UNIVERSITÄT TÜBINGEN

BACHELOR THESIS

Long-term variability of Be X-ray binaries

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Eidesstattliche Erklärung

Hiermit erkläere ich, Eva LAPLACE, dass ich die vorliegende Bachelorarbeit mit dem Titel 'Long-term variability of Be X-ray binaries' selbständing verfasst und dabei keine anderen als die angegebenen Quellen und Hilfmittel benuzt habe:
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'All my life through, the new sights of Nature made me rejoice like a child.'

Marie Curie

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Zusammenfassung

Mathematisch Naturwissenschaftliche Fakultät
Institut für Astronomie und Astrophysik

Bachelor of Science

Long-term variability of Be X-ray binaries

von Eva LAPLACE

In dieser Bachelorarbeit wird die Langzeitvariabilität von Be-Röntgendoppelsternsystemen (BeXRBs) untersucht. Diese faszinierenden Objekte bilden die größte Unterkategorie von Neutronenstern-Röntgendoppelsternsystemen, Doppelsternsysteme, die aus einem Neutronenstern und einem normalen Stern bestehen. Eine Stichprobe von 28 der bekanntesten BeXRBs wurde untersucht, wobei Daten von drei Röntgenmonitoren verwendet wurden: RXTE/ASM, Swift/BAT und MAXI. Alle Quellen in der Stichprobe außer einer sind transiente Quellen, das heißt, sie zeigen für eine gewisse Zeit Röntgenemission, gefolgt von einer Periode, in der sie nicht detektiert werden.
Der erste Schritt in der Charakterisierung der Langzeitvariabilität war die Diskriminierung zwischen dem 'aktiven' und 'inaktiven' Status dieser Systeme mithilfe eines neuen Ermittlungsverfahrens für Transienten, welches von Belanger [7] entwickelt wurde. Diese Methode basiert auf der statistischen Bestimmung der Verteilung des inaktiven Status, was eine systematische Ermittlung von transienten Ereignissen erlaubt. In dieser Arbeit zeige ich für jeden der in der Studie verwendeten Röntgenmonitore, inwieweit die Nutzung einer Studentschen t-Verteilung die Hintergrundverteilung vollkommen charakterisiert. Die Verteilung kann für jedes Instrument individuell parametrisiert werden, indem der gewichtete Mittelwert der Beobachtungen im inaktiven Status, die gewichtete Standardabweichung sowie ein Freiheitsgrad-Parameter, der durch statistische Methoden berechnet werden muss, verwendet werden.
Mit dieser Charakterisierung habe ich den Duty Cycle der BeXRBs berechnet, der als das Verhältnis zwischen der Anzahl an aktiven Ereignissen und der Gesamtzahl der Beobachtungen definiert ist. Es wurde gezeigt, dass der Duty Cycle eine sehr glatte Verteilung für alle untersuchten Quellen aufweist. Bei dem Vergleich mit ihren Orbital-Parametern (Exzentrizität, Rotationsperiode und Orbital-Periode) und auch mit einem Maß ihrer Leuchtkraft wurde kein linearer Zusammenhang gefunden, was die Ergebnisse von Reig [68] in Frage stellt, eine Studie, die auch Daten von RXTE/ASM verwendet.
Außerdem wurden Anzeichen eines linearen Zusammenhangs zwischen der Magnetfeldstärke von BeXRBs und deren Exzentrizität (Bestätigung der Ergebnisse von Yamamoto u. a. [84]), deren Orbital-Periode sowie eine Potenz-Abhängigkeit zwischen der Magnetfeldstärke und der Rotationsperiode gefunden.
Eine Einführung in die Studie wird im ersten Kapitel (Kapitel 1) gegeben, gefolgt von einer Einleitung in die relevanten mathematischen Konzepte und dem astro-physikalischen Hintergrund (Kapitel 2). Im nächsten Teil werden die Instrumente und die Datenanalyse präsentiert (Kapitel 3), woraufhin eine detaillierte Beschreibung der Studie folgt (Kapitel 4). Eine Zusammenfassung sowie eine Diskussion der Ergebnisse können im letzten Kapitel (Kapitel 5) gefunden werden.

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Abstract

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Long-term variability of Be X-ray binaries

by Eva LAPLACE

In this Bachelor thesis, the long-term variability of Be X-ray binaries (BeXRBs) is investigated. These fascinating astrophysical objects constitute the most populated sub-class of neutron star X-ray binaries, binary star systems which emit X-ray radiation and where one of the stars is a neutron star and the other one a normal star. A sample of 28 of the best known BeXRBs has been studied, using data of three X-ray monitors: RXTE/ASM, Swift/BAT and MAXI. All sources in the sample but one are transient sources, in other words, they show X-ray activity for a period of time (from days to months) which is followed by periods of inactivity.

The first step in the characterization of the long-term variability was the discrimination between the "active" and "inactive" states of these systems using a new transient detection method developed by Belanger [7]. It is based on the statistical determination of the distribution of the inactive states, which enables the detection of transient events in a systematic way. In this work, I show how the use of a Student's t-distribution fully characterizes the background of any transient source for all of the X-ray monitors used in the study. The distribution can be parametrized individually for each instrument with the weighted mean and the weighted standard deviation of the inactive state, as well as a degrees of freedom parameter which has to be calculated using statistical methods.

Using this characterization, I have then studied the duty cycle of the BeXRBs in the sample, defined as the number of active events over the total number of observations. The duty cycle has been shown to have a very smooth distribution for all the systems studied here. Comparing it to the orbital parameters of the systems (orbital period, spin period, eccentricity) as well as to a measure of their luminosity, no correlation was found, challenging the results from Reig [68] who also analysed RXTE/ASM data.

Furthermore, the indication of a linear relation between the magnetic field of BeXRBs and their eccentricity (confirming findings from Yamamoto et al. [84]) and their orbital period, as well as a power-law relation with their spin period was found.

An introduction to the work will be given (chapter 1), followed by an introduction to the mathematical methods and the astrophysical background (chapter 2). In the next section, the instruments and the data reduction is presented (chapter 3), after which a detailed report on the study (chapter 4) will be made. Conclusions and a discussion of the results can be found in the final section (chapter 5).

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Chapter 1

Introduction

Neutron star X-ray binaries are among the most fascinating objects in the X-ray Universe. In these systems the physics of matter in extreme conditions of magnetic field (around 10^{12} G) and density (around 10^{14} g cm^{-3}) can be studied through the observation of the intense X-ray radiation emerging from these sources.
Be X-ray binaries (hereafter BeXRBs) are composed by a neutron star (the so-called accretor) and by a companion Be star. Be stars are giant stars characterized by very fast rotation, observation of emission lines in its spectrum and by the presence of a large equatorial Keplerian disc formed by matter released from the star due to its strong stellar wind. It is the interaction between the neutron star and this circumstellar disc that produces the X-ray radiation observed from these fascinating binary systems.
In fact, as in many other examples in the Universe, an interesting phenomenon, only observable in these circumstances, can be observed when massive objects interact: accretion. When plasma from the donor companion enters the gravity well of the compact object, it falls into its deep gravitational potential and is accelerated very rapidly towards the central mass. In the case of neutron stars, extremely high magnetic fields cause the accreted matter to be funnelled along the magnetic field lines onto the magnetic poles, forming an accretion structure. The kinetic energy of the accreted matter is then radiated away. The energies reached are so high that X-rays are produced.
In BeXRBs, the observed X-ray radiation is characterised by a very pronounced variability at different time-scales. The short-term variability (from seconds to kilo-seconds) has been studied extensively in the last years (see for example Finger, Wilson and Harmon [24], Fürst et al. [26]). This is related to the fact that it is easier to observe X-ray sources with a pointing telescope for a relatively short amount of time (10 to 100 ks). Only recently, the systematic observation of BeXRBs over long time-scales has been made possible by the operation of all-sky X-ray monitors. In this work, data from two X-ray monitors which are currently operational, MAXI and Swift/BAT, and archival data of a third one, RXTE/ASM are being used.
The sources studied in this work show an interesting long-term variability, the interpretation of which is still difficult from a theoretical point of view (see for example Okazaki and Negueruela [56] and Negueruela et al. [54]). All of them (except one) are transient sources, showing sudden (quasi-periodic) increases of the X-ray flux for a small amount of time, followed by a (longer) decrease and (generally) by inactivity. Characterizing and discriminating between active and inactive states of these sources is an ongoing challenge and a new method for performing this discrimination systematically based on the statistical understanding of the X-ray radiation over time (the so-called light-curve), is proposed in this Bachelor thesis.

A study of the long-term X-ray variation has been tried in the past by Reig et al. [66], using data from RXTE/ASM. The author found the hint of a correlation between the rms (root mean square) of the light-curve (a measure of the variability sensible to the amplitude of the variability and the timing variability) and the orbital parameters (eccentricity, orbital period, spin period) of the BeXRB. Here, another measure of variability is used: the duty cycle. This quantity measures the activity over time of a given source (see also Romano et al. [70]).
Using the RXTE/ASM, Swift/BAT and MAXI instruments, the first systematic study of long-term X-ray emission from BeXRBs is presented here. Using different instruments sensitive at various energies helps gaining a better understanding of the observed variability and in our case, to comprehend the evolution of this variability over time.
In this study, 28 BeXRBs sources are being studied and the latest measured orbital parameters of these systems have been searched in the literature. Using these parameters, a study of the relation between the known magnetic field of some of the systems for which a cyclotron line has been measured and the orbital parameters is performed.
In a first part of the study, we propose a new method to characterize the detection of a transient event, based on the work of Belanger [7]. This allows to discriminate between active and inactive states in the observed light-curves of BeXRBs. In the second part, this classification is used to study the long-term activity of BeXRBs in a systematic way. Last, the known global parameters of BeXRBs are compared to understand the global properties of these systems.
This thesis will start with a global introduction of the mathematical methods used here in order to detect transient events, followed by an introduction of the astrophysics of the studied systems (Chapter 2). The tools, instruments and the data reduction are presented in the following part (Chapter 3) and the next part is dedicated to the scientific study (Chapter 4). A discussion of the results and the conclusion are found in the final part (Chapter 5).

Chapter 2

Theoretical Background

2.1 Mathematical background

This work makes use of various mathematical and statistical methods to obtain the results presented in what follows.
To characterize the behaviour of the X-ray flux received from the various Be X-ray binaries (see section 2.2.4), the concepts of distributions, detection methods and statistical tests are of fundamental importance and will be presented in this section.

2.1.1 Detection of transient events

This study is based on a detection method for transient events detailed in Belanger [7]. It is based on a statistical approach which uses a comparison of likelihood ratios.

The likelihood function

The key quantity in our approach is the likelihood, which gives a quantitative description of a measurement: "before making a measurement, we have probabilities; after making the measurement, we have likelihoods"[1].
Using the statistical distribution characterizing the behaviour of an observed quantity, the likelihood of making any measurement which agrees with this distribution can be easily computed. This is made possible through the likelihood function, L, which is a description of the measurement distribution.
The likelihood quantifies the possibility of a measurement to have a certain value. As an example, we consider the number of photons arriving on a detector during one second. In this example set-up, after 1000 measurements, the average number of photons detected during one second is 10. This process is known to be described by Poisson statistics because it is a discrete process with constant probability in arrival time. We can use the Poisson likelihood function: $L_{poisson}$, characterized by a parameter ν. For a Poisson process, this parameter is equal to the average and also to the variance of the population. In our example, we would therefore have $\nu = 10$. We can now compute the likelihood of a measurement of n photons to be made, using the single likelihood function:

$$L_{poisson}(\nu|n) = \frac{\nu^n e^{-\nu}}{n!} \tag{2.1}$$

[1]Quoted from Belanger [7]

The likelihood of the entire set of measurements is then given by the product of the single likelihood of each measurement. It is called the joint likelihood function. Using the example of a Poisson distribution, it can be expressed mathematically as:

$$L_{poisson}(\nu|n) = \prod_{i=1}^{n} \frac{\nu^{n_i} e^{-\nu}}{n_i!} \tag{2.2}$$

Note that although in our example the distribution parameter was known in advance, the likelihood ratio method can also be used to find the best value of these parameters using the result of the likelihood function (see Belanger [7] for more details).

The likelihood ratio

To detect a transient event, we make use of the fact that the behaviour of our observed sources can be divided in two categories: on and off or detected and undetected. By specifying the features of the measurements when the observed quantity is in the undetected state, we can compute the likelihood that this event belongs to the undetected state. This implies finding the corresponding mathematical distribution and computing the likelihood of the measurement.
To get a normalized measure of the likelihood of the non-detection of a transient, we set the maximum likelihood to one. In mathematical term, it means that instead of computing a likelihood function, we will compute the likelihood ratio between the single likelihood function of a given measurement and the joint likelihood function at the maximum likelihood value. In the case of a Poisson distribution, the maximum likelihood is given by the single likelihood function at the reference value (See Belanger [7]).

$$p = \frac{L(x; \mu, \sigma, ...)}{L(\mu; \mu, \sigma, ...)} \tag{2.3}$$

It is important to emphasize here that the computed quantity is equal to the likelihood of a measurement to correspond to an **off** state. In other words, what is calculated here is the possibility of **not** detecting an event. The measurements corresponding to a detection therefore have a likelihood ratio close to 0%.
After defining a threshold of detection, results **smaller** than the threshold can therefore be classified as detected transient events.

2.1.2 Distributions

In the previous section, the importance of a good knowledge of the distribution of the flux during the off state of a source has been mentioned. To be able to characterize a given distribution, knowledge about their mathematical description and their origin is crucial. In this section, I will present the three most important distributions for this work.

The normal distribution

The most famous and widely used distribution is without a doubt the normal or Gaussian distribution. It's fame is closely related to the Central Limit Theorem, discussed in section 2.1.2.

The normal distribution can be expressed mathematically using two (independent) parameters μ, the sample's mean and σ, the sample's standard deviation.

$$p(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \tag{2.4}$$

The normal distribution has various useful properties. To name only two: it is symmetric and allows an analytical computation. What really makes it special is the fact that all distributions tend to become the normal distribution if the number of measurements is high enough, as stated by the Central Limit theorem.

The Poisson distribution

As presented in the example above, a Poisson distribution is a discrete distribution which arises in situations in which a number of events occurring in a fixed interval of time is counted, for which an average number is known. Examples are the amount of mail received in a mailbox or the number of cars arriving at a traffic light in a fixed time interval.
It is described mathematically by:

$$p(k|\mu) = \frac{\mu^k e^{-\mu}}{k!} \tag{2.5}$$

Where k is the number of successes in a number of trials N and μ is the mean of the sample.

Student's t-distribution

This distribution was first presented in a paper by W.S. Gosset under the pseudonym "Student", hence its name. A popular story in statistics (see Ivezic et al. [34]) states that W.S. Gosset was a statistician working for the Guinness brewery and was forced by the company to use a pseudonym, preventing competition to find out the company's secret: employing a statistician.
A quantity follows a Student's t-distribution when it is drawn from a population following a normal distribution where the sample size is small, the mean is being estimated and the standard deviation is unknown. This function can be expressed mathematically by:

$$f(x;\nu) = \frac{\Gamma\left(\frac{\nu+1}{2}\right)}{\sqrt{\nu\pi}\cdot\Gamma\left(\frac{\nu}{2}\right)}\left(1+\frac{x^2}{\nu}\right)^{\frac{-\nu+1}{2}} \tag{2.6}$$

where ν are the degrees of freedom of the sample and $\Gamma = (n-1)!$ the Gamma function (see Feigelson and Babu [22]).
It can be rescaled using the estimated mean of the sample μ and its standard deviation σ:

$$p(x;\mu,\sigma,\nu) = \frac{\Gamma\left(\frac{\nu+1}{2}\right)}{\sigma\sqrt{\nu\pi}\cdot\Gamma\left(\frac{\nu}{2}\right)}\left(1+\frac{(x-\mu)^2}{\nu\sigma^2}\right)^{\frac{-\nu+1}{2}} \tag{2.7}$$

Central Limit Theorem

Given a distribution characterized by a sample mean and variance, when a measurement is repeated enough times, the sample mean will follow approximately a normal distribution. With even more measurements, the approximation gets even closer.
This great finding results in the fact that a measurement's accuracy improves with more measurements and can simplify various problems thanks to the nice properties of the normal distribution (See 2).

2.1.3 Comparing distributions

Several tests have been invented to state if two measurements are drawn from the same population. It is greatly simplified when the distribution of one of the measurements or a theoretical distribution is known and we will focus on this case in this section.
It is important to remind oneself that a statistical test is only a probability statement. If the resulting value is small, measurements are only unlikely to be from the same distribution. It can therefore be useful to use different tests and techniques to make a statement about the comparison of distributions.

Likelihood ratio test

One of the first ways to assess the goodness of a distribution for a sample is to use the likelihood ratio and to maximize it, computing the so-called p-value. This means assuming a given distribution D and computing the probability of a measurement given the hypothesis $P(x|M)$.
If the result is smaller than a given threshold, the hypothesis is rejected. It is important to keep in mind that this test is only a probability statement.
A widely used approach is also to use the natural logarithm of this value (using the fact that the logarithm is a monotonically increasing function, so that the maximum value is reached for the maximum value of the function), because the computation can often be simplified.
For finding a best fit, it is therefore common to minimize the negative log-likelihood function.

The Kolmogorov-Smirnov test

A very useful approach is the K-S test. It makes use of the cumulative distribution functions F_1 and F_2 of two samples to compute the maximum distance between them. A remarkable property of this test is the fact that it is non-parametric. In other words, no assumption is made about the underlying distribution and the parameters grow with the data itself, without being fixed in advance. In our study, we use the p-value of the K-S test with a theoretical distribution.
Mathematically, it can be expressed as:

$$D = max\left(|F_1(x_1) - F_2(x_2)|\right) \tag{2.8}$$

Where x_1 are the measurements of the first distribution and x_2 of the second.

Quantile-quantile plots

Another way to assess the correspondence of two distributions is to use the the graphical method of the quantile/quantile (Q-Q) plot. Quantiles are the ordered measurements of a sample. For theoretical distributions, quantiles can be estimated in several ways, one of the most common being Filliben's estimate.
In a Q-Q Plot, if the quantiles agree with the x=y line, their distributions are equal. It can easily be seen if they are linearly related when the quantiles follow a line different from a x=y line.
It is critical for the interpretation of a Q-Q plot to understand that the measurements do not have to strictly follow an exact line, especially for the case of distributions with long tails, as for example the Student's t-distribution.
Filliben's estimate for theoretical quantiles is the following:

$$m(i) = \begin{cases} 1 - m(n), i = 1 \\ \frac{1-0.317}{n+0.365}, i = 2, 3, ..., n-1 \\ 0.5^{1/n}, i = n \end{cases} \tag{2.9}$$

2.1.4 Evaluation of duty cycles

In the case of transient sources, according to Romano et al. [70], duty cycles (DC) are defined as "The fraction of time during which the sources are active"[2], or mathematically:

$$DC = \frac{T_{active}}{T_{Tot}} \tag{2.10}$$

The term "activity" must be defined for the type of system encountered. Most of the time it denotes the measurements above a threshold fixed using a scientifically interesting value or given by the instrument (see Romano et al. [70] for more details). The duty cycle is a useful quantity to understand the global activity of a system which is characterised by two states "on" (active) and "off" (inactive). Thus, transient sources like BeXRBs are good subjects for using the duty cycle, provided there is a long-term observation available at regular intervals, such as monitors.

2.2 Astrophysical background

This work is a study of a subclass of binary star systems emitting in X-rays. In this section, the astrophysical background of the studied systems will be explained. I will present the latest relevant theories and refer to them in the discussion, summarized in chapter 5.

2.2.1 X-ray binaries

X-ray binaries are binary star systems composed by a compact object (a white dwarf, neutron star or black hole) also called the accretor, and a companion star also called the donor. These systems have the particularity to show physical processes rarely seen elsewhere in the Universe and to help understanding

[2]Quoted from Romano et al. [70]

the properties of compact objects through their interactions with the companion star. In astrophysics, binary systems help to constrain significantly some physical parameters which are generally difficult to be measured in single star systems, e.g. the mass.
X-ray binaries are commonly divided in two classes according to the mass of the companion star: High Mass X-ray Binaries (hereafter HMXBs) with a mass of $\mathrm{M_{HMXB}} > 10\ \mathrm{M_\odot}$ and Low Mass X-ray Binaries (hereafter LMXBs) with a mass of $\mathrm{M_{LMXB}} < 10\ \mathrm{M_\odot}$.

Accretion

One of the most interesting phenomena common to X-ray binaries is accretion. As explained in the introduction (see chapter 1), accretion is the process in which matter is attracted by a massive object and is accelerated onto its surface, releasing its gravitational energy and producing an intense thermal radiation in X-rays. The basic physical process is the same for all these systems, but two main accretion mechanisms are distinguished: wind accretion and Roche-lobe overflow, referring to the way matter is transported into the gravitational field of the accretor.
The luminosities reached by X-ray binaries through accretion are extremely high, of the order of $10^4 - 10^5$ the total luminosity of the Sun (see Longair [42]). This luminosity can be roughly approximated by the kinetic energy of the falling matter $E_{kin} = \frac{Mv_{\mathrm{ff}}^2}{2}$, where M is the mass of the accreted matter and v_{ff} the free fall velocity. Using the mass accretion rate $\dot{M}$, we obtain for the luminosity:

$$L = \frac{\dot{M}v_{\mathrm{ff}}^2}{2} \tag{2.11}$$

It is important for any physical interpretation of the X-ray radiation to keep in mind that the luminosity is closely related to the mass accretion rate.

Roche-lobe overflow

Common in low mass X-ray binaries, the mechanism of Roche lobe overflow is a very efficient accretion process. It takes place in systems in which the donor star fills its Roche lobe, the equipotential region around it in which matter feels the gravitational attraction from both stars. As described in Roche [69], when point masses are used as approximation for the stars, a simple expression can be found for the equipotential line. With M_i the mass of the star, r_i the distance to each star, ω the angular velocity of the binary system and r the distance to the rotation axis, we obtain:

$$\phi = \frac{GM_1}{r_1} + \frac{GM_2}{r_2} - \frac{\omega^2 r^2}{2} = const \tag{2.12}$$

Matter within this region can be captured by the accretor, falling into a circular motion because of the conservation of its angular momentum and leading to the formation of an accretion disc. In order for the disc to be formed, the so-called circularization radius R_{circ}, the radius in which the matter would conserve its angular momentum and loose energy, should be larger than the size of the accretor. With J the angular momentum of the falling matter and M the mass of the compact object, this radius is given by Pringle [61]:

$$R_{\text{circ}} = \frac{J^2}{GM} \tag{2.13}$$

Through a process thought to be related to magneto-hydrodynamical turbulence, parts of matter in the accretion disc loose angular momentum at some point and are eventually accreted on the compact object.

Wind accretion

When the donor star does not fill its Roche lobe, another type of accretion, which is much less efficient, can take place. In this scenario, matter coming from the stellar wind of the companion star can be captured in the gravitational potential of the compact object. Because the stellar wind is ejected in every direction, only a tiny fraction of this matter is accreted, contrary to what happens in the case of Roche-lobe overflow.
For a star with an orbital motion v and a stellar wind velocity v_w, it has been shown that matter from the wind can be captured if it passes within a cylindrical radius r_{acc} of the star, which is characterized by a mass M. In Bondi and Hoyle [11], this accretion radius is given by:

$$r_{acc} = \frac{2GM}{v^2 + v_w^2} \tag{2.14}$$

Because of the properties of this process, the accreted matter possesses much less angular momentum than in the case of Roche-lobe accretion. It is therefore difficult to know when exactly an accretion disc is formed, although the existence of a disc has been observed in several cases.

2.2.2 Neutron stars and accretion

Neutron stars are very interesting objects discovered in the last century which are one of the possible end products of stellar evolution. They are the densest objects without event horizons in the Universe with a density around 10^{14} g $\cdot$ cm^{-3} (consequence of a radius of about 10 km and a mass of about 1.5 $M_{\odot}$) and have the strongest magnetic fields (around 10^{12} G). Many of their properties are still part of active research and studying BeXRBs and their interactions with the companion star are a very good way to understand them better.
One of the most prominent characteristics of these objects is the pulsations with a period ranging from milliseconds to thousands of seconds they exhibit in many different wavelengths. In fact, neutron stars, also known as pulsars, were discovered by Jocelyn Bell and her supervisor Antony Hewish in 1967 through the finding of a very periodic signal in the radio range originating from point-like sources in the sky (see Hewish et al. [32]). This periodicity was shown to originate in the so-called light-house effect, in which the neutron star produces radiation from two magnetic poles. Because the magnetic axis is tilted with respect to the spinning axis, a periodic signal is emitted towards the observer.
The pulse period of neutron stars in BeXRBs has also been observed to change over time, especially during outbursts and in the long-term.
When neutron stars, with intense magnetic fields, are the compact objects in

X-ray binaries, accretion is strongly influenced by the magnetic field. The accreted matter is prevented to radially fall into the compact object at a certain distance from the neutron star, known as the Alfvén radius (typically at 10^8 cm, see Lamb, Pethick and Pines [38]). Instead, matter (which is ionized) follows the magnetic field lines of the neutron star and is funnelled onto the magnetic poles, where it falls onto the neutron star surface. A representation of an accreting neutron star is given in figure 2.1:

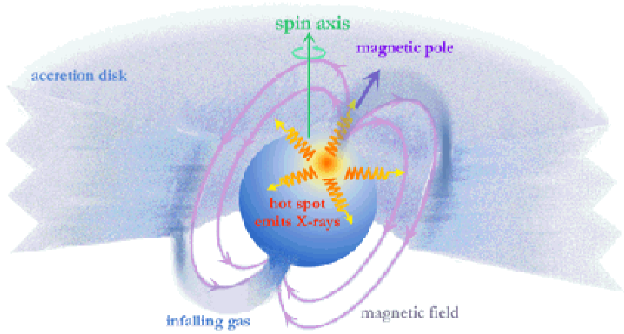


FIGURE 2.1: Representation of an accreting neutron star, taken from [13]

For magnetic systems with an accretion disc, the existence of the disc can be probed by the presence of spectral lines and their changes related to the spin period of the neutron star, as well as by the observation of Quasi Periodic Oscillations (QPOs) (see Middleditch and Priedhorsky [47]).
A prominent feature observed in the spectrum of strongly magnetized neutron star X-ray binaries, is the presence of a cyclotron resonance scattering feature (CRSF) which provides direct evidence of the magnetic field. The first discovery of a CRSF was reported in Truemper et al. [80] for Her X-1. The cyclotron resonance frequency is a common feature resulting from resonant scattering of photons with electrons accelerated along the magnetic field and quantized into Landau levels. The energy of this line is directly proportional to the magnetic field strength:

$$E_c = 11.6 \cdot B \cdot (1 + z)^{-1} \text{ keV} \tag{2.15}$$

where B is the magnetic field and z the gravitational redshift.
Observing a CRSF is therefore a very good measure of one of the most important characteristics of neutron stars.

2.2.3 Classes of X-ray binaries

As mentioned earlier, X-ray binaries are classified in two main groups: LMXBs and HMXBs. An overview of their characteristics is given in table 2.1:

Characteristics	HMXB	LMXB
X-ray spectra:	kT $\geq$ 15 keV (hard)	kT $\leq$ 10 keV (soft)
Type of time variability:	regular X-ray pulsations, no X-ray bursts	only a very few pulsars, often X-ray bursts
Accretion process:	wind (or atmos. RLO)	Roche-lobe overflow
Timescale of accretion:	10^5 yr	$10^7 - 10^9$ yr
Accreting compact star:	high B-field NS (or BH)	low B-field NS (or BH)
Spatial distribution:	Galactic plane	Galactic center and spread around the plane
Stellar population:	young, age <10^7 yr	old, age >10^9 yr
Companion stars:	luminous, $L_opt/L_x > 1$, early-type O(B)-stars>10 $M_{\odot}$ (Pop. I)	faint, $L_opt/L_x \ll 0.1$ blue optical counterparts $\leq 1M_{\odot}$ (Pop. I and II)

TABLE 2.1: Characteristics of LMXBs and HMXBs, from Tauris and Heuvel [79]

From this table, it is apparent that these systems have a very different behaviour related to many of their characteristics. However, some of the characteristics do not apply to all systems but are a general trend seen in the different groups. As an example, some LMXBs, such as Her X-1 and GX 1+4, show relatively high magnetic fields. A representation of LMXBs and HMXBs can be found in figure 2.2.

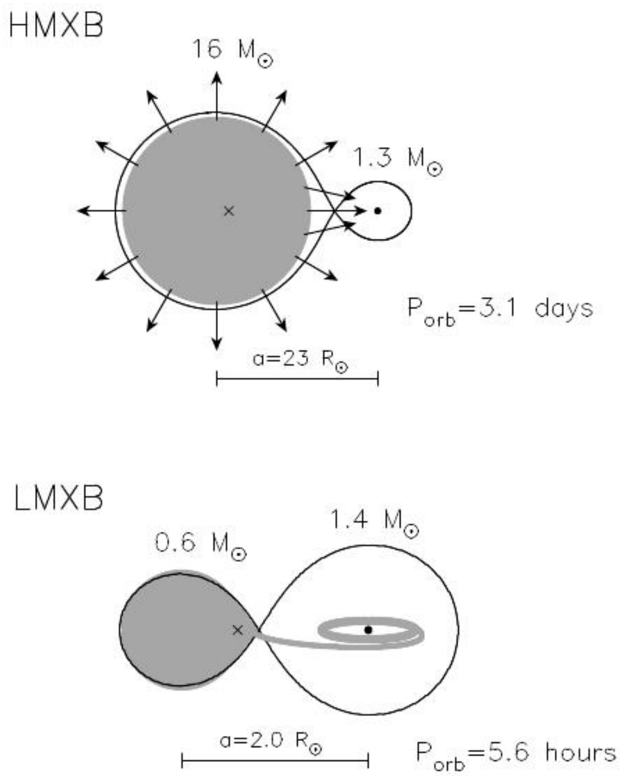


FIGURE 2.2: Representation of a typical HMXB and a typical LMXB. The solid lines show the Roche lobes. The figure is taken from Tauris and Heuvel [79]

2.2.4 Be X-ray binaries

BXRBs are the most populated group of High Mass X-ray Binaries. They are binary star systems composed by a giant blue Be star, which has been observed

to display strong emission lines, and a compact object (see Reig [67]). So far, the compact object has always been found to be a neutron star, except for a single case, discovered recently (see Casares et al. [12] and Munar-Adrover et al. [51]), where it is a black hole. A representation of such a system can be found in figure 2.3. The small number of BeXRB with black holes can be due to detection difficulty (Zhang, Li and Wang [85]) or to the rarity of the formation of such systems (Belczynski and Ziolkowski [8]).
BeXRBs have unique properties which make them interesting laboratories for modern astrophysics. From the interaction between the Be star and the neutron star, a range of unusual effects can be found. One of the most prominent and obvious characteristics of a BeXRB is the X-ray radiation it emits. According to the standard model (Shakura and Sunyaev [72]), X-ray radiation is produced by the accretion of matter from the companion star onto the compact object.

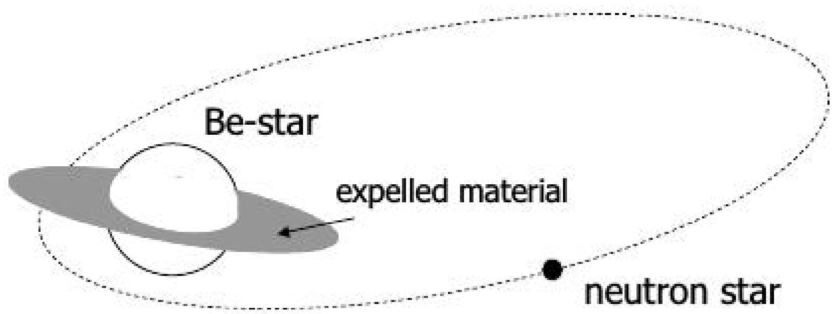


FIGURE 2.3: Representation of a BeXRB, taken from Tauris and Heuvel [79]

When observing the X-ray flux per unit of time emitted by a BeXRB on a period of time ranging from seconds to years (the so-called light-curve), it is immediately apparent that these systems exhibit dramatic X-ray variability at very different time-scales. The most visible feature in the days to months range are sudden increases of the X-ray radiation followed by a (slower) decrease of the radiation, so-called outbursts. These outbursts are not seen in all BeXRBs, but most of them exhibit at least one of the two most common types of outbursts. The first type corresponds to a luminous ($L_x \sim 10^{36} - 10^{37} erg\, s^{-1}$) and quasi-periodic outburst (type I) and the other type to a very luminous ($L_x > 10^{37} erg\, s^{-1}$) and not periodic (type II) outburst (see Stella, White and Rosner [75]). Interestingly, some systems display almost only type I outbursts, some only type II outbursts (see figure 2.5), some a mix of both (see figure 2.4) and some a different type entirely, like continuous radiation for example from so-called persistent sources.

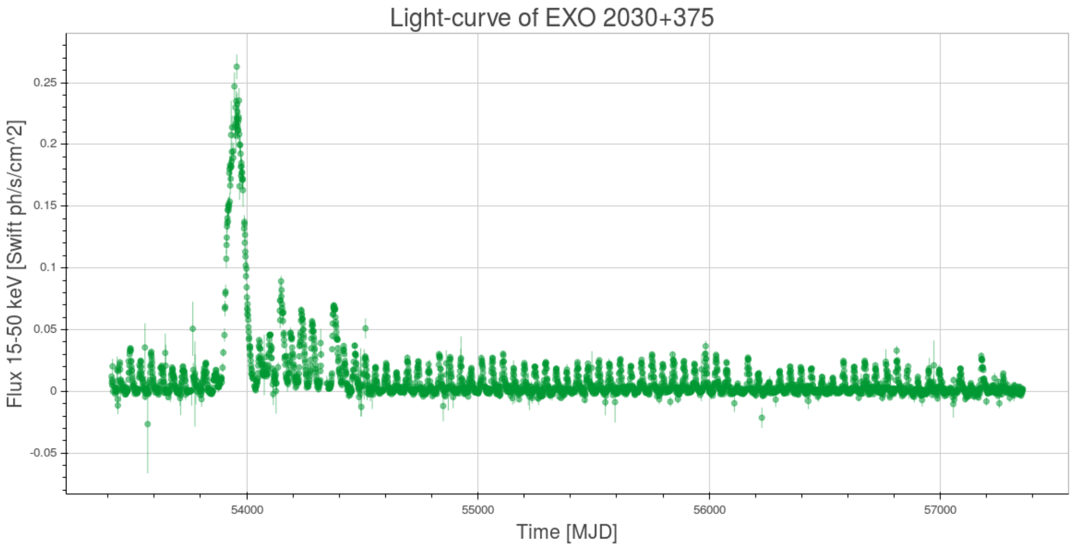


FIGURE 2.4: Example of the Swift/BAT light-curve of the BeXRB EXO 2030+375, showing very regular type I outbursts and also a giant type II outburst

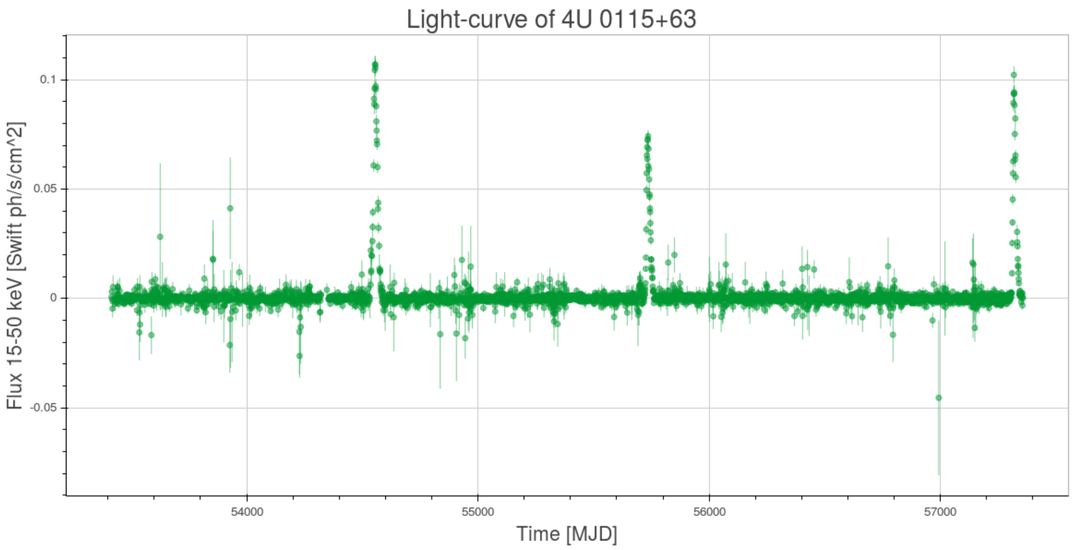


FIGURE 2.5: Example of the Swift/BAT light-curve of the BeXRB 4U 0115+63 with giant type II outbursts

Moreover, properties originating from the Be star itself are also characteristic of BeXRBs. In these systems, the Be star is a rapidly rotating star which is not a super-giant. The presence of a variable Hα emission line and also of He and Fe emission lines (Hanuschik [29]) as well as the presence of particularly high radiation in the Infra-Red (IR) range, which are not observed in smaller stars, are both attributed to the existence of a large equatorial "decretion" disc around the Be star (see Reig [67] and references therein).
The Hα line is particularly prominent. It has been observed that it is varying with time, giving important constrains on the envelope shape and dynamics of the equatorial disc (see Hummel and Vrancken [33]). The observed optical and

IR features in BeXRBs are thought to result from free-free and free-bound absorption in the disc of the central star's optical and UV radiation. A correlation between the two features has been observed in many cases, strongly supporting the presence of an equatorial disc.
Very massive stars like Be stars are characterized by a very strong stellar wind, ejecting radiation and hot gas from the star. Due to gravitational effects, this matter is thought to be confined to a Keplerian disc around the Be star. Furthermore, the passage of the neutron star close to or even through the disc is believed to lead to a dramatic change and to an increased accretion flow, leading to the observed X-ray radiation at periastron.

Outbursts

One of the main subjects of interest in this work is the study of the various outbursts present in the X-ray light-curve of BeXRBs. Type I outbursts are the ones which can be understood best from current models. Most of them occur periodically at a time corresponding roughly to the periastron (closest to the companion star) passage of the neutron star. This indicates the periodic accretion of matter at a time of close encounter with the companion star and agrees very well with current models (see Okazaki and Negueruela [56]).
Much less understood are the type II or "giant" outbursts. These occur in general less frequently than type I outbursts and can last for several orbital periods. They can occur far from the periastron passage, sometimes even during apastron and it is still difficult to understand their origin. Because of the higher luminosities, more matter is being accreted in those outbursts but the mechanisms leading to their formation are still largely unknown. QPOs have also been observed during many of these especially bright outbursts, indicating the presence of an accretion disc (see Psaltis [62]). One of the goals of this study is to reach a statistical understanding of their occurrences and their physical properties.

2.2.5 The viscous decretion disc model

The leading and most accepted model for explaining the intriguing behaviour of BeXRBs is the truncated viscous disc model, first formulated by Okazaki in Okazaki et al. [57], Negueruela et al. [54] and Negueruela and Okazaki [53] after the observation of a truncation of the disc by Reig et al. [66]. Truncation occurring in a disc at certain distances from the companion star leads to less material present for the neutron star to accrete, which could explain the lack of X-ray radiation observed in some systems.
This model, which has been successfully simulated for the first time in 3D in recent years (Okazaki [55]), is based on the interaction between the Be disc and the neutron star, as well as on the intrinsic properties of the Be disc, which is thought to be supported by viscosity. The main idea is very similar to the well established accretion disc model, with the difference of a negative mass flow. Viscosity, in this case, is responsible for leading the matter from the inner edge of the disc outwards. The inner edge of the disc gets its angular momentum from the companion star's angular momentum in a mechanism which has still to be explained, until the velocities reached are Keplerian. Matter from the companion star accumulates faster in a denser disc for this model than for isolated Be stars. The truncation of the disc can be explained easily by tidal interactions with the neutron star. It has been successfully modelled in the case of 4U

0115+63 (see Negueruela et al. [54]) and seems to strongly depend on orbital parameters.

2.2.6 Long-term X-ray variation

Studying variations of the X-ray radiation over long time-scales has only possible in recent years because long term monitoring in X-rays has been performed. Using the RXTE/ASM instrument (see also 3.2.3), a variability study using the rms (root mean square) of the light-curve has been performed (see Reig [68]). The author claims to find an anti-correlation with several orbital parameters, namely the orbital period, the eccentricity and the spin period, which would confirm the viscous decretion disc model.

BeXRB systems

The BeXRB systems studied here and their properties are given in table 2.2.

Source Name	Orbital period [d]	distance [kpc]	Ref distance	$P_{spin}[s]$	Ref P_{spin}	e	ref e	E_{Cycl}	Ref E_{Cycl}	RA	Dec
1A 0535+262	111,1	3.8 ± 0.33	[16]	105	[67]	$0,47 \pm 0.02$	[24]	45, 100+	[36],[35], [43]	84,727	26,316
2S 1417-624	42,12	7.0 ± 0.74	[16]	17,6	[67]	0.446 ± 0.002	[23]	-	-	215,303	-62,698
2S 1553-542	29,56	10	[59]	9,26	[63]	<0.09	[63]	-	-	239,454	-54,415
2S 1845-024	242,18	10	[28]	94,3	[56]	0.88 ± 0.01	[25]	-	-	282,074	-2,42
4U 0115+63	24,3	5.3 ± 0.44	[16]	3,6	[67]	0.34 ± 0.005	[64]	14, 24, 36, 48, 62	[81], [31], [71]	19,633	63,74
Cep X-4	23,85	3.7 ± 0.52	[16]	66,3	[67]	-	-	28	[48]	324,878	56,986
EXO 2030+375	46,03	3.1 ± 0.38	[16]	41,8	[67]	0.41 ± 0.001	[82]	11	[82]	308,064	37,637
GRO J1008-57	249,48	4.1 ± 0.59	[16]	93,5	[67]	0.68 ± 0.02	[15]	76	[9]	152,442	-58,292
GRO J1750-27	29,82	$12 - 22$	[74]	4,45	[63]	0.360 ± 0.002	[10]	-	-	267,291	-26,637
GS 0834-430	105,8	7.1 ± 4.2	[16]	12,3	[67]	0.12 ± 0.05	[10]	-	-	128,979	-43,185
GX 304-1	132,2	1.3 ± 0.10	[16]	272	[67]	>0.5	[67]	51	[83]	195,321	-61,602
H 1145-619	187,5	4.3 ± 0.52	[16]	292,4	[67]	>0.5	[67]	-	-	177	-62,207
IGR J13020-6359	-	5.5 ± 1.5	[14]	-	-	-	-	-	-	195,498	-63,968
KS 1947+300	40,4	8.5 ± 2.3	[16]	18,76	[67]	0.034 ± 0.007	[27]	12.5	[26]	297,398	30,209
LS V +44 17	155	2.9 ± 0.37	[16]	203	[67]	-	-	-	-	70,247	44,53
MAXI J1409-619	-	15	[58]	500	[58]	-	-	44, 73, 128	[58]	212,011	-61,983
MXB 0656-072	-	7	[49]	160,4	[67]	-	-	33	[3]	104,6	-7,2
RX J0146.9+6121	-	2.5	[46]	1412	[67]	-	-	-	-	26,751	61,357
SAX J2103.5+4545	12,7	8.0 ± 0.78	[16]	358,6	[67]	0.401 ± 0.018	[2]	-	-	315,899	45,752
Swift J045106.8-694803	-	SMC	[41]	168,5	[4]	-	-	-	-	72,778	-69,801
Swift J1626.6-5156	132,9	10	[65]	15,4	[65]	0.08 ± 0.01	[6]	10	[20]	246,65	-51,941
Swift J1843.5-0343	-	-	-	42,5	[77]	-	-	-	-	280,899	-3,73
Swift J2000.6+3210	-	-	-	890	[60]	-	-	-	-	300,091	32,1898
V 0332+53	34,25	6.9 ± 0.71	[16]	4,4	[67]	0.31 ± 0.03	[76]	27, 51, 74	[44]	53,75	53,173
X Per	250,3	1.2 ± 0.16	[16]	837	[67]	0.111 ± 0.018	[21]	29	[30]	58,846	31,046
XTE J1858+034	-	-	-	221	[63]	-	-	-	-	284,688	3,432
XTE J1859+083	-	-	-	9,8	[19]	-	-	-	-	284,775	8,25
XTE J1946+274	169,2	6.2 ± 3.0	[16]	15,8	[67]	0.417 ± 0.007	[64]	36	[30]	296,417	27,356

TABLE 2.2: Studied sources, their parameters and references

Corbet-diagram

The spin period and the orbital period of X-ray binaries are related. This can be observed with the help of the Corbet diagram (see Corbet [17] and Corbet [18]). It is known from previous studies (see Reig [67]) that Be X-ray binaries display a positive correlation and in doing so form a distinct group from other types of neutron star X-ray binaries (Super-Giant X-ray binaries and LMXBs for example) in this diagram. Moreover, the source SAX J2103.5+4545 is known for its peculiar behaviour, displaying optical/IR emission similar to that of BeXRBs and at the same time having X-ray properties close to wind-fed systems (for more information see Reig [67] and references therein).
The Corbet diagram for the sources in our sample is displayed in figure 2.6.

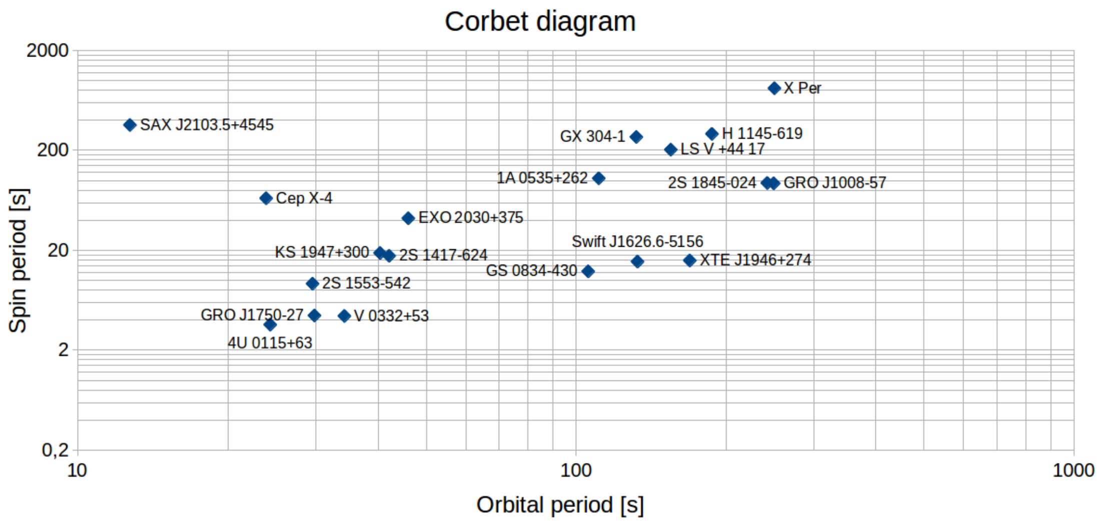


FIGURE 2.6: Corbet diagram of our sample.

The linear relation found in BeXRBs is explained by a quasi-equilibrium state in which the Alfvén radius of the systems and the co-rotation radius are almost the same. Because the Alfvén radius depends on the density of the medium and therefore on the orbital period of the system, a relation between the spin period and the orbital period is found. It can be approximated empirically by a power-law with an added correction for the eccentricity of the systems (see Corbet [18]).

Chapter 3

Tools, instruments and data reduction

3.1 The BeXRB monitor

The BeXRB monitor is a web-based tool[1] which I developed last year during a trainee-ship with the ESA trainee program at the European Space Astronomy Centre in Madrid (Spain). My supervisors were Dr. Peter Kretschmar, Mr. Emilio Salazar and Mr. Miguel Arregui. The monitor makes use of freely available data from three X-ray monitors (MAXI, Swift/BAT and Fermi/GBM) to detect activity in a sample of 28 known BeXRBs. The activity detection is based on an algorithm calculating the distance between the last measurements. This type of detection is not based on statistical properties. One of the goals of the work presented here is to find out if, using statistical properties to detect activity, would lead to better results than the existing algorithm.

3.1.1 Relevance for this work

The BeXRB monitor has been used for the study presented here by providing the database, some python scripts and references to relevant literature. Many aspects of this work were facilitated by the fact that crucial information about the data to be used and the properties of the systems studied were available through the BeXRB monitor. Along with this study, the BeXRB monitor was improved, especially in the front end. The development of a binary black holes monitor[2] was started as well.

3.2 Instruments

For characterizing long-term X-ray variability, observations on a time scale of several years are needed. Using light-curves from X-ray monitors is therefore a natural option. In our era of intense space exploration, several X-ray monitors are currently looking or have recently looked at Be X-ray binaries. Their data is freely available. Moreover, the fact that the instruments we are using operate in different energy bands provides an additional information about the spectral variability.

Because of atmospheric absorption, X-rays are best studied from space. This is why all of the instruments presented here operate on-board satellites orbiting the Earth.

[1] http://integral.esac.esa.int/bexrbmonitor/webpage_oneplot.php

[2] http://integral.esac.esa.int/blackholemonitor/black-hole-monitor.php

3.2.1 MAXI

The Monitoring All Sky X-ray Images (MAXI) is a mission of the Japanese Aerospace Exploration Agency (JAXA) on-board the International Space Station (ISS) on the Japanese Kibo Module and has been operative since August 2009. It consists of gas slit cameras instruments with a high sensitivity. It is a monitor operative in the energy range of 2-30 keV, particularly useful for studying BeXRBs (Matsuoka et al. [45]). Every 96 min, the ISS makes a complete orbit around the Earth. During this time, MAXI scans the sky through two semi-circular fields of view. Data from MAXI can be missing when the ISS or the Sun come in the field of view.

FIGURE 3.1: The Monitoring All Sky X-ray Images on-board the ISS (from *NASA - Monitor of All-sky X-ray Image* [52])

MAXI carries two main instruments: the Gas Slit Camera (GSC) and the Solid-state Slit Camera (SSC). The GSC consists of 12 cameras and a proportional counter filled with Xe and features a time resolution of 0.1 ms. It has a large detection area of 5350 cm^2 and covers the energy range $2 - 30$ keV.
The SSC consists of 32 chips of X-ray CCD, is sensible in the 0.5-12 keV energy band, has a time resolution of 5.8 s and a smaller field of view of 200 cm^2 with a sensitivity of 5 mCrab/week (Matsuoka et al. [45] for more information). For this work I made use of the 1-day binned publicly available data, which is built using the MAXI/GSC instrument, on the MAXI home page[3].

3.2.2 Swift/BAT

Swift is a NASA mission launched in 2004 designed specifically for the search of Gamma-ray bursts. It began operations in February 2005. We made use of the Burt Alert Telescope (BAT), a monitoring instrument looking for transient events in the 15-50 keV band.

[3]http://maxi.riken.jp/top/index.php?cid=1&disp_mode=source

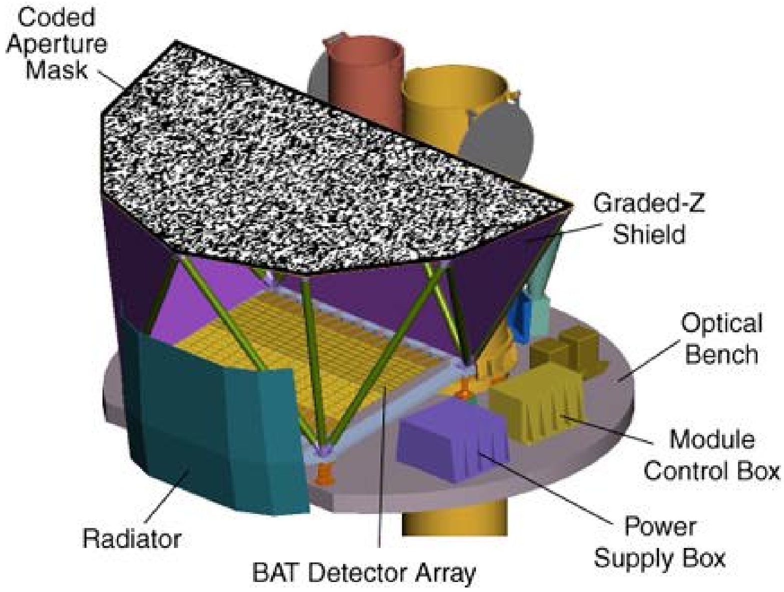


FIGURE 3.2: The Burt Alert Telescope (from *Swift: About Swift - BAT Instrument Description* [78])

The BAT is a coded aperture imaging instrument with a large detection area (5200 cm^2), sensitive in the 15-150 keV band. It is composed by 256 modules of 128 elements and has a sensitivity of 16 mCrab. It covers 80% to 90% of the sky per day. The 1-day binned data was taken from the "Hard X-rays Transient Monitor" page[4], see Krimm et al. [37].

BAT 70 months survey

After some exchange with Hans Krimm from the BAT instrument about the early findings of my work, I followed his suggestion to make use of the re-processed data from the survey release, which has a much better statistic and for which the background subtraction has been done more precisely (see Baumgartner et al. [5]). This data, taken from the official web-site[5], proved to be of higher quality than the monitoring real-time data. Using it, a Student's t-distribution for the background was found to be an exact fit very early in the study, confirming the first findings. For an example of the quality of the survey data and the resulting goodness of the fit, see the top-left plot in figure 4.1.

3.2.3 RXTE/ASM

The Rossi X-ray Timing Explorer was a successful NASA mission launched in December 1995 and operative until January 2012. It consisted of several instruments, the most famous probably being the Proportional Counter Array, but only the All Sky Monitor (ASM) is in use for this study and will be presented here.
The ASM was composed by three wide angle scanning shadow cameras with Xe proportional counters reaching a total collecting area of 90 cm^2. It had a monitoring capability of 80% of the sky per minute, a sensitivity of 20 mCrab per minute and was operative in the 2-10 kev band (see Levine et al. [40] for more

[4] http://swift.gsfc.nasa.gov/results/transients/
[5] http://swift.gsfc.nasa.gov/results/bs70mon/

information). It should be noted here that the sensitivity of this instrument is not as high as the ones in Swift/BAT and MAXI, leading to higher uncertainties in the data.

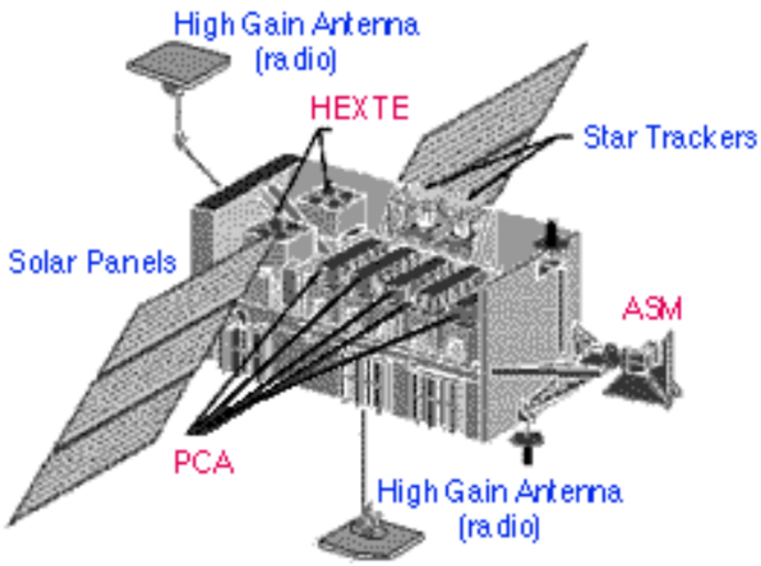


FIGURE 3.3: The Rossi X-ray Timing Explorer and the location of its All Sky Monitor (from *About RXTE* [1])

The light curve data from the official ASM archive[6] was used and processed to obtain a similar data format as the one available in MAXI and Swift/BAT. Afterwards, it was re-binned with one day to agree with the time resolution of the other instruments in use.

3.3 Python libraries

This work made extensive use of the freely available python libraries *scipy* and *numpy* and their multiple components (especially *scipy.stats*). The documentation and source code[7] was used for the statistical study presented here.
For plotting purposes, the *matplotlib*[8] and *bokeh*[9] modules were used.

[6] http://heasarc.gsfc.nasa.gov/docs/xte/ASM/sources.html
[7] http://scipy.org/ and http://www.numpy.org/
[8] http://matplotlib.org/
[9] http://bokeh.pydata.org/en/latest/

Chapter 4

Study

4.1 Background characterization

As described in the theory chapter (chapter 2), the quality of the method used to detect transient events strongly depends on the goodness of the background characterization. Because different instruments are being used, this process has to be repeated individually for each of them.

4.1.1 Expected background distribution

The mathematical characteristic of the sources' background is its distribution. The background of an X-ray telescope is related to the physical principles of detection, the technology and the operation of the instruments. Particle induced background in the detector is the main source of background for X-ray monitors, which are not focussing instruments.

When an X-ray instrument points at any part of the sky, it inevitably detects a very faint, diffuse signal: the Cosmic X-ray background. This is related to the fact that the X-ray sky is very populated, resulting in a partly resolved (mostly AGNs, galaxy clusters and starburst galaxies) and partly unresolved background (thought to originate from the Local Bubble, the Galactic halo and the intergalactic medium), see Moretti et al. [50], Shanks et al. [73], and references therein. As a result, stray or scattered photons can hit the detector from any part of the sky.

Another possible factor concerns the instruments used in this work, which are X-ray monitors with by definition a large field of view and a poor angular resolution. When two X-ray sources are close-by, the detector will thus receive an even larger signal contamination.

Except for this last, more difficult problem to account for, background radiation can therefore be viewed as a collection of random detection events. From a mathematical point of view, this gives rise to a Poisson statistics, as explained in 2 (see also Ivezic et al. [34] and Feigelson and Babu [22]). Because the instruments we are using detect photon flux, an average is made over the detection area. Moreover, since a large number of photons are detected in the background, we expect a normal distribution to arise (see also Belanger [7]).

4.1.2 Background distributions

To verify this approach, I selected several sources from the total sample of Be X-ray binaries for which a clear discrimination could be made by eye between active (peaks) and inactive states.

Parts of the light-curve where the sources appeared to be inactive were then selected for each of these sources. An example of these selections is shown in

the appendix (see figure 6.1). The first attempt to fit the background flux distribution with a normal curve proved to be inexact and further from the normal distribution than expected.
It was then investigated if the measurements distribution, which seemed to show broader tails and a smaller and narrower peak than the normal distribution, could be approximated by a Student's t-distribution.
Using basic fitting functionalities of python, it was shown that this distribution was indeed a better estimate than the first expected normal distribution for all the instruments, as seen in figure 4.1.

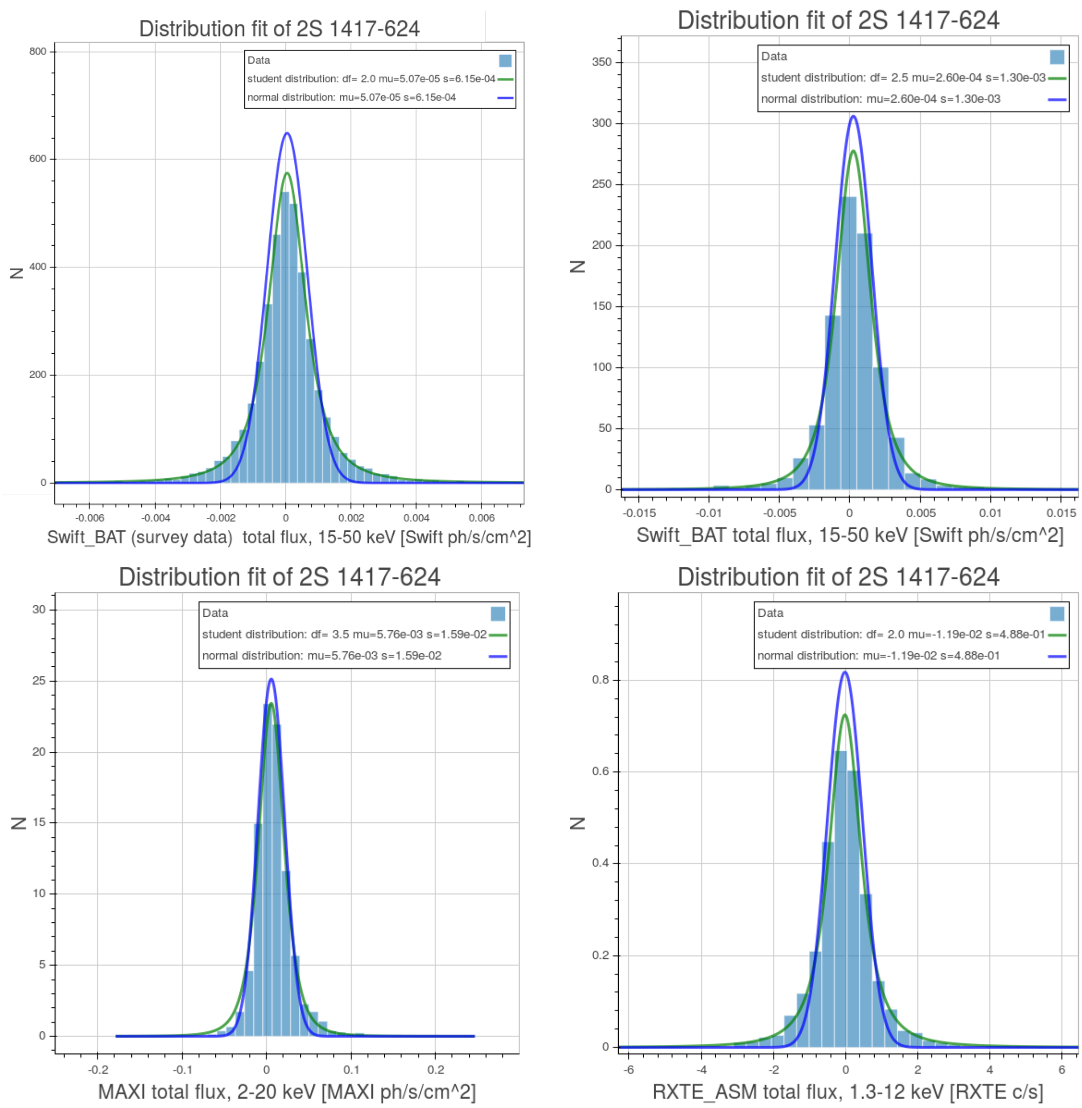


FIGURE 4.1: Example of background distribution comparisons using different instruments for 2S 1417-624

Such a distribution is known to arise when a relatively small sample is taken from a population of normally distributed measurements, where either the mean or the standard deviation of the distribution is unknown and where the measurements have a number of degrees of freedom d_f (see Feigelson and Babu [22]) .
In our case, we have established from a physical point of view that we would

expect a normal distribution with a mean of zero and an unknown standard deviation. Thus, only the degrees of freedom parameter needs to be found.

4.1.3 Parametrising the background distribution

In order to confirm our early finding that the background of a light-curve follows a Student's t-distribution and to find the unknown degrees of freedom parameter, I used several mathematical tests presented in Chapter 2. From the example of a QQ diagram presented in figure 4.2, it is apparent that the distribution is indeed very close to a Student's t-distribution. Outliers can also be seen in the QQ diagram, but their number is so low that it is not possible to distinguish them in the distribution plot. Moreover, the resulting parameters for d_f are also very close and it is difficult to discriminate them visually in the light-curve plot. The lines are also very close to the x=y line, indicating a good choice of parameters.

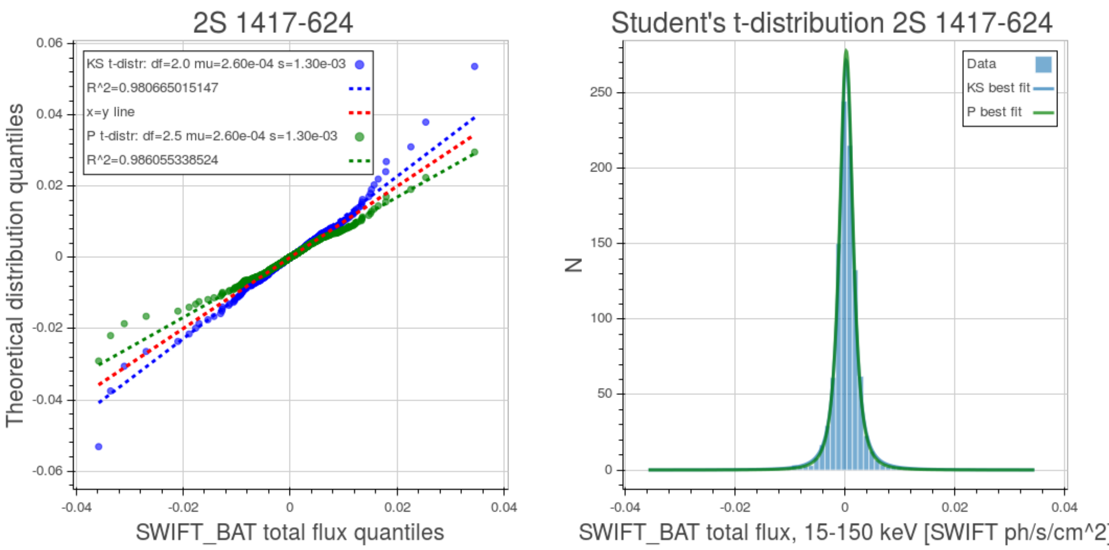


FIGURE 4.2: Example of QQ-Diagram and corresponding background flux distribution curve.

Furthermore, to verify that this distribution does not arise as an intrinsic low activity property of Be X-ray binaries, I used the same approach for the background distribution of completely different sources, i.e. AGNs and black holes. As shown in figure 4.3, the distribution was also found to follow a Student's t-distribution.

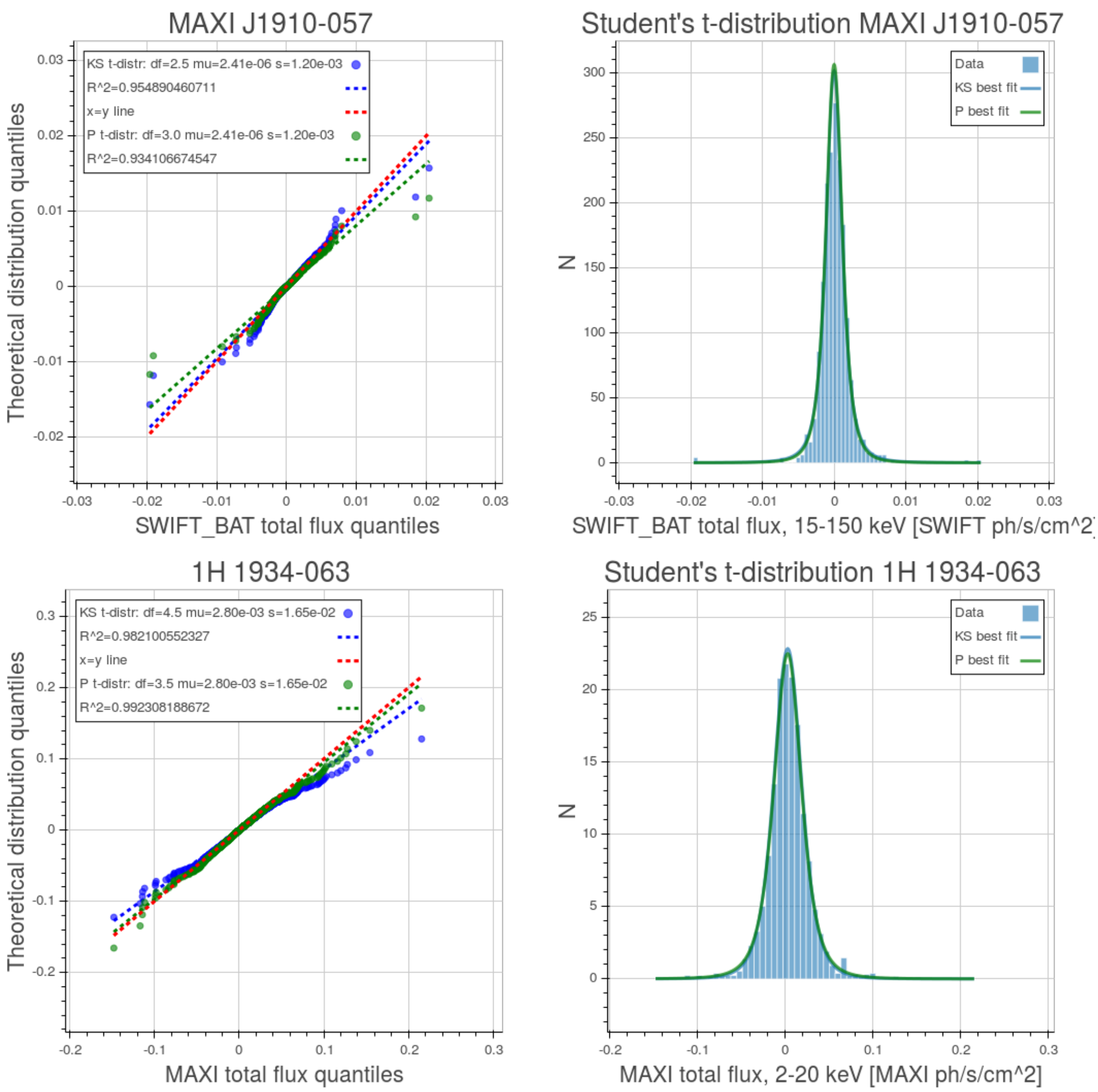


FIGURE 4.3: Example of QQ-Diagram and corresponding light-curve for the AGN 1H 1934-063 and the X-ray nova (Black hole binary) MAXI J1910-057.

Having concluded that the background can be characterized by a Student's t-distribution, the next step was to parametrize each instrument's background. Combining the found background distribution and removing the ones with especially bad data, a global background distribution could be found for each instrument. Using the maximum likelihood and the R-S Test, the best degrees of freedom parameter was calculated. To verify the resulting distributions, a Q-Q diagram was used. The resulting distribution parameters are shown in figures 4.4, 4.5 and 4.6. From these figures, it is clear that the distribution follows a Student's t-distribution for each of the instruments used. In the Q-Q diagram, the flux quantiles fit the x=y line very well and for both Swift/BAT and RXTE/ASM, the mathematical tests find the same resulting parameter for the degrees of freedom. For MAXI, even though the mathematical tests find very similar parameters, we retain a degrees of freedom value of $d_f = 3.5$ because of the slightly better linear regression.
Note that the plots present the same X-axis, from where it can be observed that

the majority of the flux quantiles lies in the distribution range. The outlying measurements are the only ones differing from the x=y line. Thus, the distribution of the background is very well characterized with this mathematical description.
Furthermore, it is interesting to observe that as expected, the accuracy of the instrument used is reflected in the broader background distribution width. It is therefore apparent that RXTE/ASM shows less accuracy than MAXI, which is in turn less accurate than Swift/BAT. Many more outliers of the Student's t-distribution can be seen in the RXTE/ASM QQ-Diagram, showing the higher degree of uncertainty of this instrument.
Moreover, the distribution mean, however close to the expected value of 0, slightly differs from it. The excess in MAXI and Swift/BAT may indicate a slightly underestimated background and the negative mean in RXTE/ASM an overestimation.

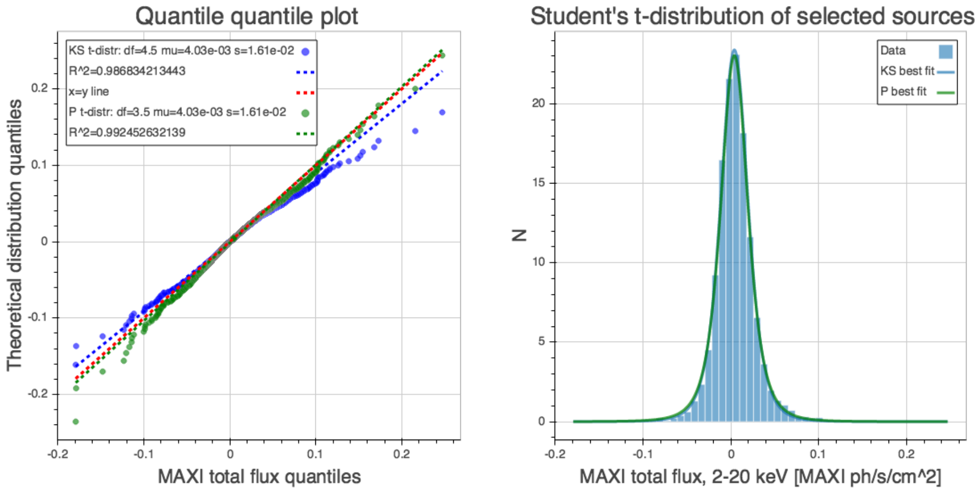


FIGURE 4.4: Distribution parameters for MAXI

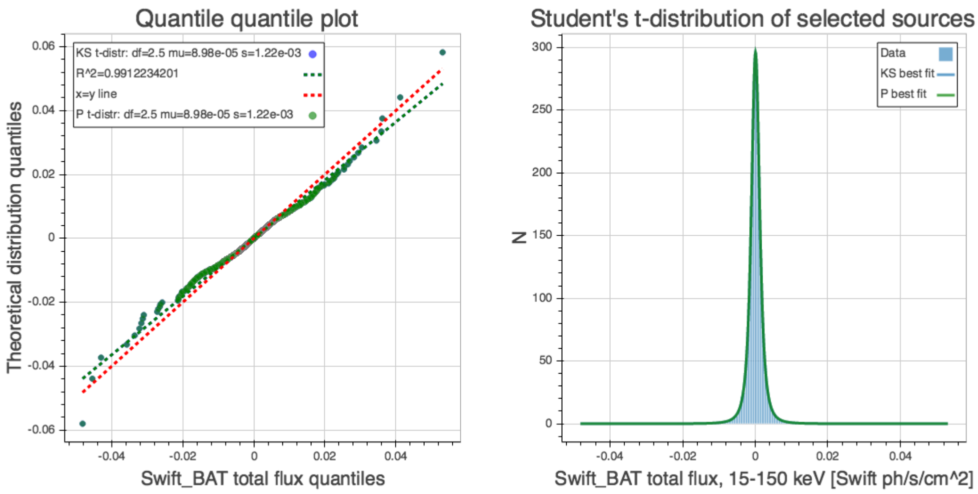


FIGURE 4.5: Distribution parameters for Swift/BAT

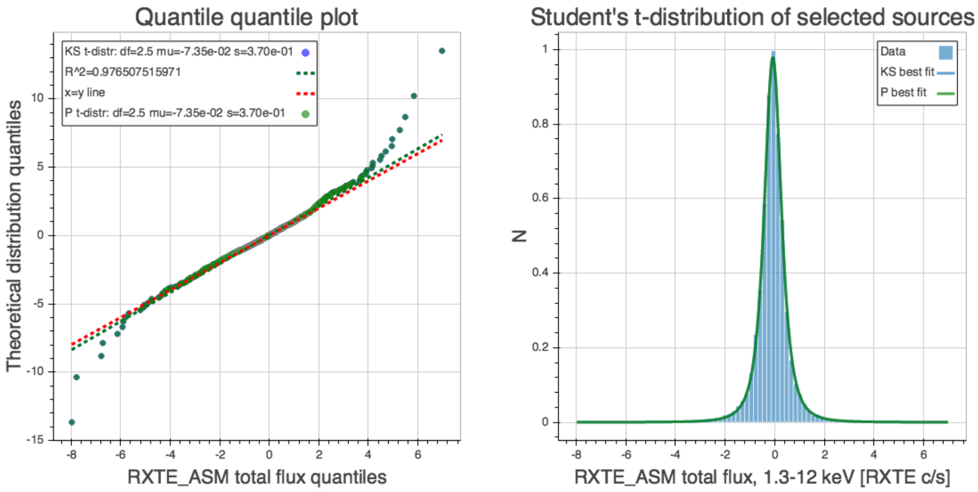


FIGURE 4.6: Distribution parameters for RXTE/ASM

The fact that a Student's t-distribution describes the background better than the normal distribution can be explained by higher errors in the datasets than is usually accounted for when using a normal distribution. Lange, Little and Taylor [39] already noted that the use of a Student's t-distribution allows a more robust statistical treatment of the data analysed, without adding too much complexity to the computation. It is also argued in this paper that the distribution and especially the degrees of freedom parameter can be estimated based on the data without adding much variance. Therefore, it seems that the found distributions can be applied to any kind of transient events detection using the found parameters.
With this, the transient detection algorithm can now be used to find active states.

4.2 Transient event detection

As explained in chapter 2, by knowing the background distribution, it is now possible to identify and quantify the likelihood that a measurement is a transient event by building the likelihood ratio of the measurement with respect to the background distribution.
Because we now have the parameters of the distribution, it is possible to calculate this quantity automatically. For this, I use the description of the Student's t-distribution, that is equation 2.7 with found parameters, as well as the likelihood ratio, like in equation 2.3. It is now necessary to define a threshold of detection in order to discriminate between transient and background events. For the study on the activity of the sources, I chose a threshold of 0.005 in order to get a very accurate detection. In other words, the measurements falling in this range have a 99.5% likelihood to be transient events.
An example of detection and the two states of the observed source is given in figures 4.7, 4.8 and 4.9. The goodness of the detection method is clearly seen by the accurate detection of outbursts which are easily identified by eye in this example. The zoom further underlines the possibilities offered by this method.

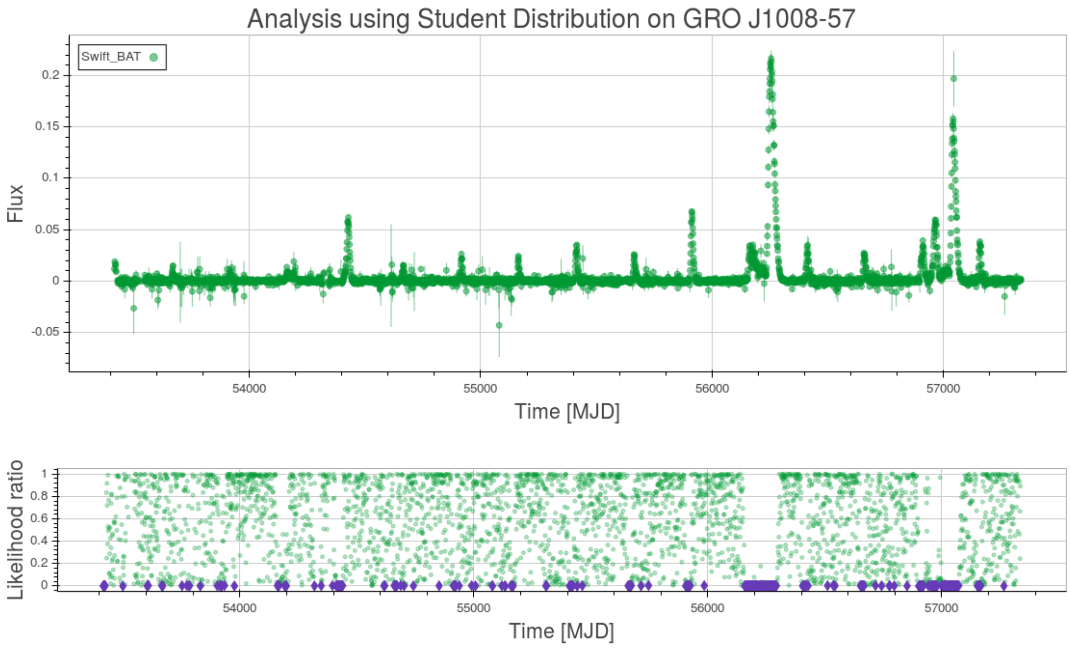


FIGURE 4.7: Example of computed likelihood ratio with a threshold of 0.005. The violet colour indicates the identification as a transient event

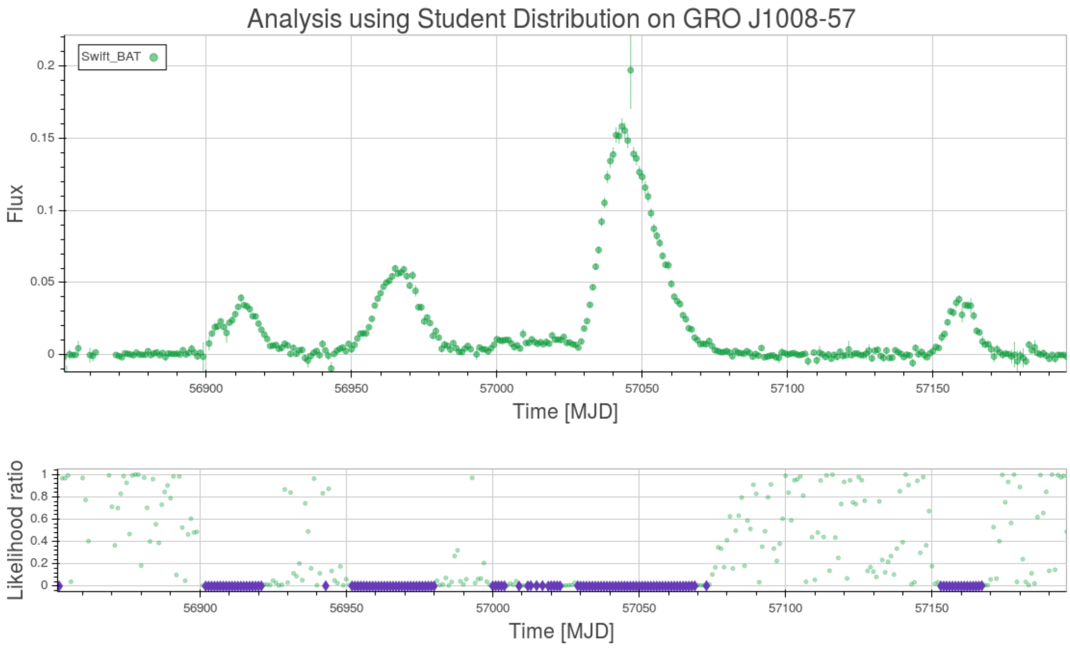


FIGURE 4.8: Zoom of figure 4.7

From the plot displaying the resulting categories of measurements, it is apparent that all negative values are also in the detected category. As the transient detection method used detects any measurements which are not in agreement with the background distribution, this is a logical consequence. Furthermore, the measurement errors were not taken into account, resulting in some doubtful detections. As a result, some filtering of the detected category is needed.
It is also interesting to observe that the beginning of an outburst also falls in the

"off" state because the flux is so low that it still agrees with the background distribution. Therefore, we concluded that the use of this algorithm for real-time event detection is not the best choice and will not replace the existing algorithm in the BeXRB monitor.

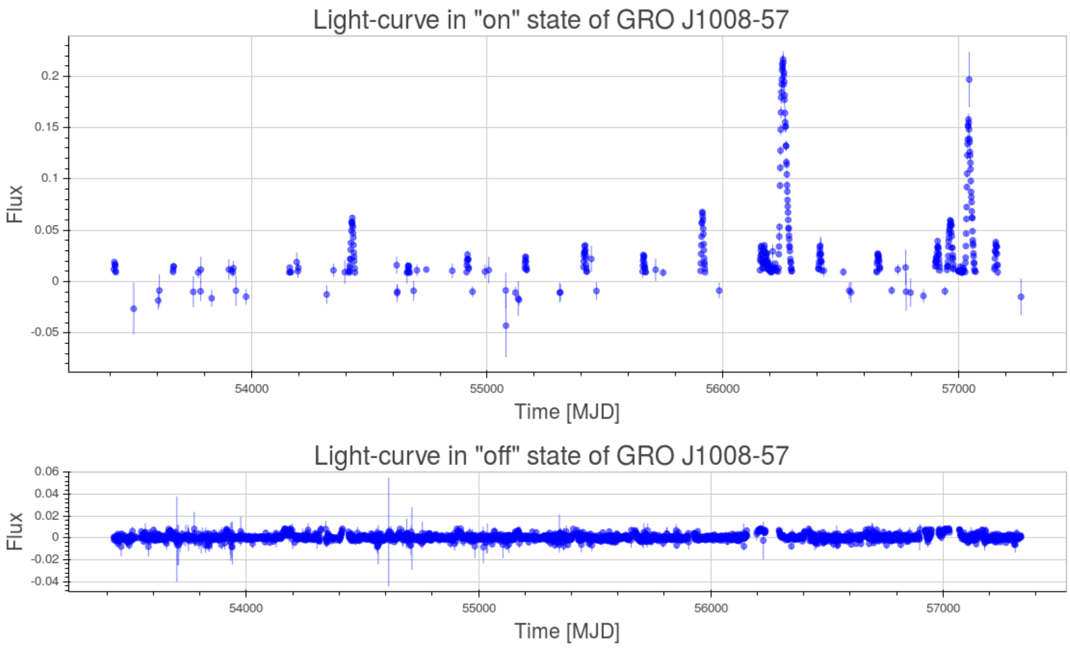


FIGURE 4.9: Display of the categorization of measurements into detected/(on) and undetected(off) state

4.2.1 Filtering

After having identified the transient events from the likelihood ratio test, some uncertainty remains on the accuracy of the detection. It arises from the measurement error of the instruments in use. To account for it, or, in other words, to discriminate measurements with large errors, the following conditions are imposed:

1. Negative measurements are ignored
2. The stand score $z = \frac{x-\mu}{\sigma}$ is computed using the known distribution parameters. All measurements with a score above 5 are kept. In other words, measurements corresponding to a 5 σ detection are retained.

The resulting difference can be observed in figure 4.10 to be compared to figure 4.9.

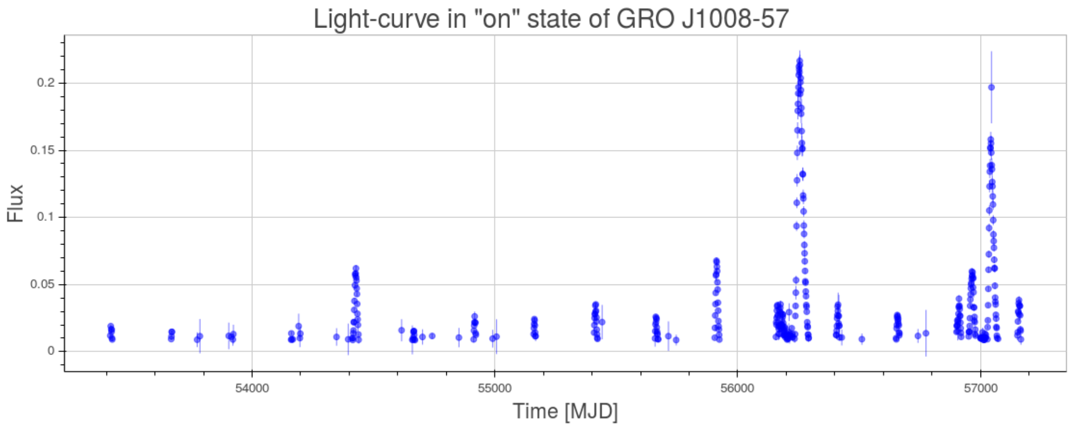


FIGURE 4.10: Display of the categorization of measurements into detected/(on) state after filtering

It can clearly be noted that the resulting light-curve is now of better quality.

4.3 Activity study

4.3.1 Duty cycle

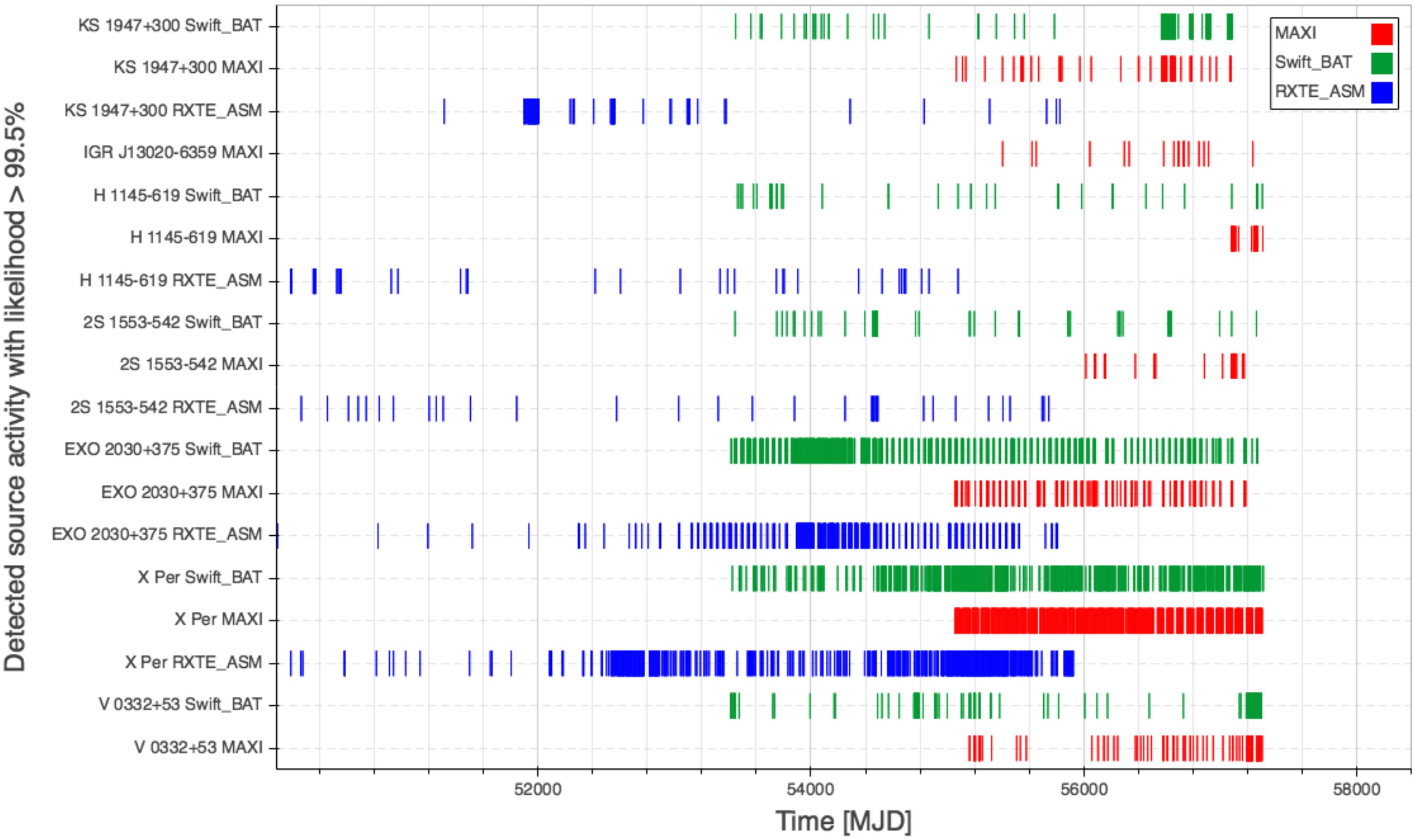
The duty cycle can now be computed for each source. As explained in chapter 2, the duty cycle is defined as the number of active events over the total number of events of a source. To make a clear discrimination between active and inactive states, a threshold of 99.5% detection probability was used. The times of activity detection for each source and the instruments with which they are observed are shown in figure 4.3.1.
The operation times of the different instruments are displayed in table 4.1 as a reference for the plots.

Instrument	Start date	Start MJD	End date	End MJD
MAXI	August 15, 2009	55058	-	-
Swift/BAT	February 12, 2005	53414	-	-
RXTE/ASM	January 5, 1996	50087	December 29, 2011	55924

TABLE 4.1: Summary of the operation dates from the different instruments used

From this plot, it can be seen that all the sources show a wide range of activity type, as known for Be X-ray binaries. It can also be clearly distinguished that most activity periods coincide between different instruments, confirming their accuracy and implying a very significant activity.

FIGURE 4.3.1 Activity per time for all sources in sample



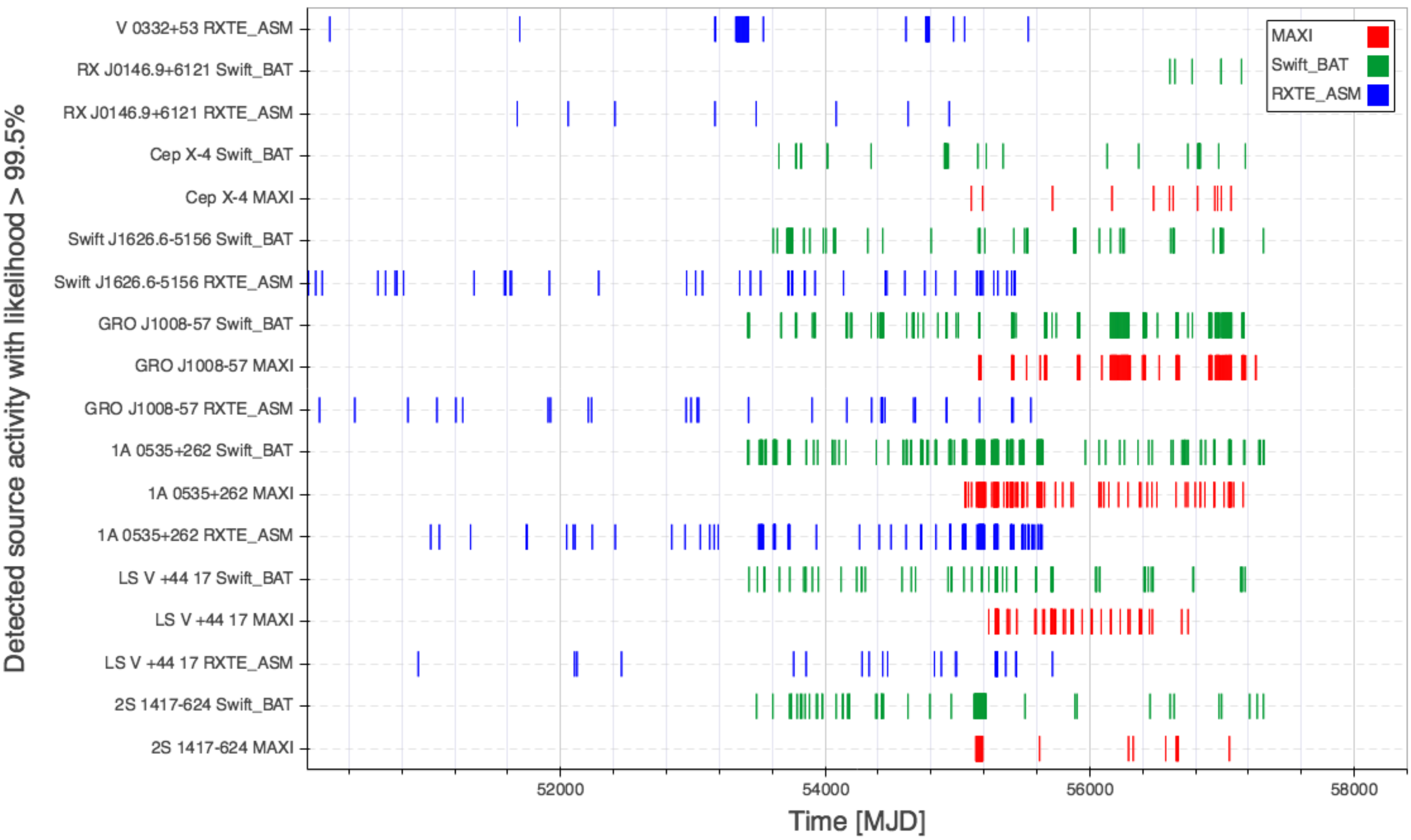
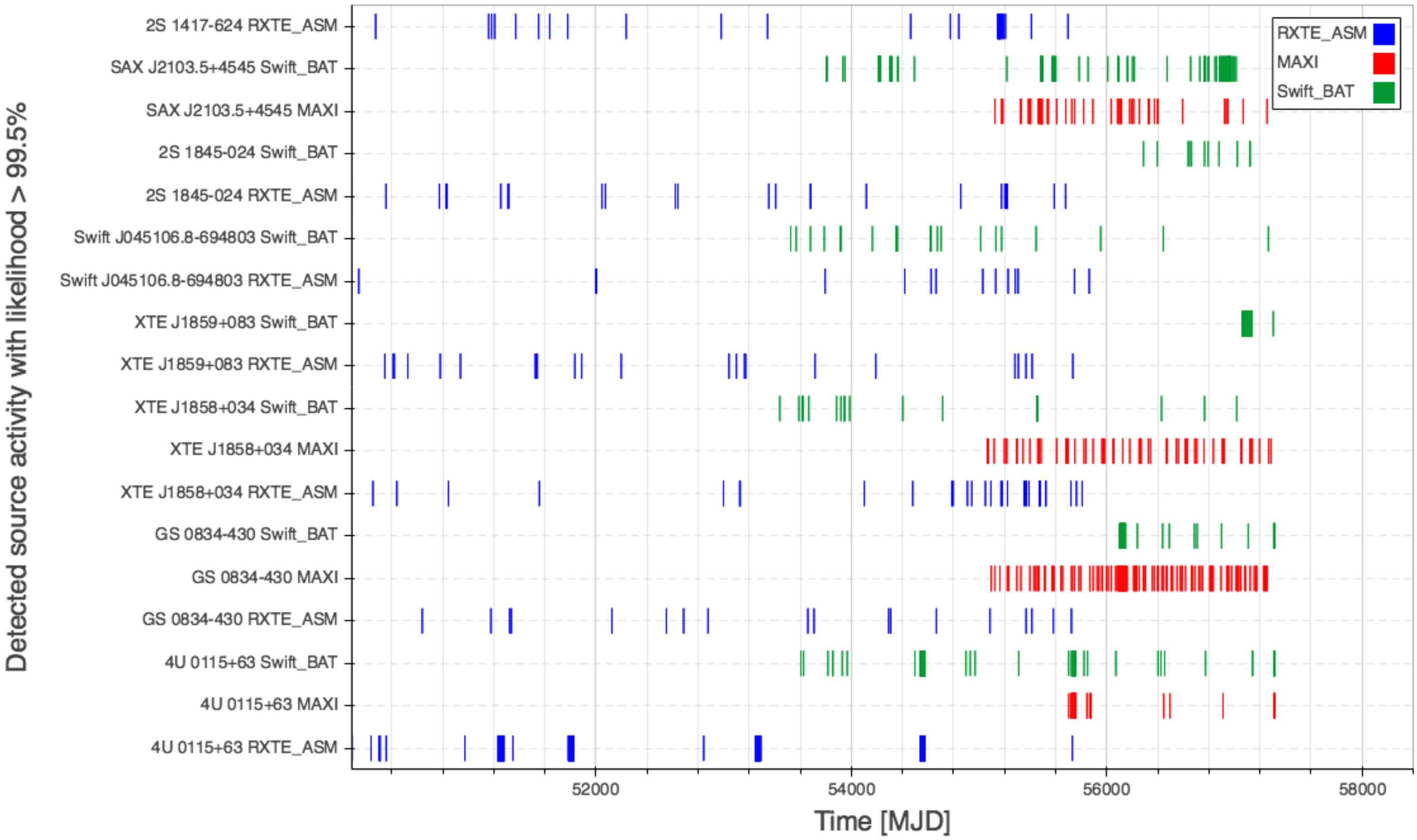
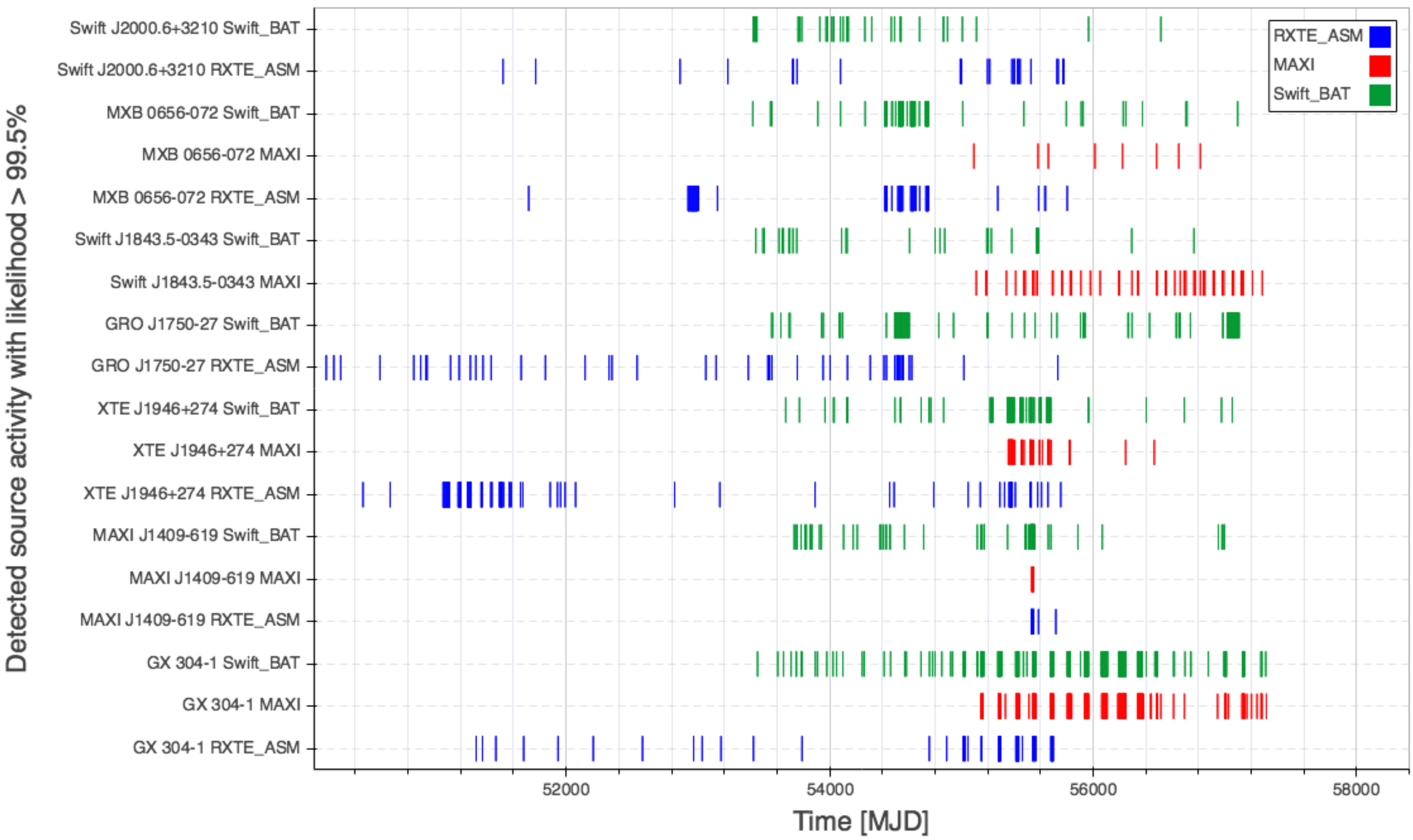
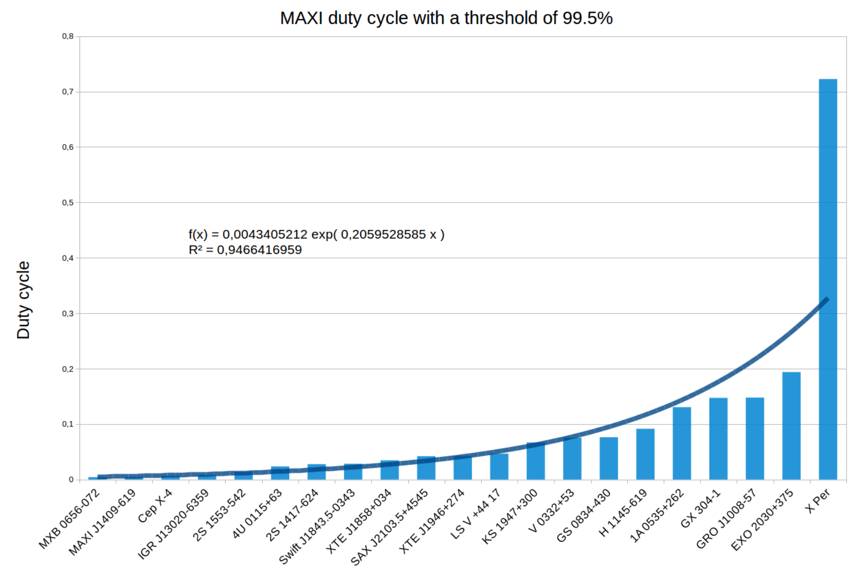


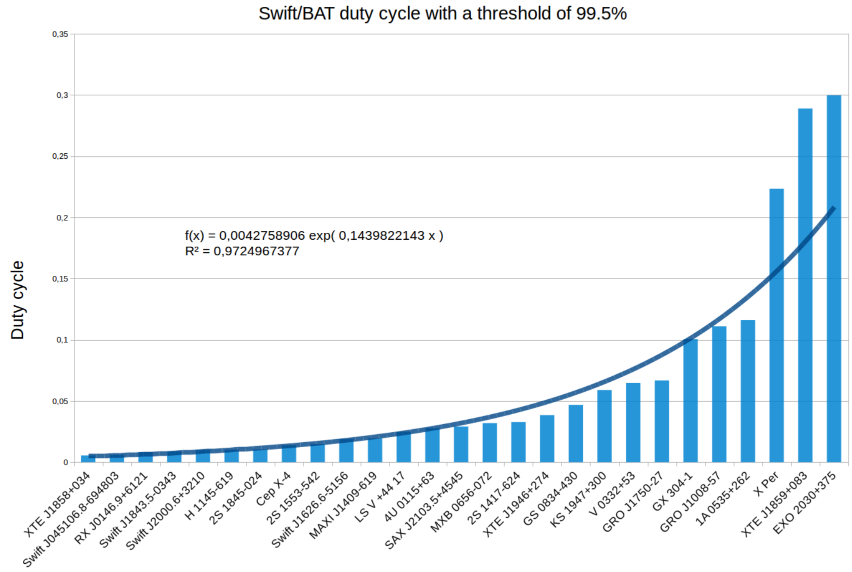
FIGURE 4.3.1 Activity per time for all sources in sample





By building the ratio of the number of measurements identified as activity periods and the total number of measurements, we obtain the duty cycle of each source and for each instrument. The resulting duty cycle distribution for each instrument is showed in figure 4.12, sorted by increasing values of the duty cycle. It is interesting to observe that a smooth exponential distribution is found, although the first assumption would have been a clustered distribution. In fact, because many BeXRBs are known to show a very frequent activity and others a less frequent one, we would expect two or more groups to be seen very distinctly and a larger similarity among sources in the groups. Remarkably, some of the most famous and well studied sources do not show a very high duty cycle, such as 4U 0115+63, because although very luminous outbursts have been observed, these occur not very often. A particular case is X Per, the only persistent source in the sample, which is classified by all instrument as particularly active, as one would expect.
The very good correlation between an exponential fit and the duty cycle distribution for every instrument points out that the selected sample displays indeed multiple forms of activity and are in different activity states. Although some sources with similar activity frequency can be found, implying a similar physical mechanism or geometrical configuration, the fact that the duty cycle distribution is exponential shows that the activity frequency depends on the same underlying physical mechanism of activity.
Because of the different time-scales of operation of all instruments, many differences can moreover be observed in the computed duty cycle. It is noticeable that the longer the time-scale of the instrument is, the lower the duty cycle. RXTE/ASM data for example, shows surprisingly low values. This is probably due to two facts: the instrument has a lower sensitivity than the others (see section 3.2.3) and there might be a selection bias in the sources studied here. The sources included in this study are particularly interesting because they have shown active in recent years and some of the sources were not active during the time RXTE/ASM was operating.





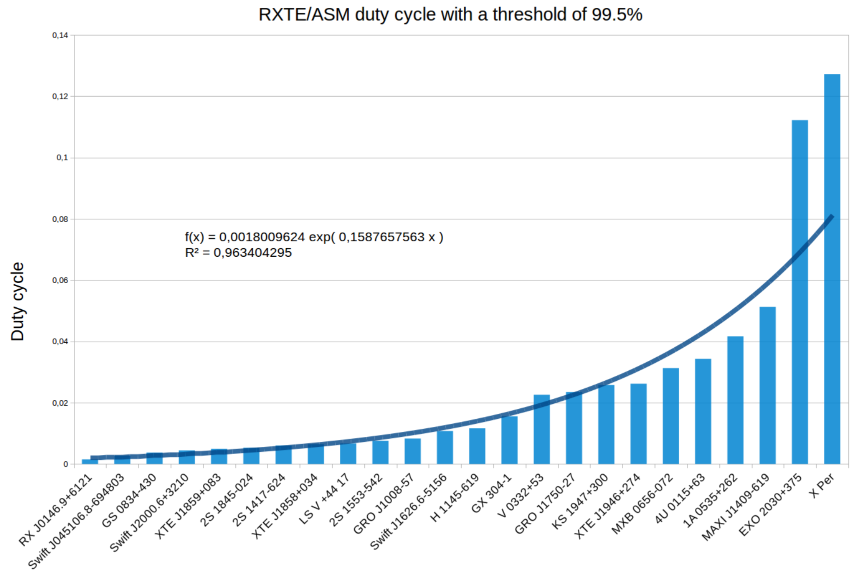


FIGURE 4.12: Computed duty cycle for each observed source in the sample and each instrument used, sorted by increasing duty cycle.

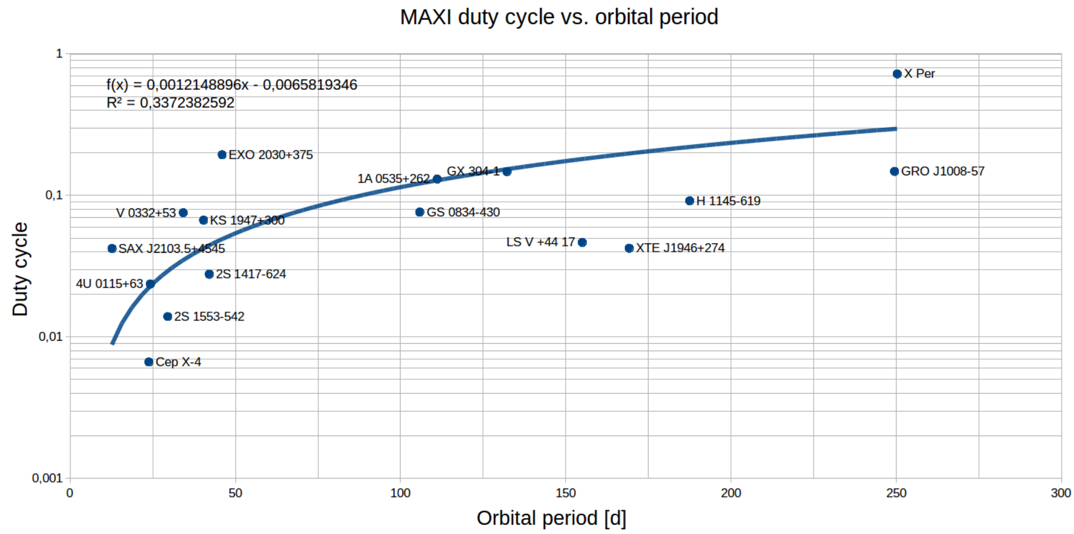
4.3.2 Duty cycle and orbital parameters

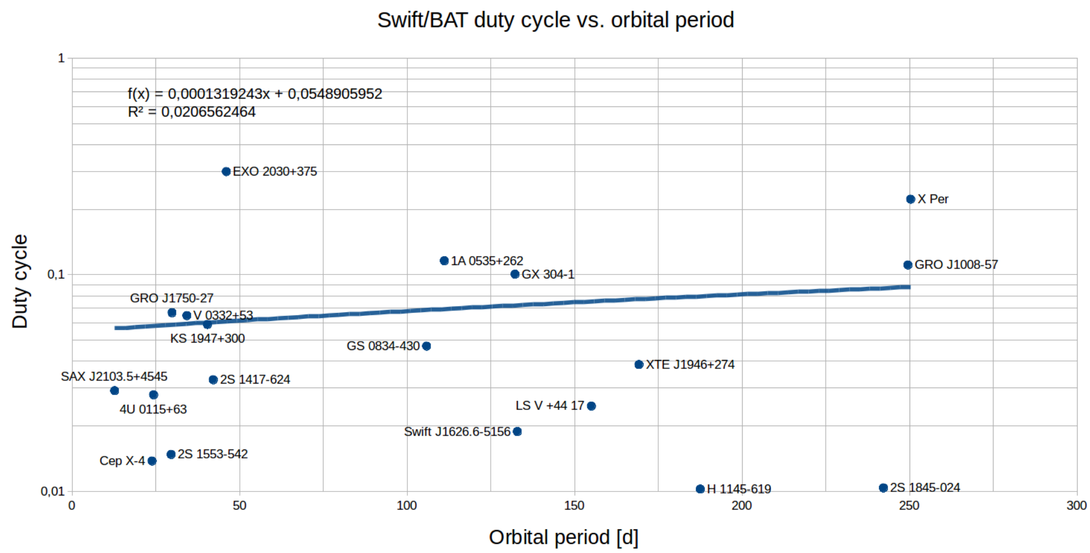
Because the duty cycle is a measure of the frequency of activity, it is natural to expect a dependency on the orbital parameters, such as the orbital period and the eccentricity of the system, since these determine the probability of accretion of matter in the circumstellar disc onto the neutron star.
After selecting sources for which these parameters have been estimated, I studied their relation with the duty cycle.

Orbital period

The Be X-ray binaries of our sample have orbital periods ranging from 12.5 days to 250.3 days. Thus, very different configurations are being studied here. Because their eccentricity is on average not very pronounced, dependencies

with the orbital period imply a relation with the role and/or position of the neutron star in the system.
The relation between the duty cycle and the orbital period is displayed in figure 4.13 for each instrument.





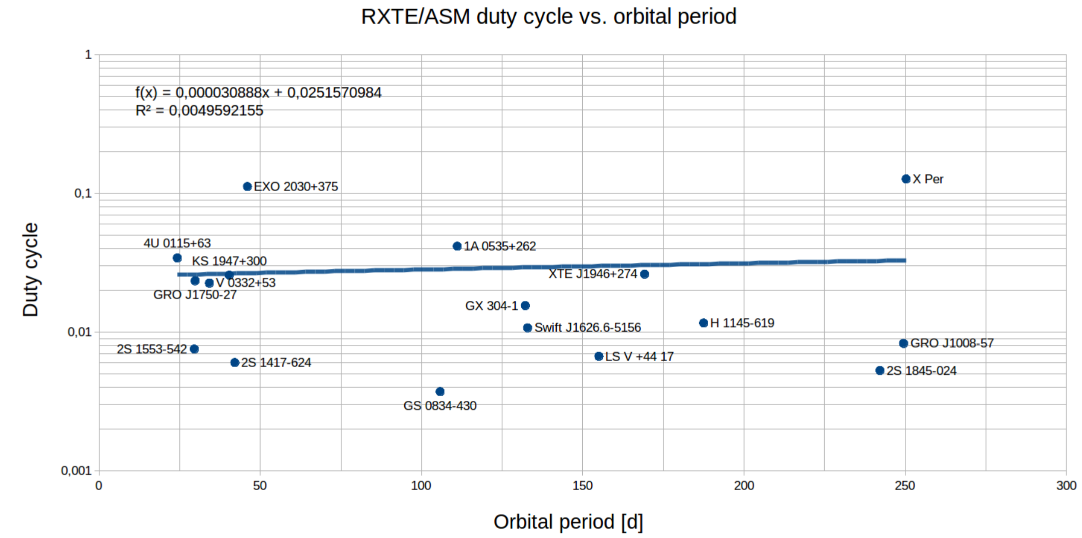
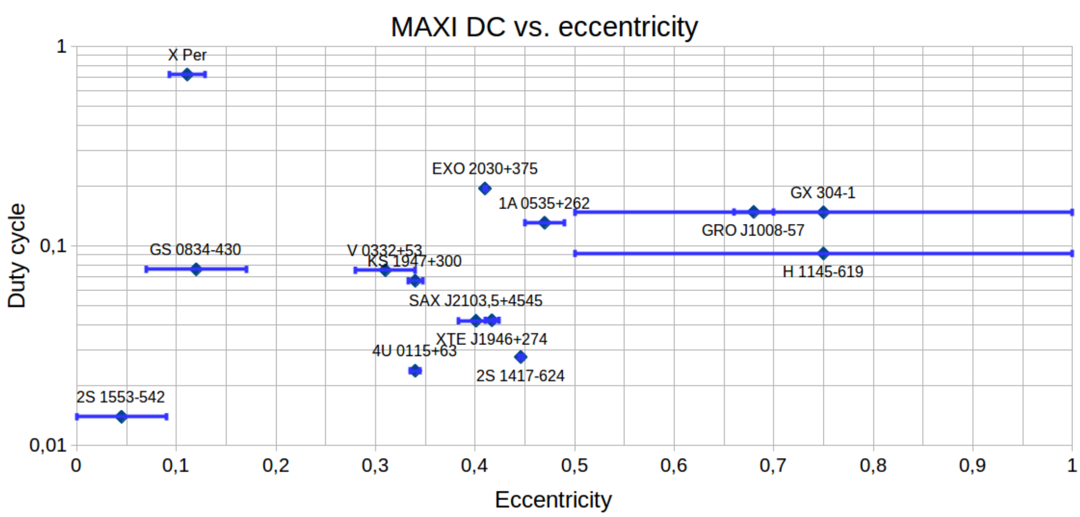


FIGURE 4.13: Relation between the duty cycle and the orbital period. A linear regression line has been plotted to indicate possible correlations.

From the obtained relation it can be observed that no obvious correlation is found between the orbital period and the duty cycle, indicating that the activity frequency is not closely related to the neutron star itself. The possible linear trend observed in MAXI is not conclusive enough by itself and further studies are necessary to understand their relation better.

Eccentricity

Another interesting orbital parameter is the eccentricity. Although very poorly known for most of the studied systems, its relation with the duty cycle of the studied sources is of importance to constrain different models of Be X-ray binaries. This relation can be observed in figure 4.14.



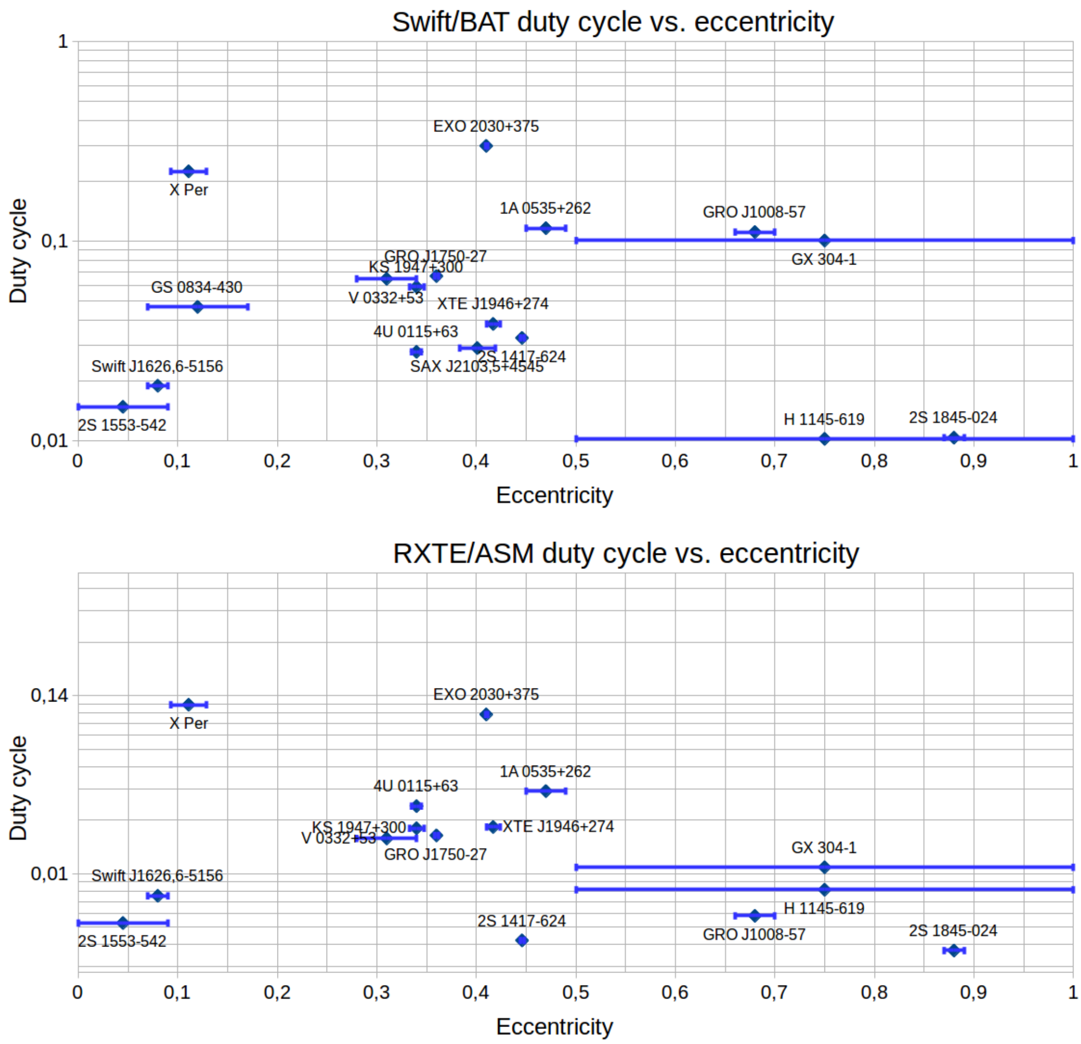


FIGURE 4.14: Relation between the duty cycle and the eccentricity.

Again, no clear correlation can be found, although some sources seem to have similar values.

Spin period

The spin period is a key property of the neutron star and a direct relation with the duty cycle would quantify the influence of the neutron star's magnetosphere on the accretion flow. The studied relation is displayed in figure 4.15.

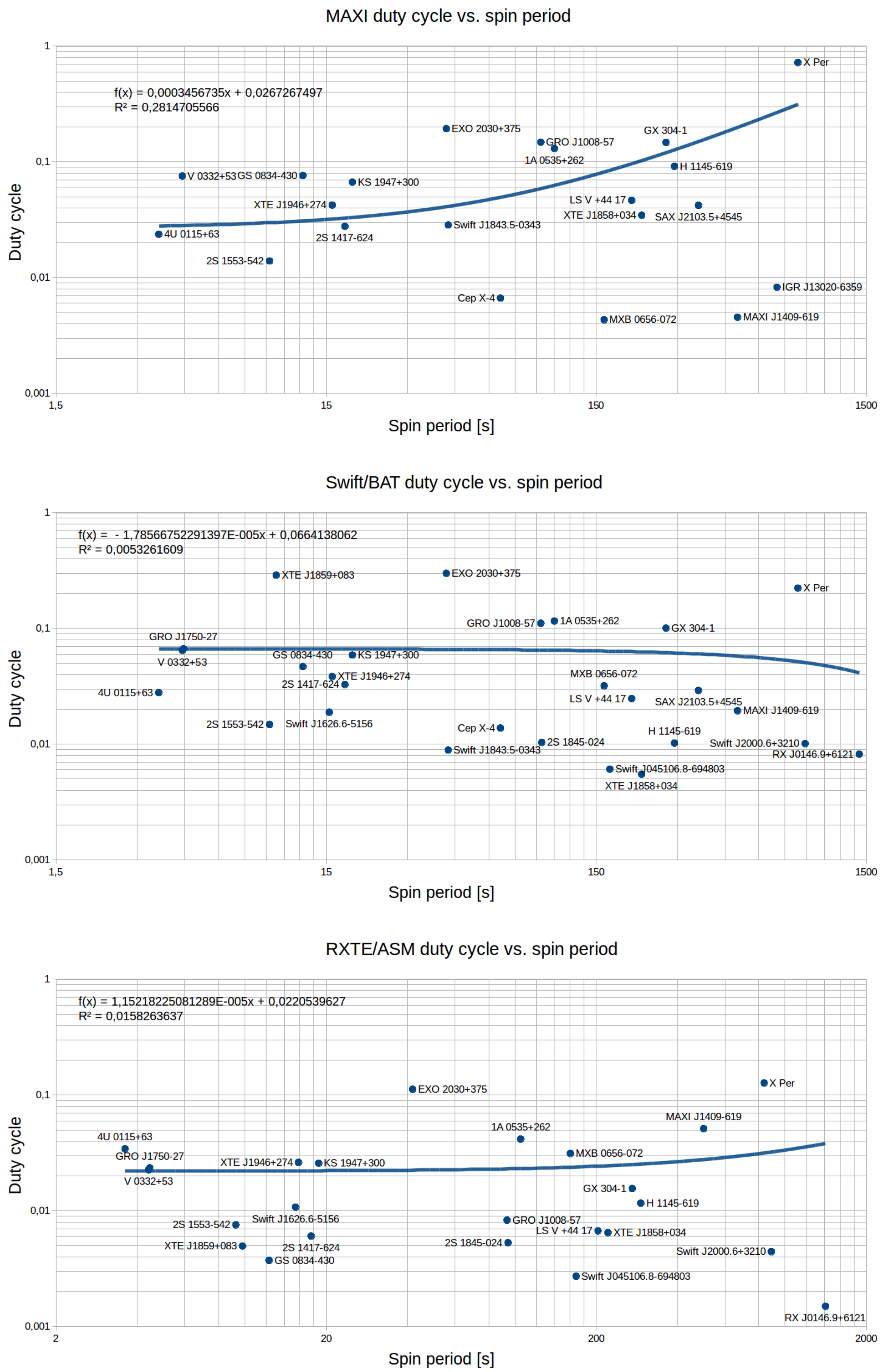


FIGURE 4.15: Relation between the duty cycle and the spin period. A linear regression line has been plotted to indicate possible correlations.

A similar trend seems to be followed by all Be X-ray binaries but no clear correlation is visible.
In summary, we do not find any correlation between the duty cycle and the orbital parameters, which is in contradiction with the findings reported in Reig [68]. A possible explanations for this difference lies in the parameter used to characterize variability. In fact, the use of the root mean square or "rms" parameter is reported in the paper, which is also sensitive to changes in the amplitude and not only in time. Moreover, the author has binned the data in a 5 days interval, loosing information about variability and possibly adding a bias leading to different results than the ones we found.
Additional studied are needed to understand the origin of these differences.

4.3.3 Luminosity

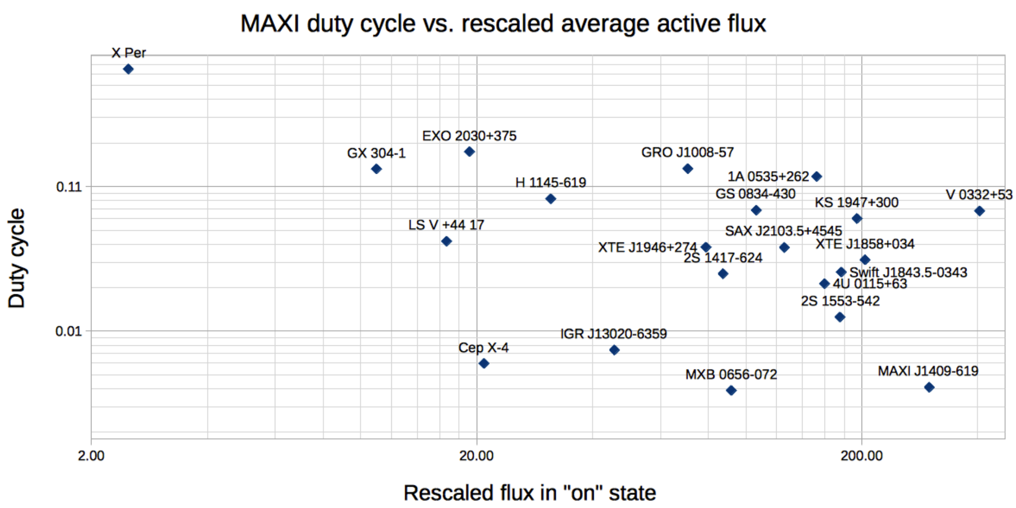
The relation between the duty cycle and the sources luminosity was also studied.
Two quantities were considered in particular: the average luminosity of the source and the maximal luminosity. The former is more related to the luminosity of type I outbursts and the latter to the importance of the type II outbursts.
In order to correct for the distance d to the sources and get a first idea of the source luminosity L, I rescaled the flux F to the luminosity with a simple distance relation assuming a spherical and homogeneous radiation:

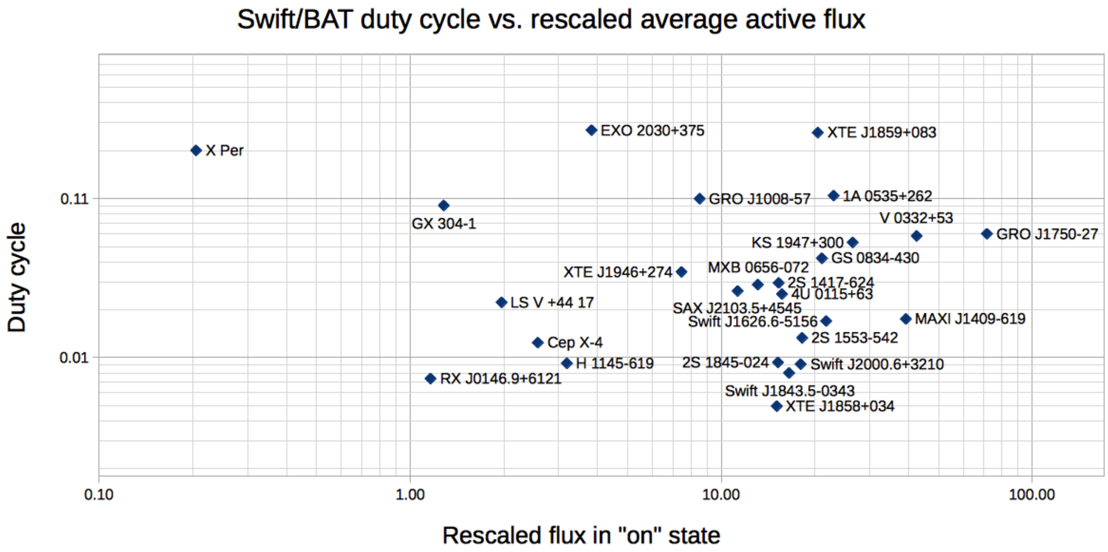
$$L = \frac{F}{4\pi d^2}$$

Because the instrument used only operate for a restrained energy band, this estimate of the luminosity (hereafter rescaled flux) is biased. Nonetheless, it provides a first correction for the source distance.

Average rescaled activity flux

The average flux of the detected states gives a first measure of the luminosity of type I outbursts, if present. Results for the different instruments can be found in figure 4.16.





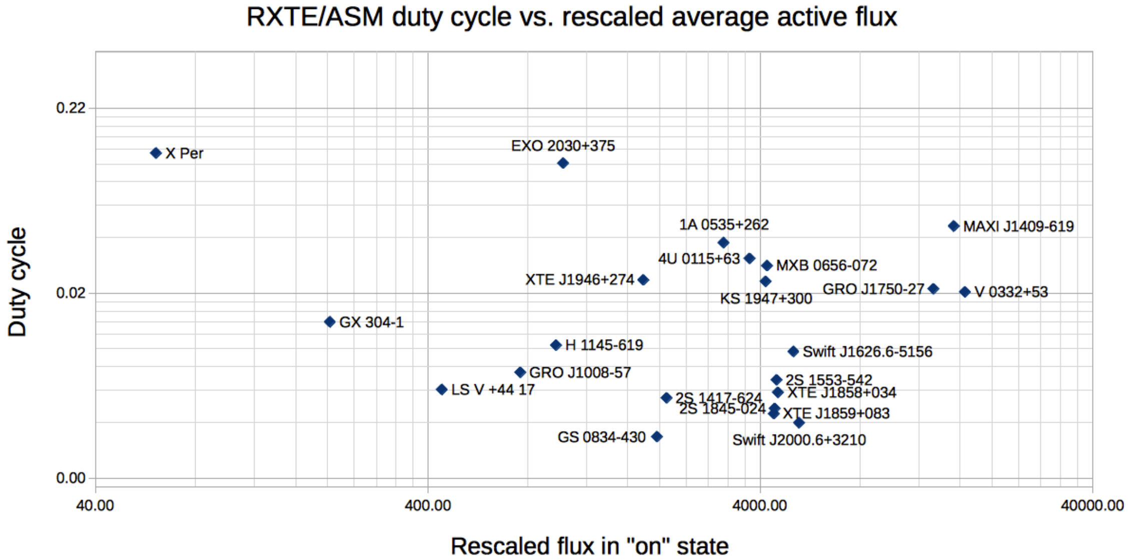
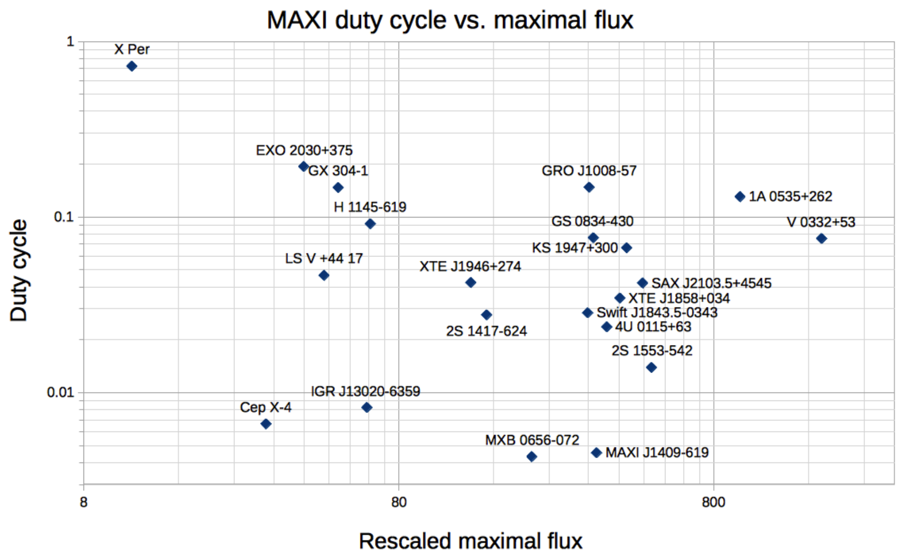


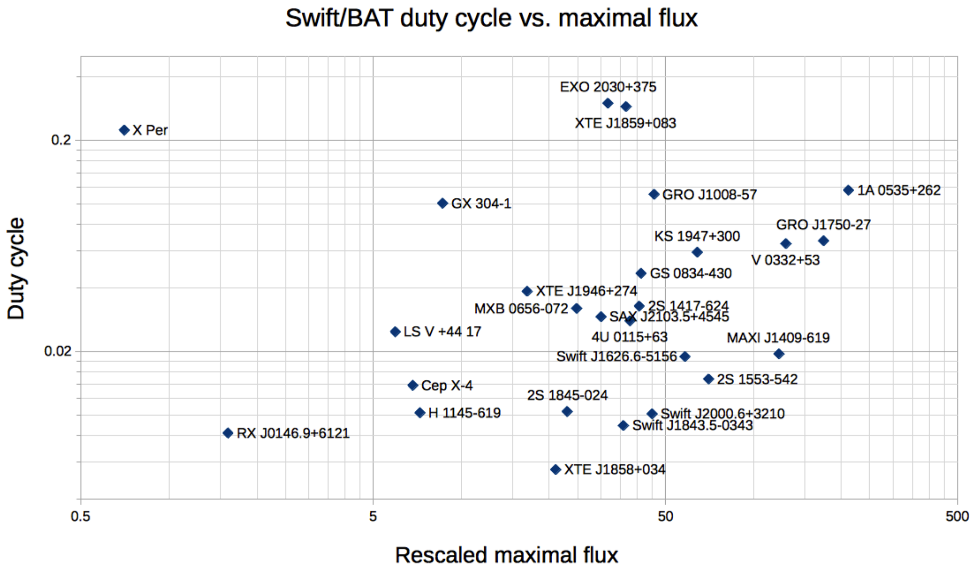
FIGURE 4.16: Duty cycle as a function of the average rescaled flux.

From this result, it is seen that no linear correlation is visible. Many sources seem to have, however a similar behaviour. It is also immediately apparent that some sources show a particularly high average luminosity: V 0332+53, MAXI J1409-619 and GRO J1750-27. For the first source in particular, it might be of interest to further investigate the mechanisms leading to this high luminosity. Furthermore, X Per shows also a very different behaviour from all the other sources, being particularly active and particularly faint at the same time. This property is a confirmation of its classification as a persistent source.

Maximal rescaled activity flux

The maximal rescaled activity flux is also an interesting measure of the activity strength. Comparing it to the activity frequency can restrain the formation and occurrence of type II outbursts. From figure 4.17, it is apparent that most of the sources have a similar relation between the maximal rescaled flux and the duty cycle. However, some sources show an extreme behaviour, in particular V 0332+53, MAXI J1409-619 and GRO J1750-27, which also show a high average flux. In addition, for the Swift and MAXI era, 1A 0535+262 shows a very high maximal flux, owing to a very luminous type II outburst in this time.





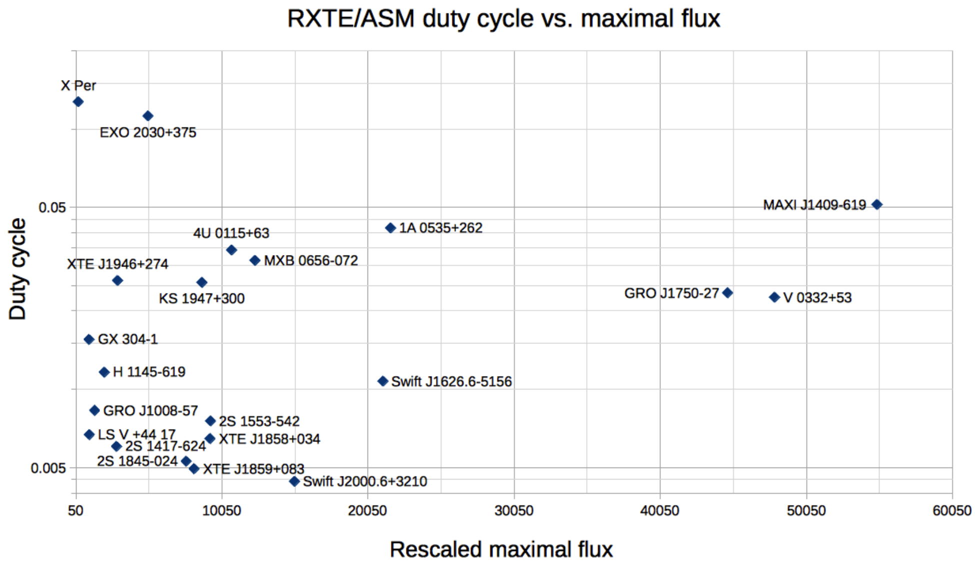


FIGURE 4.17: Duty cycle as a function of the maximal rescaled activity flux.

Average and maximal rescaled activity flux

From the similarities found in the previous studies, it is of interest to observe the relation between the average and the maximal activity flux. The average is intrinsically influenced by the maximal flux, because the maximum shifts the average to larger values. However, because of the large number of measurements, the influence of the maximum can be neglected. Finding a correlation between the maximum and the average would mean a relation between the average power of the produced X-ray radiation, related to the power of type I outbursts, and the maximal power reached, related to type II outbursts.
In figure 4.18, the resulting relation is displayed. A correlation exists in all cases and it seems very close to linear. This result suggests a relation between the type II outbursts' power and the type I outbursts' power. This can be a help to models explaining the formation of type II bursts. However, further investigation is needed.

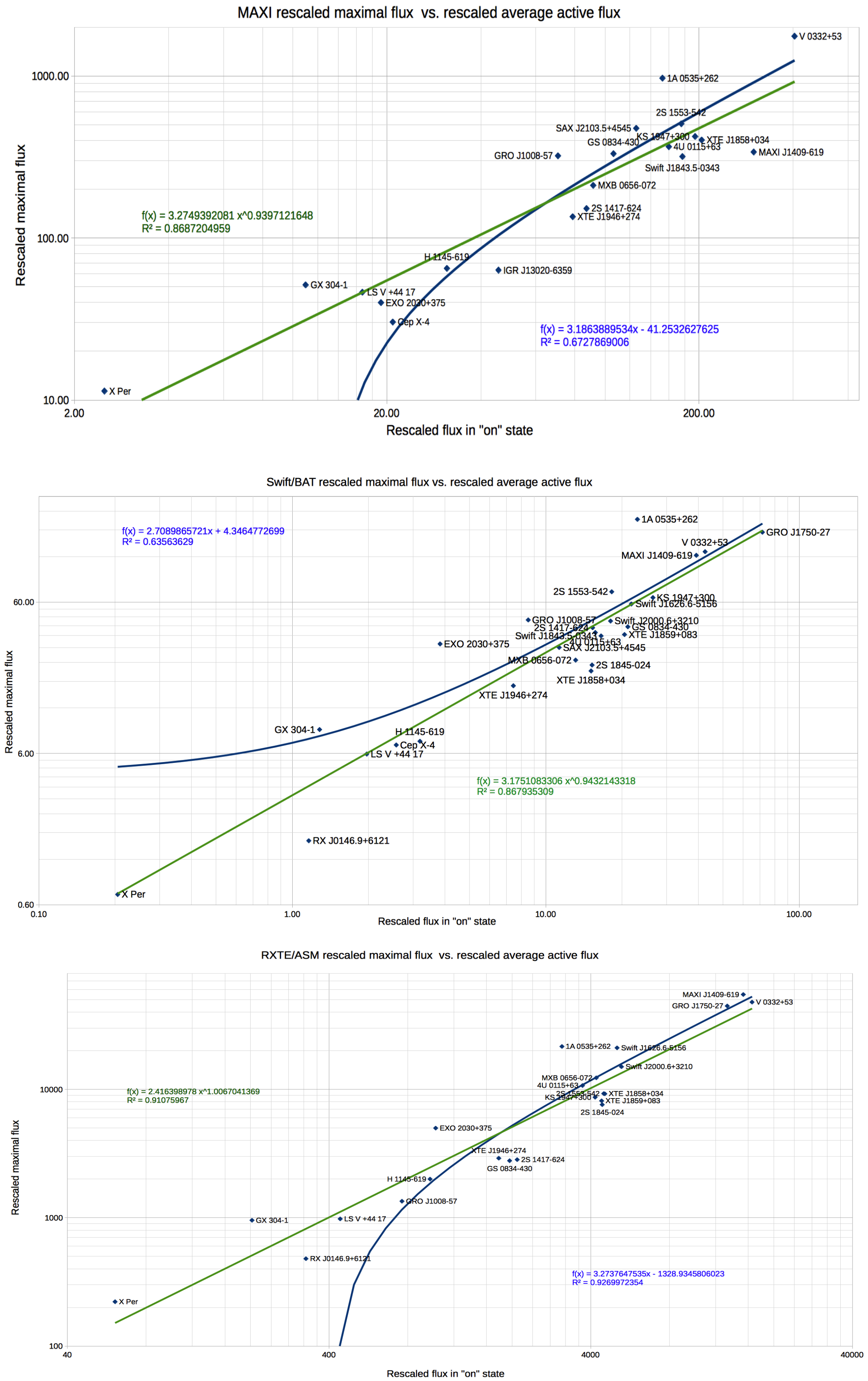
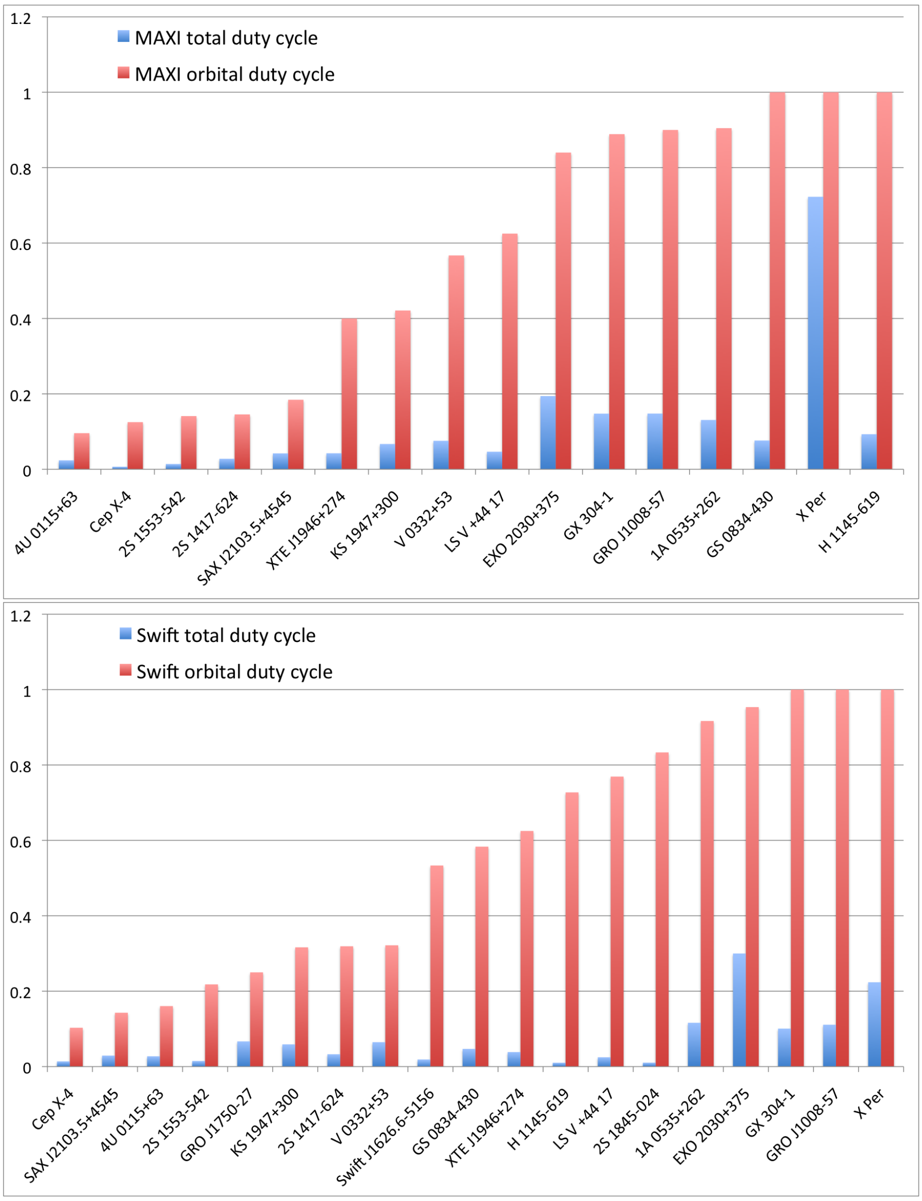


FIGURE 4.18: Maximal rescaled activity flux as a function of the average rescaled activity flux. A linear and a powerlaw trend line have been plotted to quantify the correlation found. The blue equation corresponds to the linear trend line

4.3.4 Orbital duty cycle

To understand the activity cycle of the studied sources according to the orbital period of the source, an additional quantity was computed, the orbital duty cycle. The light-curves of the selected sample were divided into sections of the length of one orbital period, while keeping periodic bursts inside each section thus defined. The selected start period and the resulting light-curve division can be seen in figure 6.2 in the appendix.
After this selection, it was possible to compute the orbital duty cycle, defined as the number of orbital periods displaying activity over the total number of orbital periods. The resulting values are displayed in figure 4.19 in ascending order as compared to the duty cycle. This quantity shows a behaviour which is closer to the expected categorisation of different sources, with many sources showing similar values and more sources categorized as always active during the observed time. It can also be noted that there is no clear correlation with the duty cycle of the sources, related to the different time-scale displayed here.



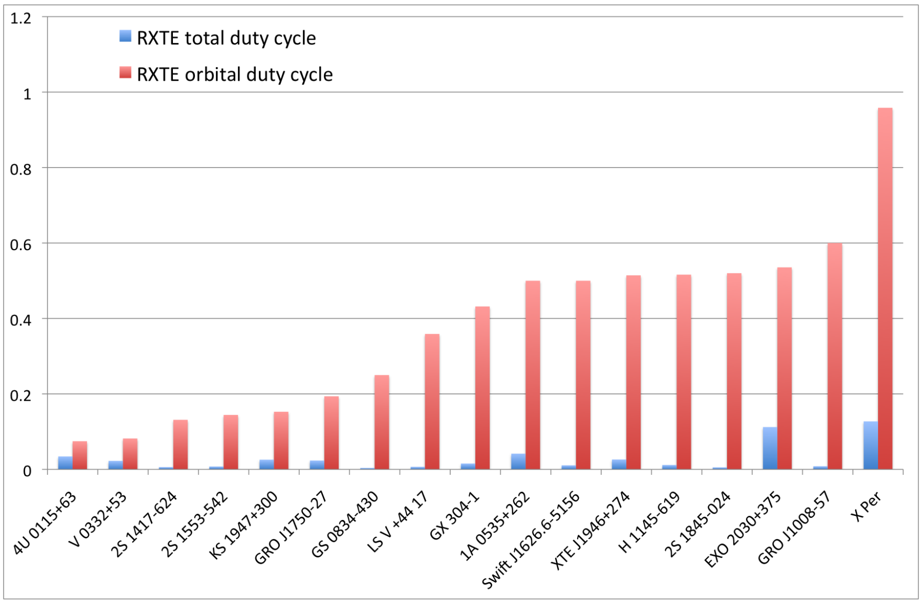


FIGURE 4.19: Computed orbital duty cycle for each observed source in the sample and each instrument used, sorted by increasing orbital duty cycle.

The dependence of the orbital duty cycle on the orbital parameters was studied, but no concluding results have been found.

4.4 Relation with the magnetic field

An additional interesting question is the relation between the sources and the magnetic field. For many sources, the magnetic field can be simply calculated using the measured cyclotron line (equation 2.15). It is important to keep in mind that the magnetic field strength, estimated on the basis of the cyclotron lines seen in the spectrum of the source, can be biased due to gravitational red-shift and uncertainties on the region in which the line is formed. The gravitational red-shift was neglected in this study.
Only estimates of the magnetic field strength based on the cyclotron line were used here.

Duty cycle

The comparison between the duty cycle and the calculated magnetic field strength can be found in Figure 4.20.

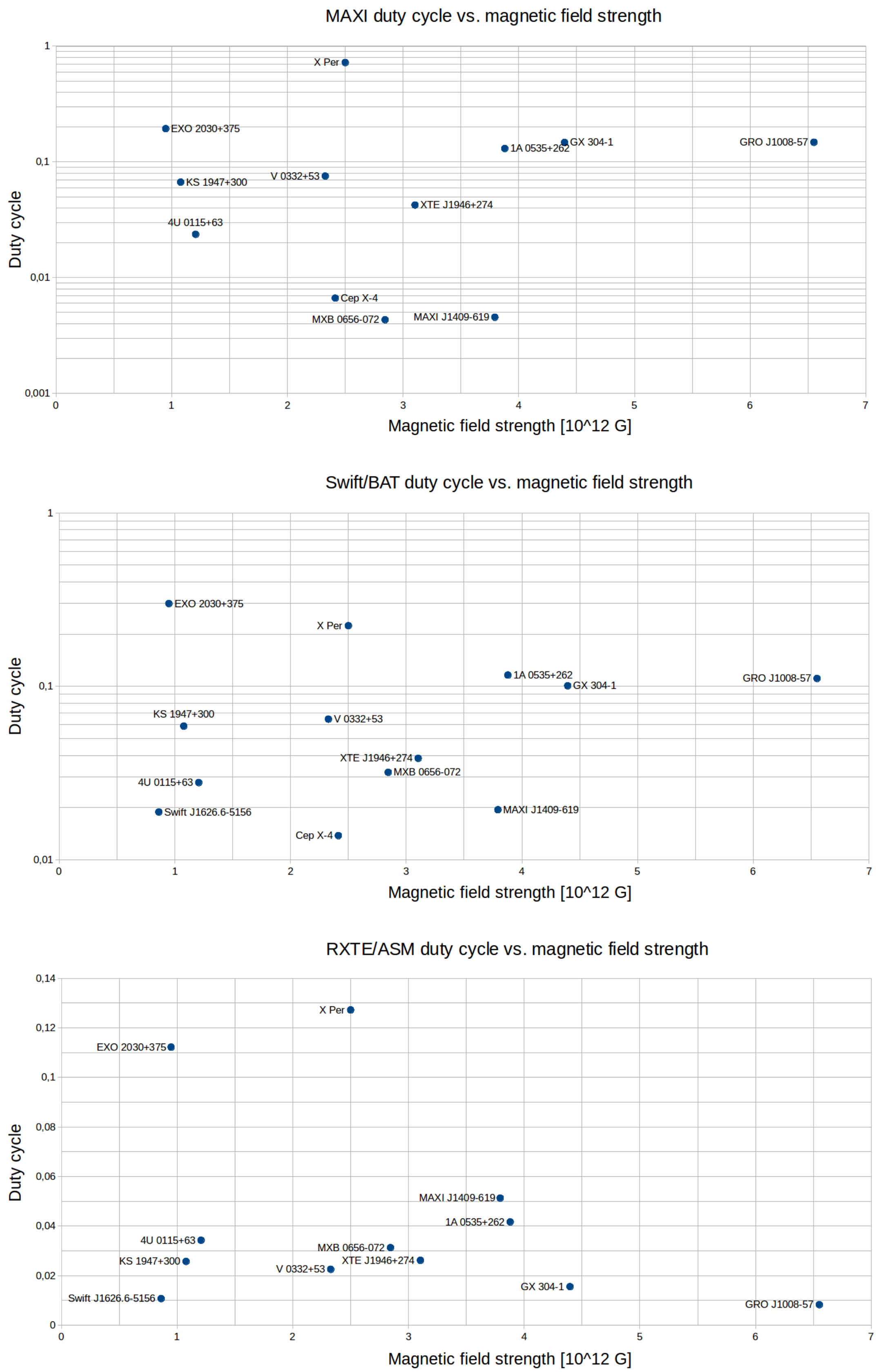


FIGURE 4.20: Relation between the duty cycle and the spin period.

Although no clear relation can be made between the magnetic field and the duty cycle, the results of the different instruments are similar.

Orbital parameters

Using the known quantities in this sample of BeXRBs, studies of general trends between the magnetic field strength and orbital parameters can be made.
A study of the dependence on the eccentricity is displayed in Figure 4.21.

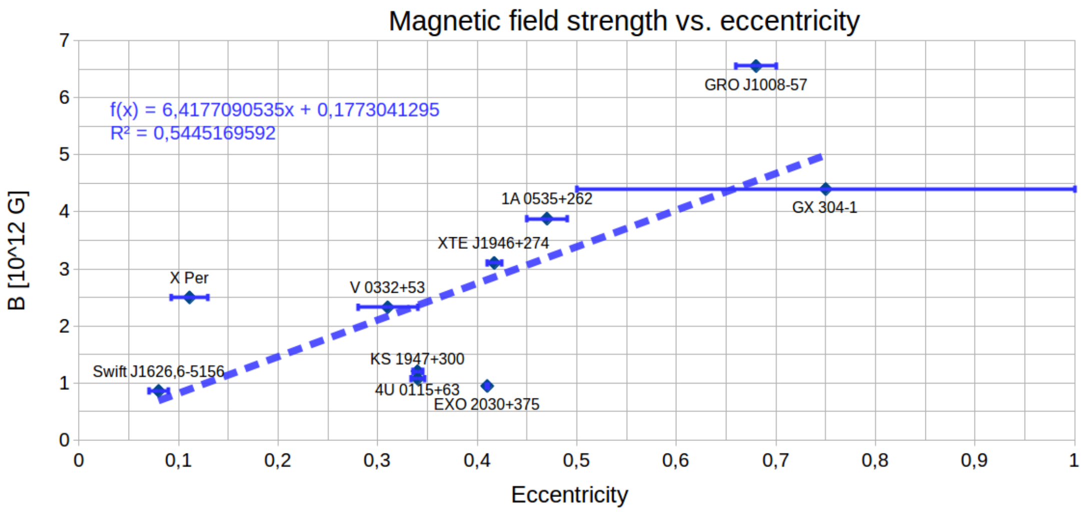


FIGURE 4.21: Magnetic field strength vs. eccentricity

From this work, it can be seen that a linear trend seems to exist between the two quantities. However, the linear relation fails for the very well determined sources KS 1947+300, 4U 0115+63 and EXO 2030+375. The similarity between these sources is quite striking.
A similar relation between the eccentricity and the magnetic field strength was reported in Yamamoto et al. [84]. This paper shows a study of the relation between the magnetic field and the eccentricity for neutron star X-ray binaries in general and has fewer BeXRBs sources. Interestingly, the sources added in this work are the ones showing a clearly different relation than the linear trend and all have a well determined eccentricity. If this linear trend was confirmed, it could help to constrain theoretical models of BeXRBs.
Doing the same study with the orbital period, Figure 4.22, a linear trend can also be seen, although not as pronounced as in the relation with eccentricity. It should be noted again that all the quantities determined here have a high degree of uncertainty associated to them.

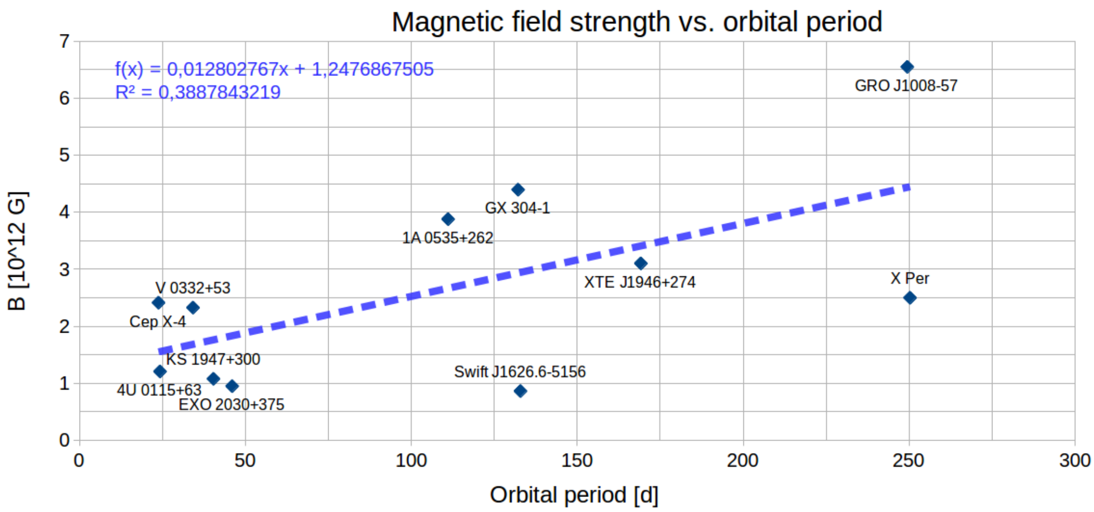


FIGURE 4.22: Magnetic field strength vs. orbital period

This could be a hint that evolutionary trends in BeXRBs are closely related to orbital parameters.
In Figure 4.23, the relation between the magnetic field strength and the spin period of the neutron star is also plotted. It is interesting to observe that not a linear trend can be seen, but a power law. There is, however, one particular source showing a different behaviour than all the other: GRO J1008-57. This is related to its record high magnetic field. Finding such a difference with other sources can help understand the origin of its very high magnetic field. Interestingly, the source agrees to the linear trend for the eccentricity and the orbital period relation.

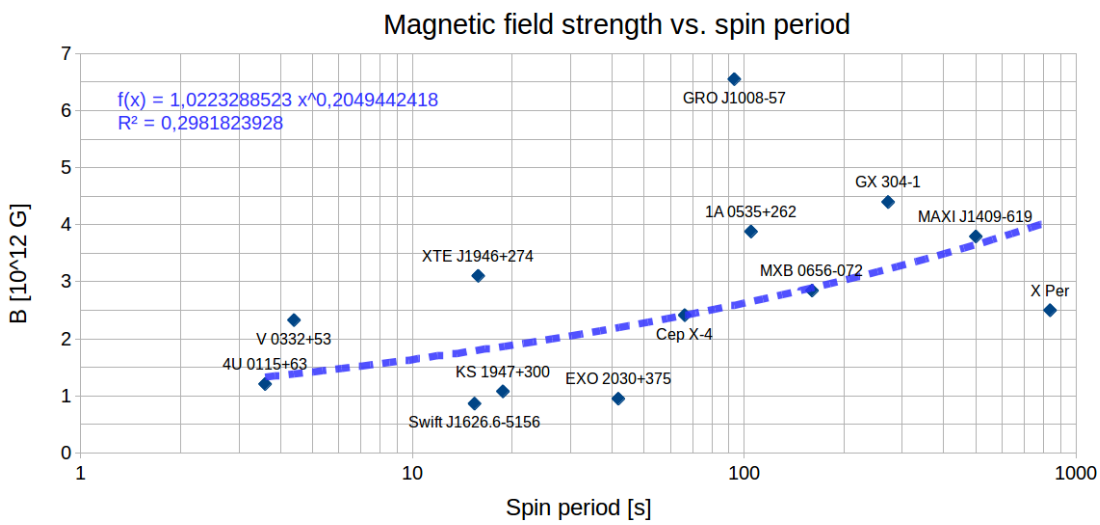


FIGURE 4.23: Magnetic field strength vs. spin period

The relation between the magnetic field and the orbital period and the magnetic field and the spin period of BeXRBs systems can also be a reference to the Corbet-diagram. In fact, the existing power law relation between the orbital period and the spin period of the systems implies a similar trend for any parameter related linearly to either of them. Nonetheless, it is interesting to observe that a linear trend is only visible between the magnetic field strength and the orbital period. This could imply a greater effect of the interaction between the circumstellar disc and the neutron star than of the neutron star itself.

Chapter 5

Discussion and conclusions

5.1 Conclusion

The main conclusions of this work can be summarised as follows:

- The flux distribution observed during the inactivity states of BeXRBs can be characterized by a Student's t-distribution and this for each of the X-ray monitors used in this study (MAXI, Swift/BAT, Swift/BAT survey data, RXTE/ASM). This is indeed a general results since we have shown that the background of other kinds of sources can be characterized as well by the same distribution.

- This distribution can be parametrized using the (weighted) standard deviation of background measurements, the weighted mean and a degree of freedom parameter which has to be determined with statistical methods.

- Using the likelihood ratio method (Belanger [7]) with the above parametrized distributions enables an accurate detection of transient events in a systematic way.

- The duty cycle of BeXRBs has been found to have a smooth distribution for all instruments used, rather than a clustered one. A distinction between persistent and transient sources clearly appears.

- No correlation has been found between the duty cycle and physical parameters (orbital period, eccentricity, spin period, magnetic field strength), contrary to what reported Reig [68]. As well no correlation has been found between the duty cycle and an estimate of the luminosity, which does not agree with theoretical models (Okazaki and Negueruela [56], Okazaki et al. [57] and Negueruela et al. [54]).

- A linear relation between the average luminosity of the system and its maximal luminosity has been found for all instruments. Although the luminosity changes with time, the relation seems to remain the same.

- The orbital duty cycle was also determined. It has a less continuous distribution and there is a good correlation between all instruments.

- A possible linear relation has been found between the magnetic field of these systems and two of their orbital parameters (eccentricity and orbital period) and a power law relation with the spin period. It confirms and extends the findings reported in Yamamoto et al. [84] for the relation with the eccentricity.

5.2 Discussion

In this work, the long-term variability of BeXRBs has been studied. I used a method for detecting transient events developed in Belanger [7]. This method, based on the statistical properties of the X-ray flux light-curves and on the instrument used, helps to determine two different kinds of source states: active and inactive. The distribution of the inactivity states (also called background) in the light-curve has been characterized. Different than expected, this distribution has been shown to be a Student's t-distribution for each of the X-ray monitors used (MAXI, Swift/BAT, Swift/BAT survey data, RXTE/ASM). This distribution can be parametrized using the (weighted) standard deviation of background measurements, the weighted mean and a degree of freedom parameter which has to be determined through statistical methods.
After determining this distribution, it has been shown that using the likelihood ratio method from Belanger [7], the detection of a transient event can be made accurately and in a systematic way.
The long-term activity of the sources has been studied systematically using the duty cycle introduced in Romano et al. [70]. The duty cycle shows a surprisingly smooth overall distribution for all instruments and has smaller values for the RXTE/ASM instrument. These arise from a combination of an apparently lower activity of the BeXRBs in the operation time of RXTE/ASM and the smaller sensitivity of this older instrument.
Furthermore, no clear correlation could be found between the duty cycle and orbital parameters, possibly contradicting the findings reported in Reig [68]. This result could be an indication that the viscous decretion disc model introduced in Okazaki and Negueruela [56], Okazaki et al. [57] and Negueruela et al. [54] has some limitations. In fact, this model predicts an anti-correlation with these parameters because the activity of a source would depend largely on the proximity of the neutron stars to the disc and the related accretion, since more matter would flow onto the neutron star, enhancing the X-ray activity.
Furthermore, the duty cycle is not related to the average rescaled flux (an approximation of the luminosity) of these systems, nor to its maximum luminosity, although groups of sources having a similar behaviour can be found. In other words, the activity frequency of the source does not seem to be related directly to its accretion rate. We would expect a relation with the geometry of the system (orbital period and eccentricity), but this has been shown not to be the case. A clear understanding of the key parameters determining the duty cycle has not yet been reached. Of course and in parallel, we have to understand whether the parameters used could have some systematic bias. Further work is needed to clarify our findings.
A linear relation between the average luminosity of a system and its maximal luminosity has been found for all instruments. Although the luminosity of the systems is different according to the operation time of the instrument used, the relation seems to stay the same. This could indicate a relation between the luminosity of type I outbursts with the type II luminosity and consequently a

relation between the usual or better average accretion rate of the system and the maximal accretion rate. This finding could help to constrain the existing models of accretion in BeXRBs.
The orbital duty cycle was also determined. Its distribution is divided in different groups. This is closer to what we expected for the duty cycle. There is a good agreement of the duty cycle between all instruments, possibly implying a characteristic time-scale of activity common to all those systems, during which similar activity frequencies can be found for different time periods. Surprisingly many systems show a very high orbital duty cycle, indicating that these systems show activity during (almost) all their orbital periods. Furthermore, the orbital duty cycle is not related to the duty cycle, showing that it is very important to define the time-scale on which activity and variability of a source is studied.
Studying the relation between the magnetic field of these systems and their orbital parameters, a possible relation has been found. This relation does not seem to hold for all of the systems, although all show similar trends. Because the calculated magnetic field of these systems still has an error due to the gravitational red-shift from the neutron star and to the uncertainties associated with the height of the production region in which the CRSF arises, this result has to be seen with caution. The implications of a confirmation of this finding would be a very good constraint for theoretical models.

5.3 Outlook

In this study, a first overview of long-term variations in BeXRBs has been obtained. As stated above, many of the findings need to be investigated further to understand these first results better. Some sources have been found to be particularly striking from their differences with respect to the other sources. X Per, the only persistent source of the sample, is different from the other sources in almost every respect and should preferably be studied as part of a different group. V 0332+53, MAXI J1409-619 and GRO J1750-27 are characterized by both very high average and maximal luminosities, and a large value of the duty cycle. To understand what could cause this difference, it would be interesting to investigate these sources further and to compare them.
Furthermore, GRO J1008-57 seems to have a completely different behaviour regarding the relation between the magnetic field strength and the spin period of the neutron star in the system. It has the highest magnetic field measured in BeXRBs and at the same time an average spin period. It would be interesting to investigate what could cause this difference.
Last, it is striking to see that the distribution of the duty cycle is so different from the expected distribution. In particular, the famous and well studied source 4U 0115+63, on which models for a BeXRB have been developed (see Negueruela et al. [54], Negueruela and Okazaki [53]) does not seem a characteristic source of the sample studied here. The use of this source as prototype for BeXRB might have led to wrong or biased assumptions about these objects.
In conclusion, this study raises more questions than it answers and more studies are needed to try to understand a little better what is going on in Be X-ray binaries.

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Chapter 6

Appendix

6.1 Example of background selection

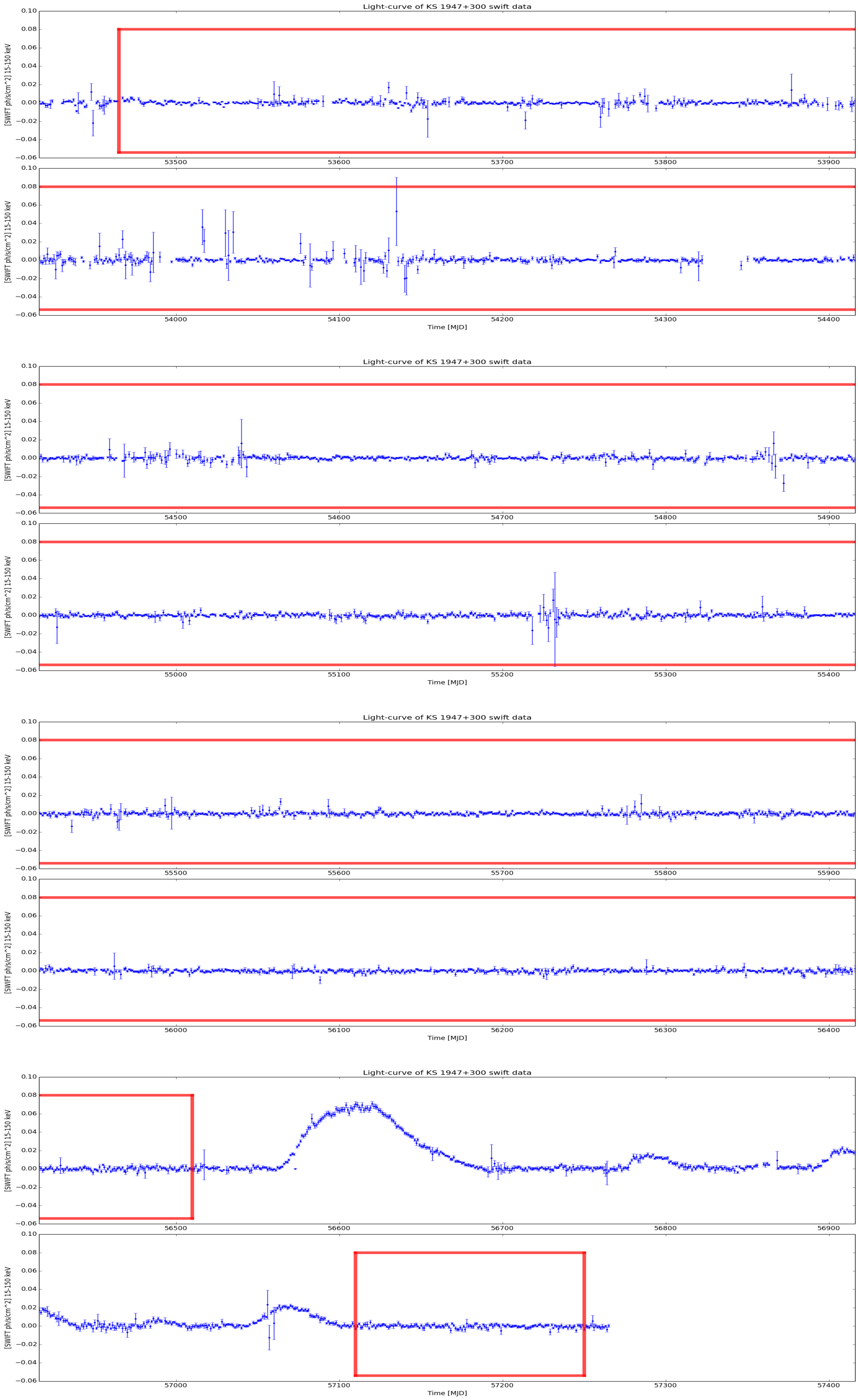

FIGURE 6.1: Example of background selection for specific source. The red boxes show which parts of the light-curves were selected as background

6.2 Active flux

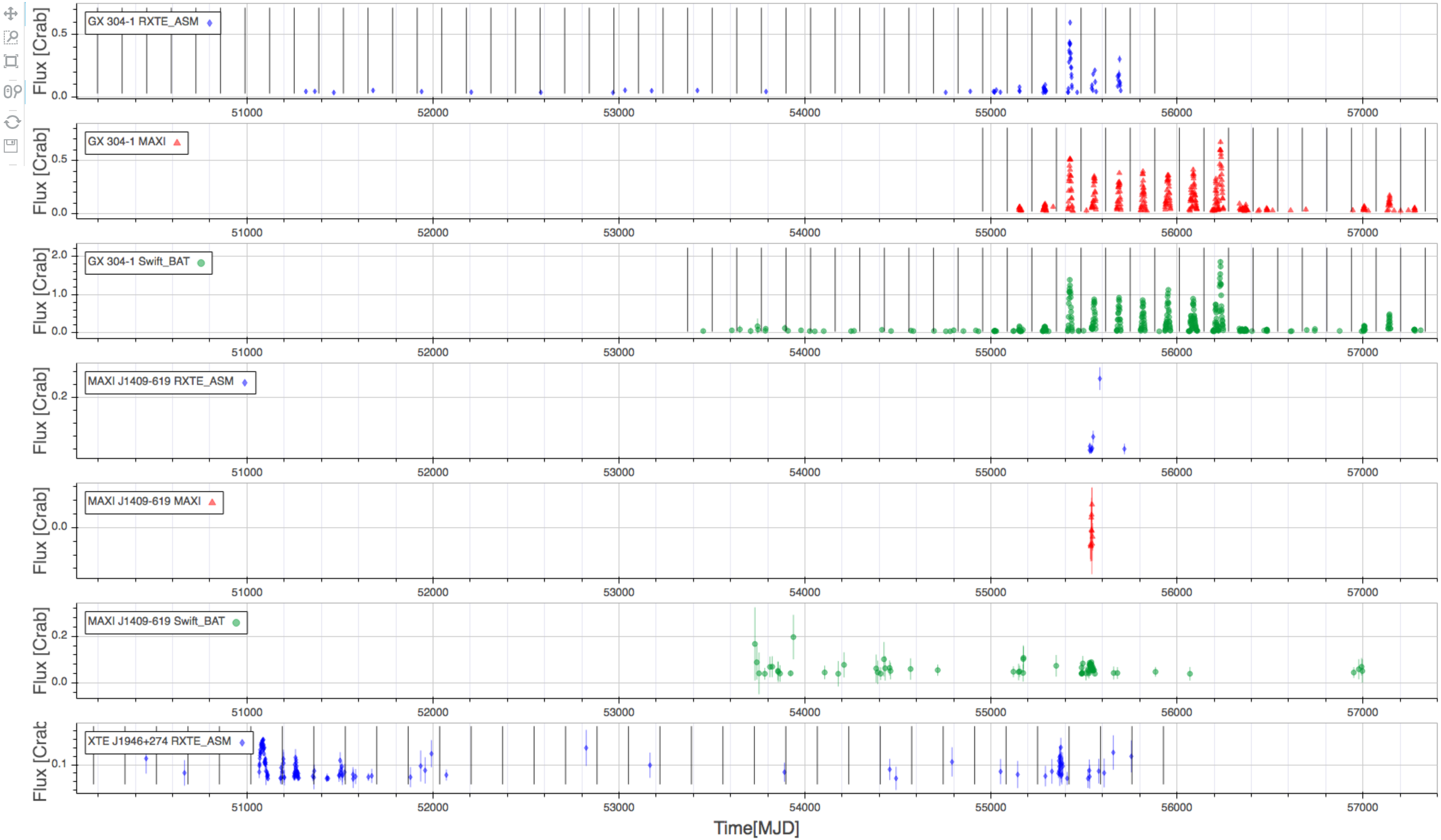

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

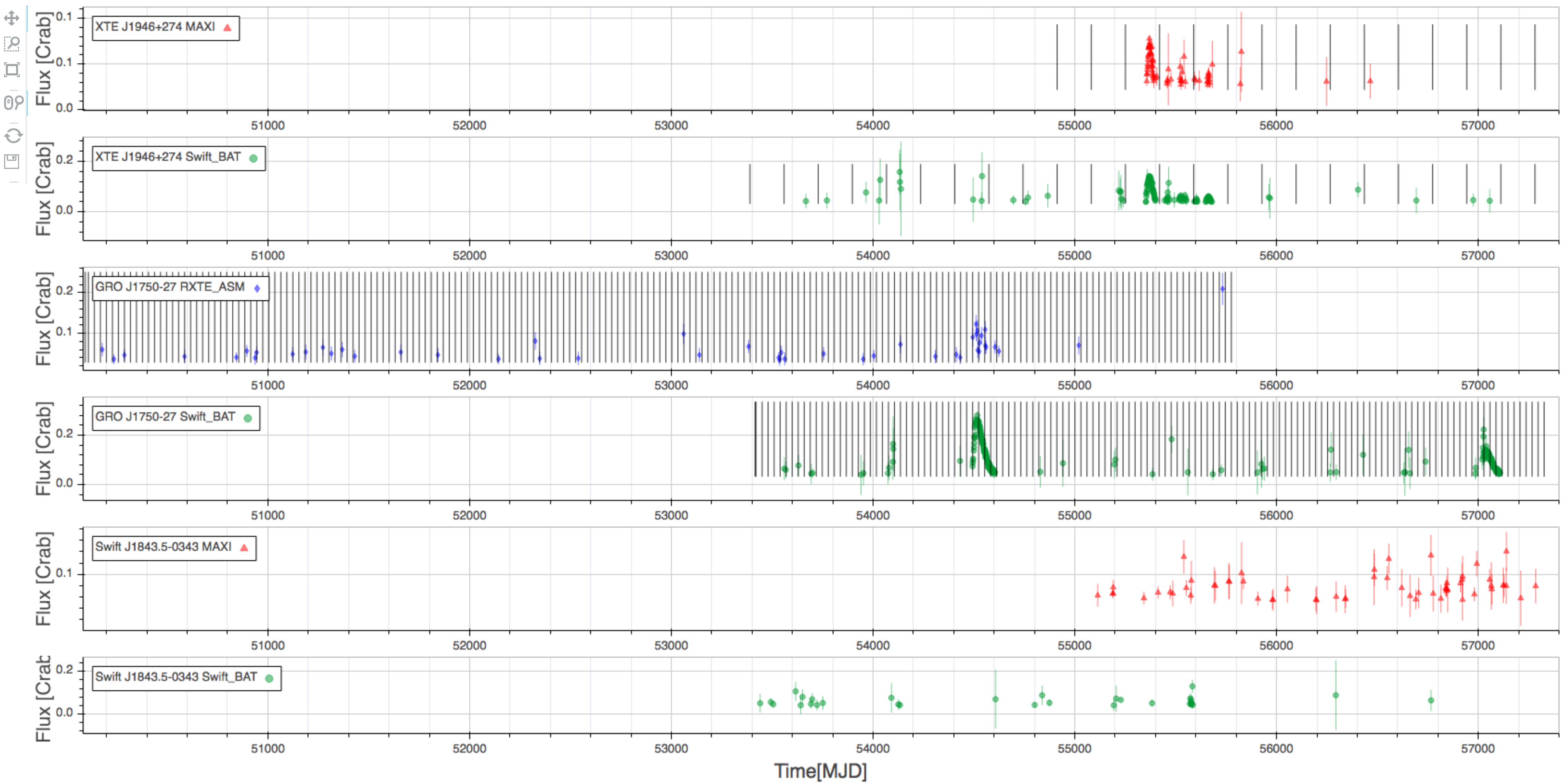

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

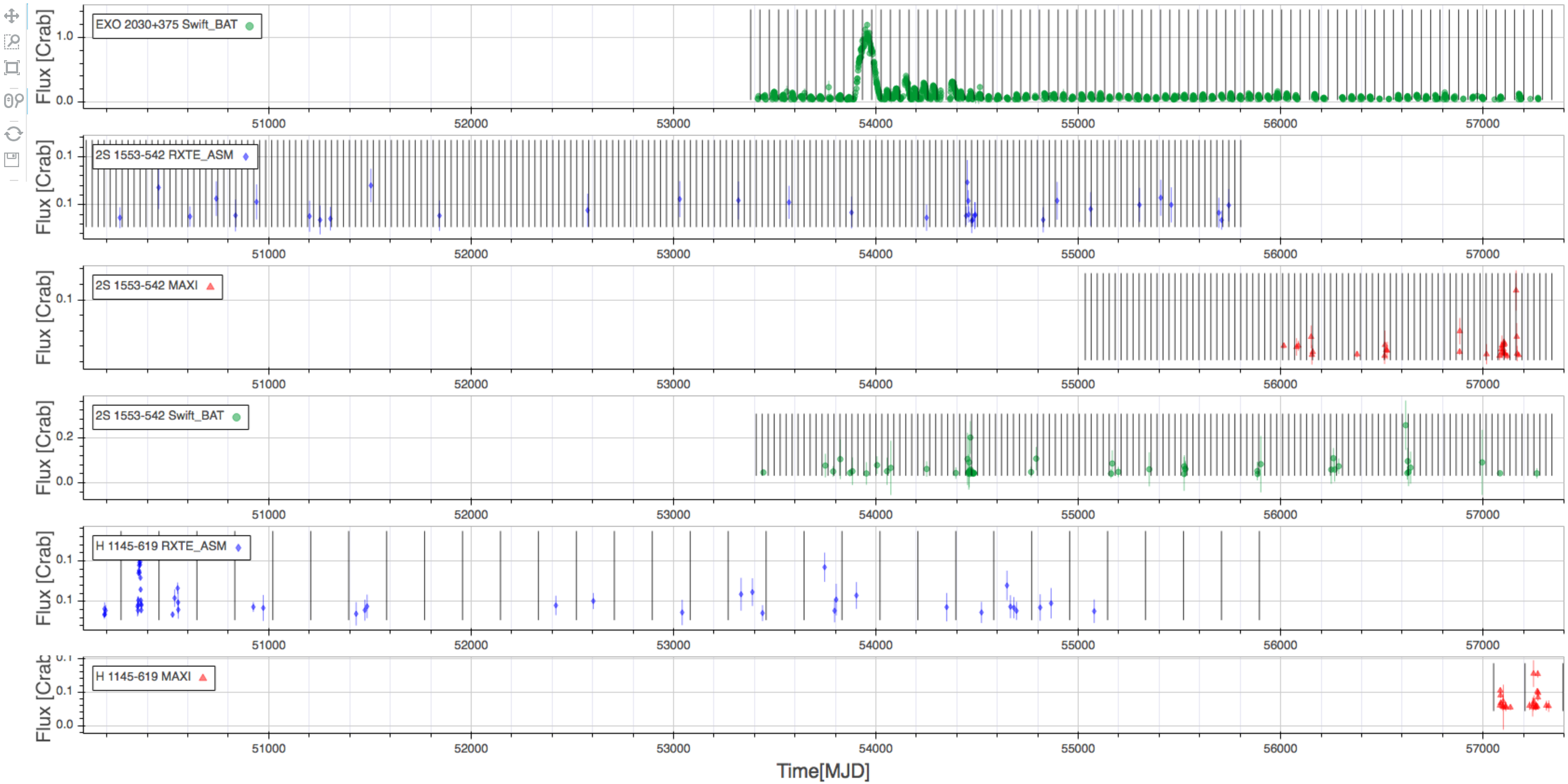

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

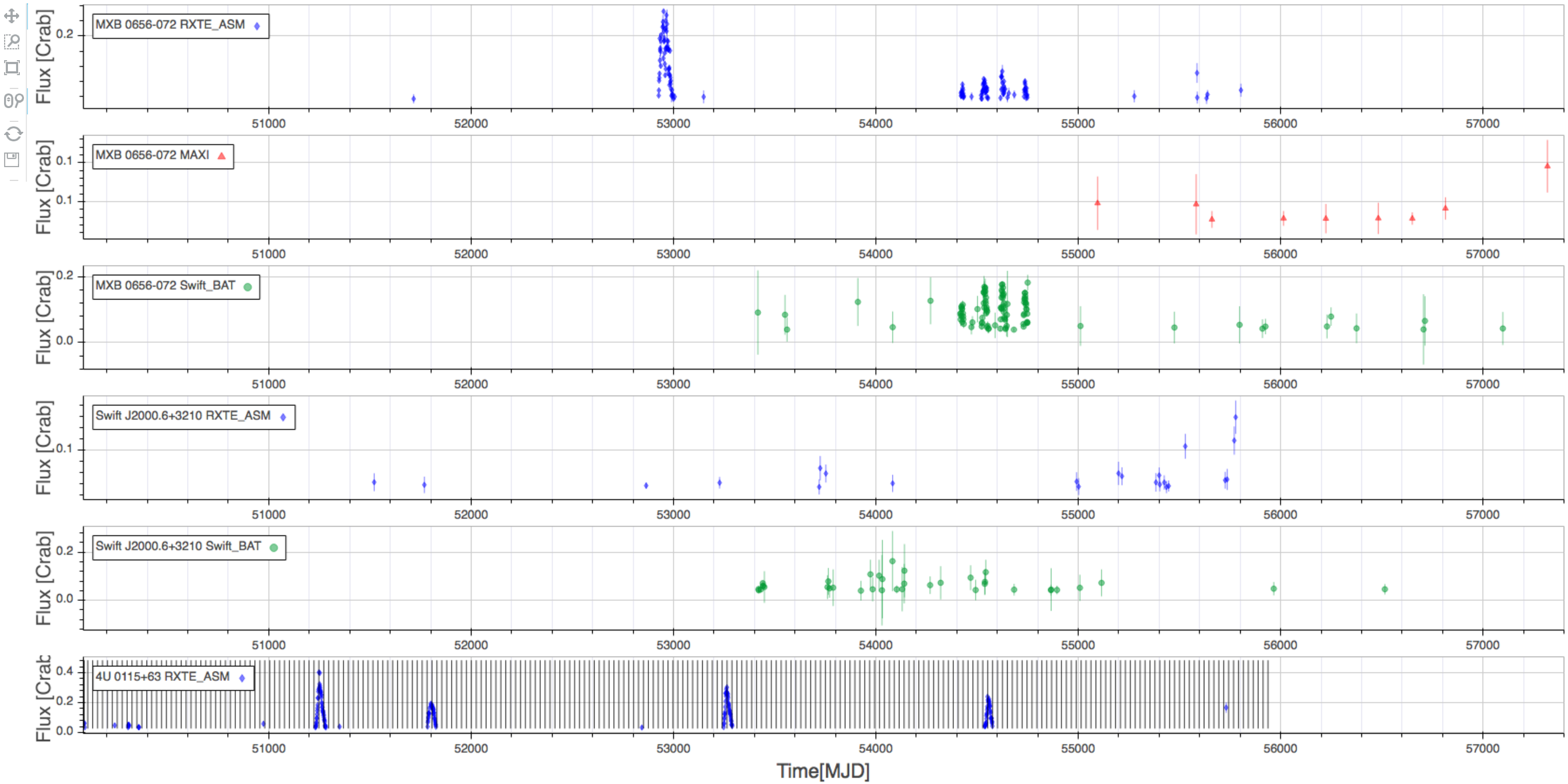

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

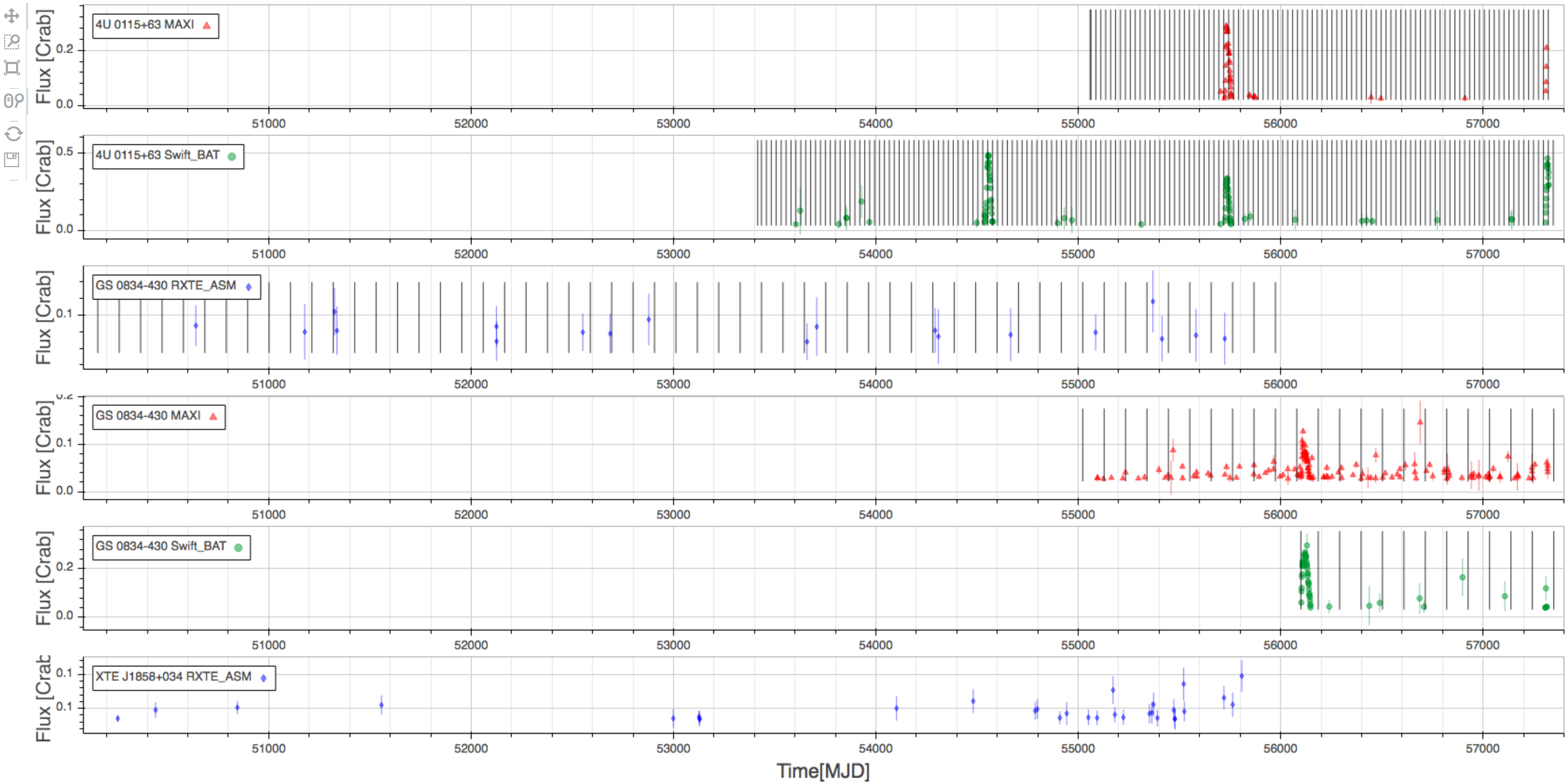

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

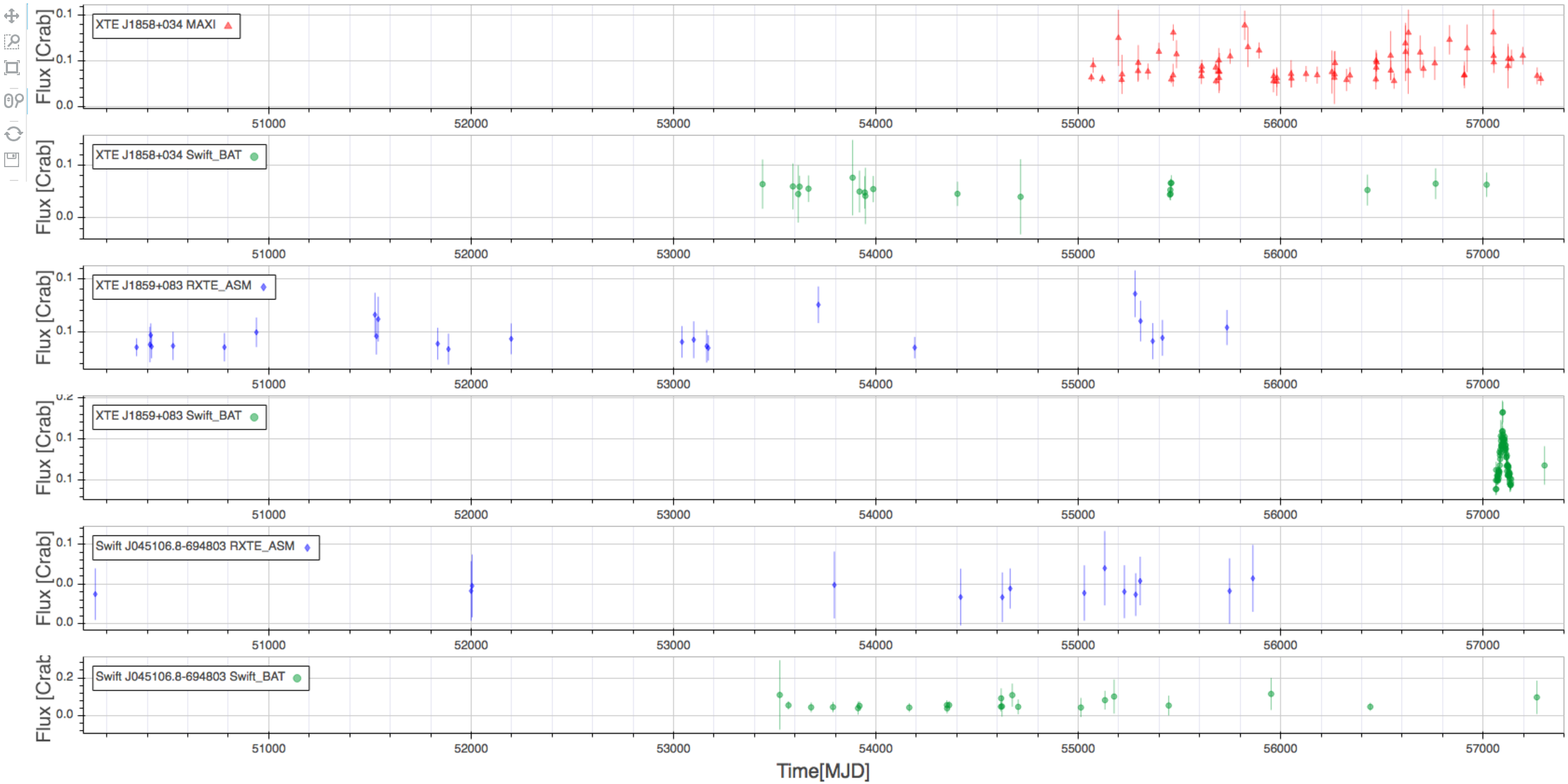

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

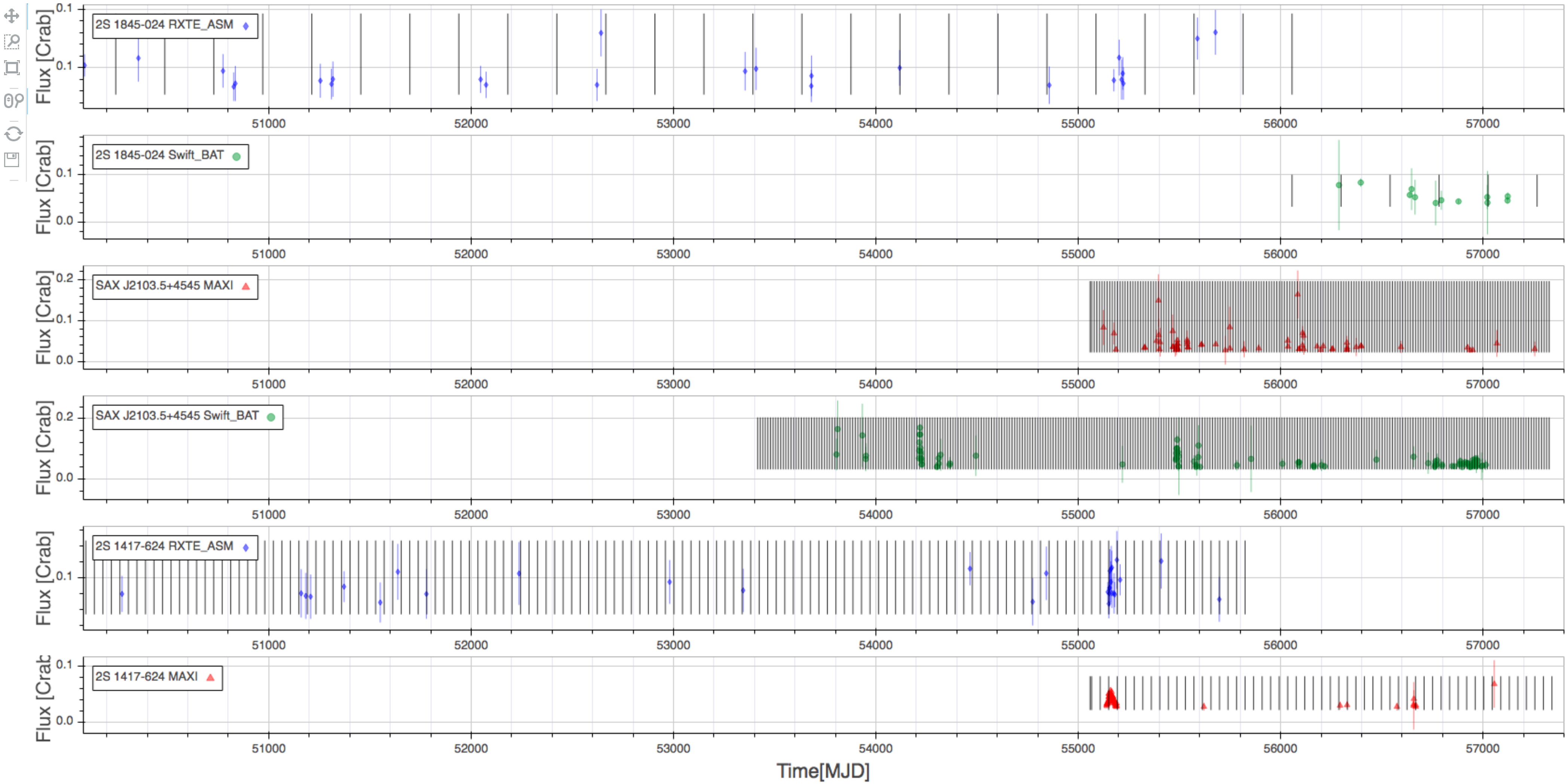

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

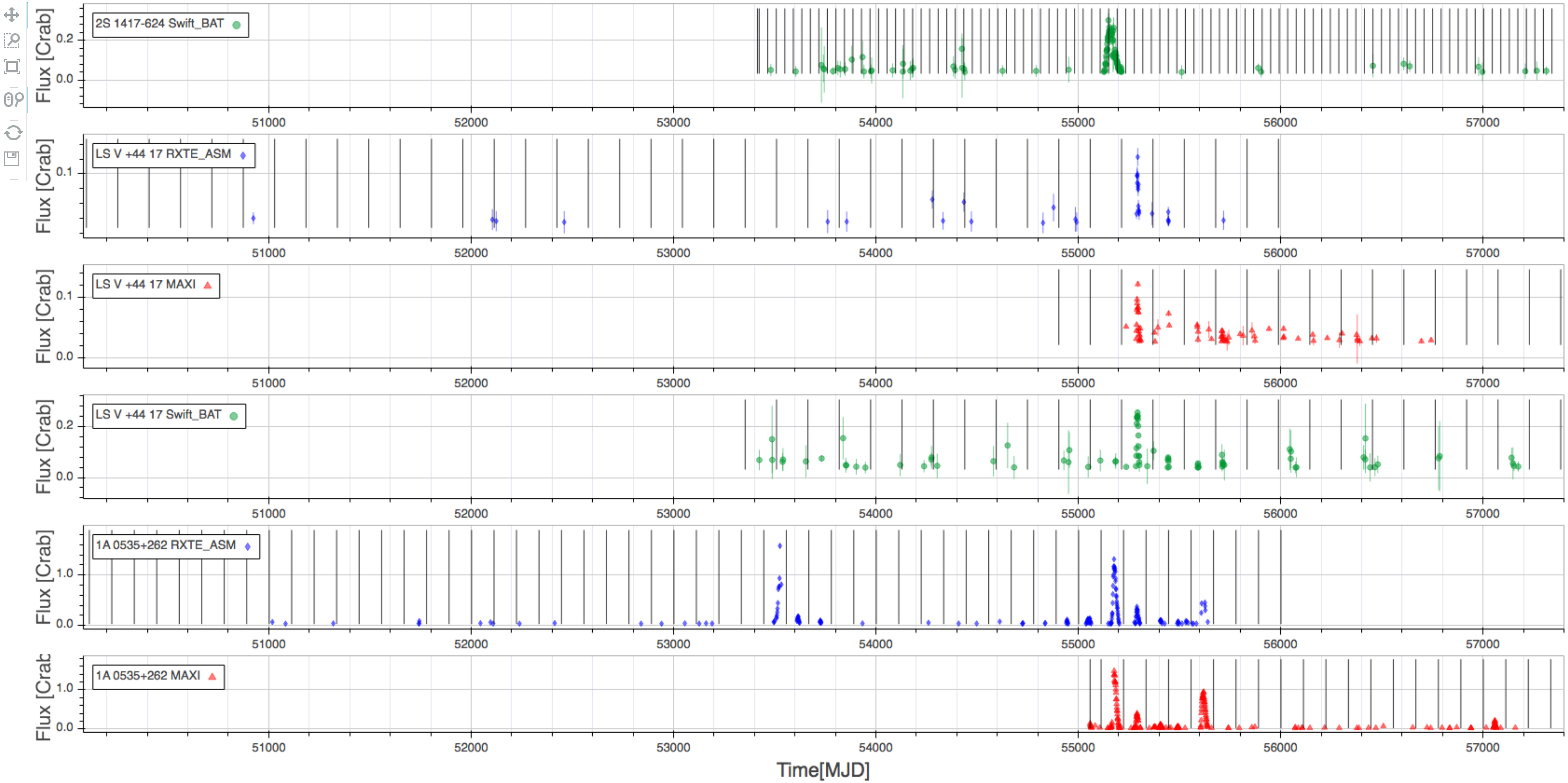

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

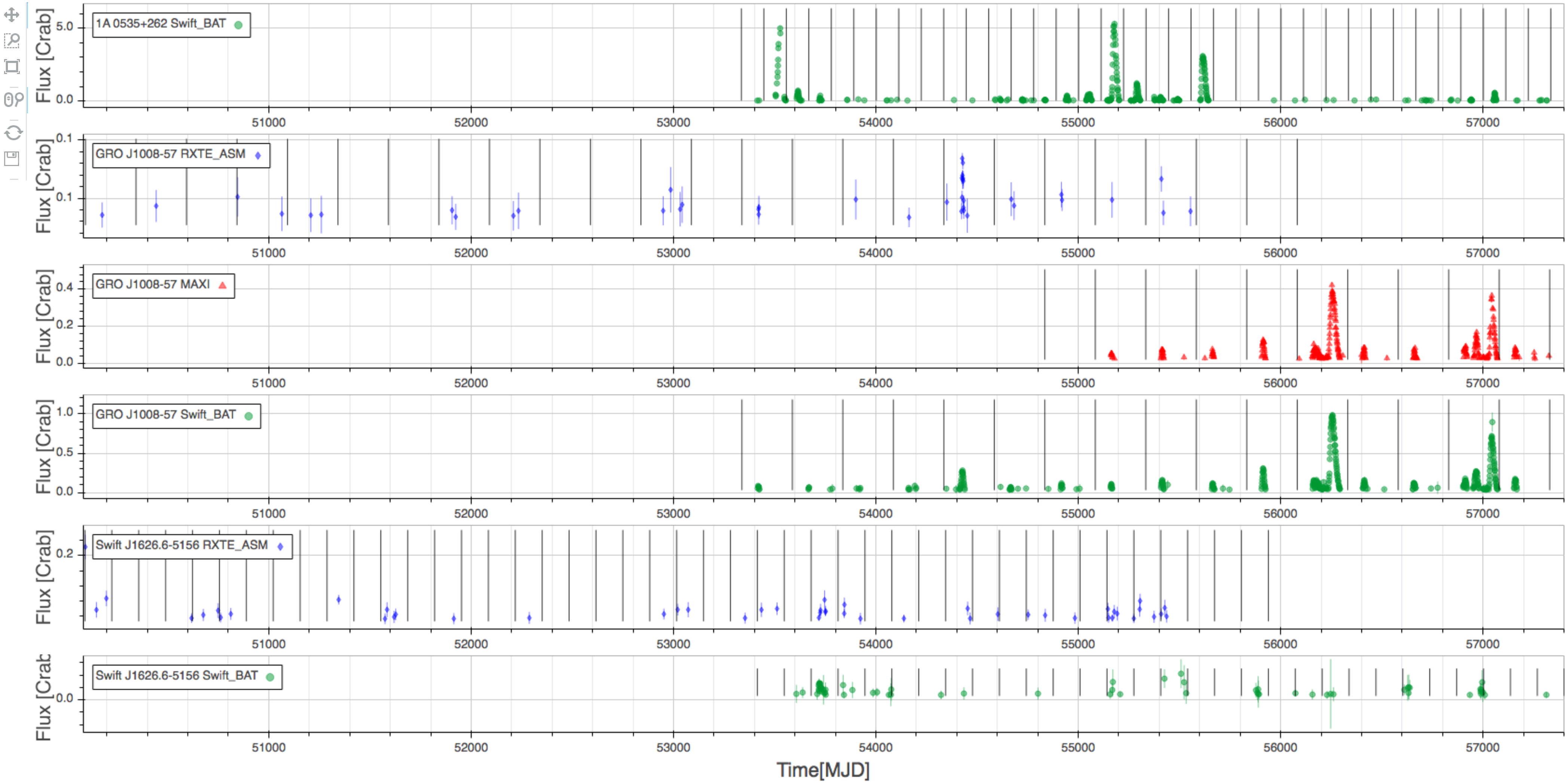

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

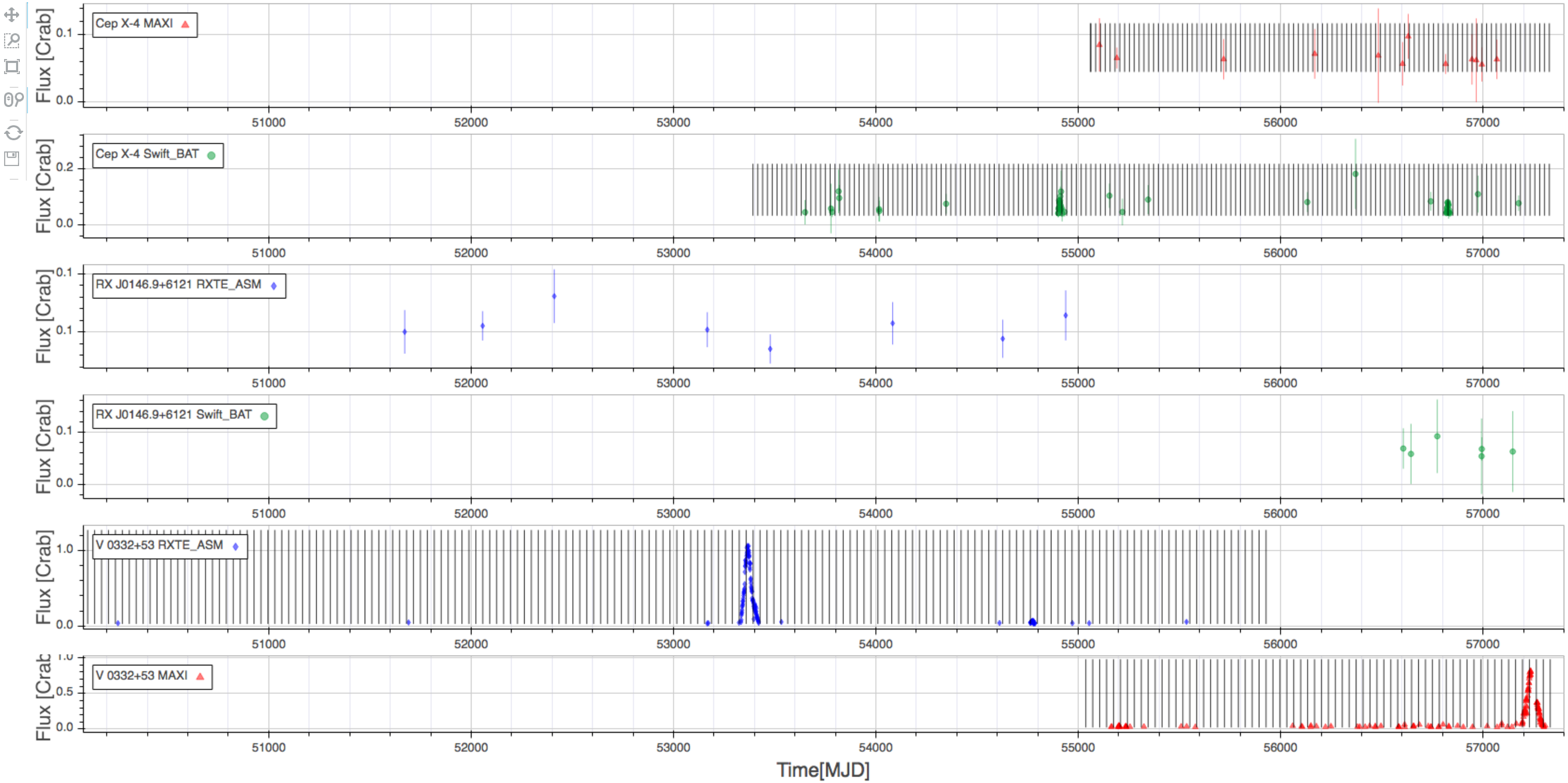

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

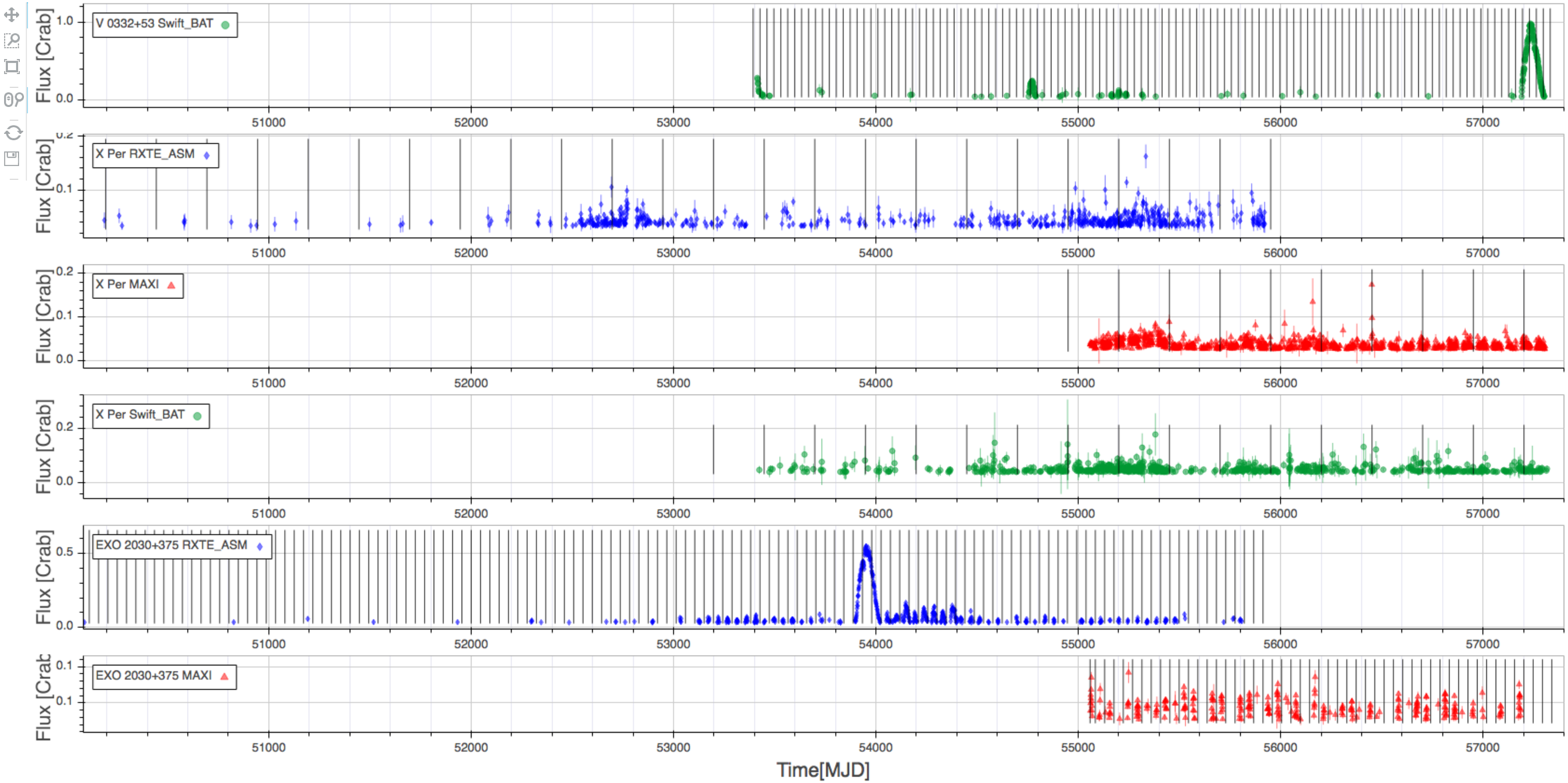

FIGURE 6.2 Active flux selected from the light-curve with defined orbital period sections

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