goals:

1. **Fit-data selection**
   The standard deviation of the background is used as a tress hold for noise detection in the following way. For each outburst data points are selected until two adjacent data points are having count rates below $2std$. This data selection is used as the input data for the Gaussian fit. This process was not performed on all *Swift* light curves because some solely contain the outburst region.

2. **Offset count rates**.
   In the original light curves the quiescence level is not at zero. And the Gaussian fit converges to zero at both sides. So to obtain the best possible fit the data points should also converge to zero at both sides. Therefore all light curves are subtracted by the average of the background.

In the case of outbursts containing a few data points (~ 4), the fit can converges to amplitudes bigger then ten times the peak count rate. To avoid the behaviour in these cases the amplitude is constraint to

$$\text{amplitude} < 1.3 \times \text{peak rate} \tag{2}$$

3.3 Outburst decay time τ_{dec}

The second outburst parameter that is determined is the decay time τ_{dec}, also referred to the *e*-folding timescale computed over the outburst decay region [2]. The decay time is, such as τ_{dur}, unrelated to instrumental sensitivity which makes it suitably for comparison between different sources from different telescopes. In order to extract τ_{dec} from each outburst a exponential function was fitted, using the `astropy` package. The exponential fit function is defined as

$$F(t) = A\exp\left(-\frac{t}{\tau_{dec}}\right) \tag{3}$$

with $F(t)$ the count rate, A the amplitude, t the time after the start of the outburst decay and τ_{dec} is the decay time. As mentioned earlier we fitted this decay model to the outburst decay region. This region is determined similarly as for τ_{dur} but the start point is fixed at the time of the peak rate. In the case of some Swift light curves which are containing solely the decay region the whole data set was used.

The fit function 3 converges to zero moving forward in time. So the get the best fit the light curves should have a average count rate of zero when in quiescence. This correction is performed by subtracting the average of the background similar to τ_{dur}.

3.4 Decay model

At the beginning of the decay when the disc is completely ionized the outburst shows a exponential decay shape. At some time t_t the irradiation cannot maintain a fully ionized disc. When the disc becomes partially ionized the decay becomes linear. The exponential shape is described by

$$F(t) = (Ft - Fe)\exp\left(-\frac{t - t_t}{\tau_e}\right) + F_e \tag{4}$$

With $F(t)$ the count rate, F_t the count rate at the transition, F_e the exponential amplitude, t the time, τ_e the exponential decay time and t_t the time at the transition. The exponential amplitude is constraint to $0.4L_t \leq L_e \leq L_t$ The linear shape is described by

$$F(t) = F_t\left(1 - \frac{t - t_t}{\tau_l}\right) \tag{5}$$

with $F(t)$ the count rate, F_t the count rate at the transition, t the time, t_t the time at the transition and τ_l the linear decay time. The final model thus looks like:

$$F(t) = \begin{cases} (4), & t \leq t_t. \\ (5), & t > t_t. \end{cases} \tag{6}$$

The model is fitted using Markov Chain Monte Carlo (*MCMC*) sampling. This is an improved version of the basic Monte Carlo sampling that produces a probability distribution from random start variables. The *MCMC* gives a probability distribution for each of the five parameters. Each fit parameter is constraint by a reasonable range matching with the outburst count rates. The probability distribution thus lies between this range and the meridian of the distribution is taken as the best fit value.

Accretion disk radius R_{circ}
With the fit parameters from this model we can derive several physical properties of the binary system. The first one is the radius of the accretion disk. This can be derived from

$$R_{disc} = 3.5 \times 10^7 \sqrt{\tau_e} \tag{7}$$

With R_{disc} the accretion disk radius and τ_e the exponential decay time

Orbital period P_{orb}
The second physical properties that is determined is the orbital period P_{orb}.

4 Results

4.1 Outburst detection

This selection resulted in 45 outburst detection's in 20 out of 24 sources.

4.2 Duration

4.3 Decay time

4.4 Decay model

4.4.1

4.4.2

4.4.3

4.4.4

4.4.5

5 Discussion

VFXB outbursts showing linear decays might be explained as partial drainings of the disc of 'normal' X-ray transients, and many VFXB outbursts may belong to this category [4].

VFXB outbursts showing exponential decays are best explained by old, short-period systems involving mass transfer from a low-mass white dwarf or brown dwarf.

In KR's disc model, the overall light-curve shape is an exponential decline if irradiation by the central X-ray source is able to ionize the entire disc. For a given outer disc radius R11 (in units of 1011 cm), this produces critical luminosities above which the light curve should be exponential in shape [4].

persistent (or quasi-persistent) VFXBs, which maintain an LX of 1034-1035 erg s-1 for years, may be explained by magnetospheric choking of the accretion flow in a propeller effect, permitting a small portion of the flow to accrete on to the neutron star's surface. We thus predict that (quasi-) persistent VFXBs may also be transitional millisecond pulsars, turning on as millisecond radio pulsars when their LX drops below 1032 erg s-1.

The outbursts of transient LMXBs often follow a fast-rise, exponential-decay shape (e.g. Chen, Shrader Livio 1997), which can be understood in a disc instability model, in which continued accumulation of matter in the disc eventually ionizes the disc and raises its viscosity, leading to rapid dumping of the disc material [4].

6 Conclusion

References

[1] Astropy Collaboration and Thomas P. Robitaille. Astropy: A community Python package for astronomy. , 558:A33, October 2013.

[2] Wan Chen, C. R. Shrader, and Mario Livio. The Properties of X-Ray and Optical Light Curves of X-Ray Novae. , 491(1):312–338, December 1997.

[3] N. Degenaar and R. Wijnands. The behavior of subluminous X-ray transients near the Galactic center as observed using the X-ray telescope aboard Swift. , 495(2):547–559, February 2009.

[4] C. O. Heinke, A. Bahramian, N. Degenaar, and R. Wijnands. The nature of very faint X-ray binaries: hints from light curves. *Monthly Notices of the Royal Astronomical Society*, 447(4):3034–3043, 01 2015.

[5] R. Wijnands, J. J. M. in 't Zand, M. Rupen, T. Maccarone, J. Homan, R. Cornelisse, R. Fender, J. Grindlay, M. van der Klis, E. Kuulkers, and et al. Thexmm-newton/chandramonitoring campaign of the galactic center region. *Astronomy Astrophysics*, 449(3):1117–1127, Mar 2006.