Bachelor's Thesis - Systematic Analysis of all Thermonuclear Bursts Observed by NuSTAR

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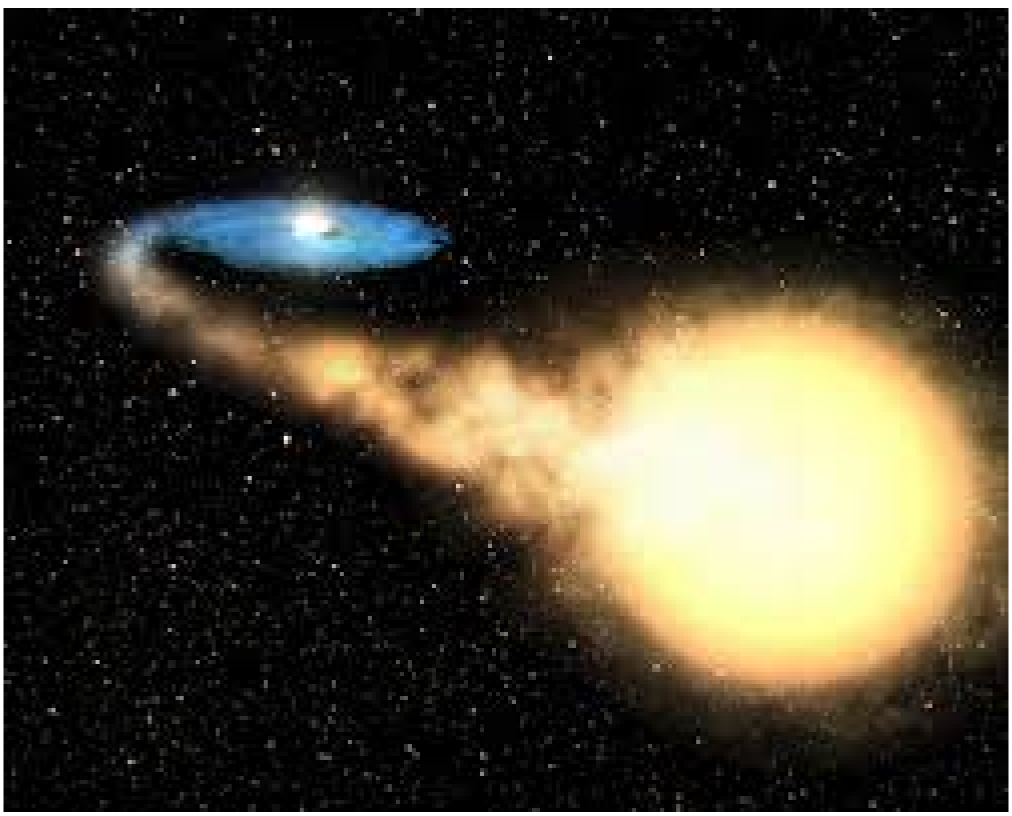


An artist's view of an x-ray binary[1]

[1] https://astrobites.org/2014/02/17/spots-and-tantrums/

Abstract

My thesis provides a new catalogue with essential physical parameters of type 1 x-ray bursts observed by the high energy satellite NuSTAR (Nuclear Spectroscopic Telescope Array). Based upon a catalogue given to me I have further developed this catalogue from not only having the epochs of when the x-ray bursts did occur, but also providing new essential information about the x-ray bursts such as fluxes, temperatures and norms. Moreover, my thesis examines the state of accretion disc prior, if possible, to x-ray bursts which may reveal interesting aspects of the nature of x-ray bursts.

Contents

1 Introduction

NuSTAR has by August 2016 observed 73 x-ray bursts[2] from the following 13 sources (number of bursts in paranthesis) 1RXS J180408.9-342058(17), 4U1608-522(1), 4U1636-536(9), 4U1728-34(10), Aql X-1(1), AX J1745.6-2901(16), GRS 1741.9-28.53(1), GS 1826-24(6), IGR J17511-3057(1), MXB 1658-298(1), SAX J1748.9-2021(8), SAX J1808.4-3658(1) and SER X-1(1), of which I have conducted a thorough analysis to be presented in a catalogue where I have calculated numerous different parameters, inter alia temperature, norm and flux of the different time intervals of the x-ray burst and the accretion (persistent) flux of the accretion disc prior to the x-ray burst. Regarding the calculation of the flux of the burst and accretion emissions, I will include both the absorbed and the unabsorbed bolometric flux. The following section will present the requisite theory in order to fully comprehend the scope of my thesis.

2 Theory - X-ray Bursts

Type 1 X-ray bursts are manifestations of a huge increase of x-rays emitted from neutron stars whose origin comes from unstable burning of accreting hydrogen and helium on the surface of neutron stars. The nature of another type of x-ray bursts, known as type 2 x-ray bursts, occurs due to the presence of a strong magnetosphere (however, not like the strength of a pulsar in high mass x-ray binaries), but only two type 2 x-ray bursters are known today (one of them exhibits both type 1 and type 2 x-ray bursts) which indicates that only a few neutron stars in x-ray binaries exist with the presence of a magnetic field strength that is between the strength of a powerful young pulsar in high mass x-ray binaries (HMXB) and an old neutron star in low mass x-ray binaries (LMXB). My thesis, however, will exclusively deal with type 1 x-ray bursts and since they are only found in LMXB's with a fairly weak magnetic field my thesis will only focus on LMXB's.

Type 1 X-ray bursts require a strong x-ray source which has a surface that can only possibly be a neutron star. Even though black holes indeed are strong x-ray sources they will not be able to support x-ray bursts because they by definition do not have any surface. Moreover, neutron stars must be in a binary system because x-ray bursts require matter transfer from a less compact object like low mass main sequence stars (LMXB) or white dwarfs (UCXB).

X-ray bursts are only found in LMXB's because the magnetic field of neutron stars in HMXB is way too high to giving way to accreting matter from the companion star on its surface. It is only accreted through its magnetic poles onto a narrow area where only stable burning can occur which is why x-ray bursts only occur in LMXB's.

[2] I interchangeably shift between the use of x-ray burst and burst throughout my thesis, however, it is exactly the same phenomenon I will talk about

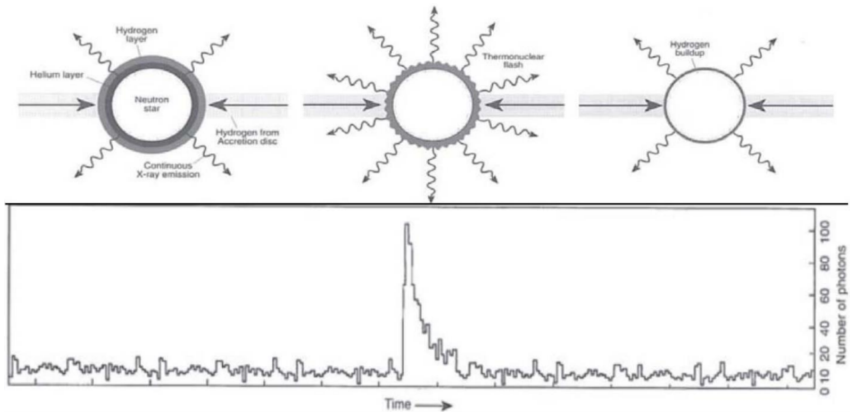


Figure 2 briefly and neatly illustrates the nature of type 1 x-ray bursts. During the first stage, the neutron star is accreting H and/or He from its companion star where layers of He and H will be created. During the second stage, the burning of H and/or He has reached a critical point in which burning becomes unstable. The general shape of x-ray bursts is its sharp rise and its subsequent exponential decay of counts. The third stage shows that the process will begin anew and hence x-ray bursts are recurrent processes.

2.1 Low mass x-ray binaries - LMXB's

LMXB's are binaries that consist of a compact x-ray source which is either a neutron star or a black hole with a companion star that typically has a mass below 1 solar mass. The known LMXB's are primarily found in the globular clusters and the galactic bulge of the Milky way which are sites of old population stars where no star formation takes place. X-ray bursters are only found in binaries with a neutron star as the compact object. Consequently, my thesis will only consider neutron stars when dealing with the compact object in LMXB's. The interesting feature of LMXB's is their presence of a Roche lobe overflow which is an accretion mechanism where the companion star has evolved to fill its Roche lobe. When the matter transferred from the companion star crosses the inner lagrange point of the system the Roche lobe overflow takes place and matter transferred by the companion star must be accreted by the neutron star.

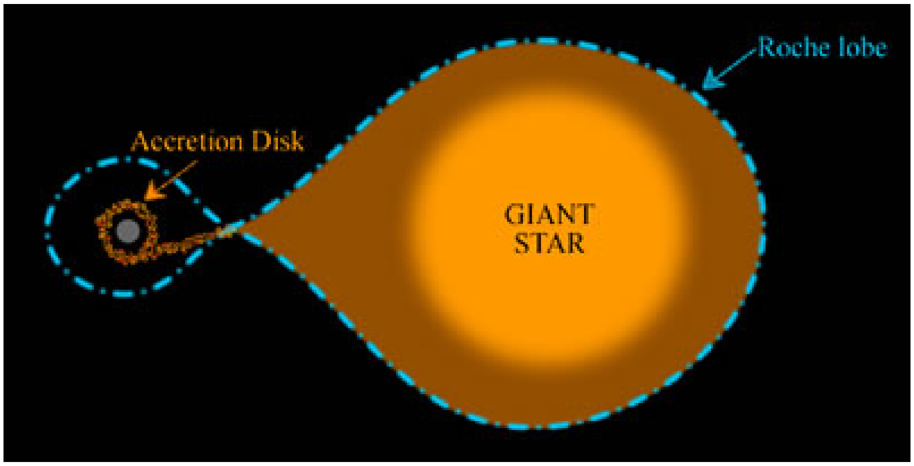


Figure 2.1 illustrates the Roche lobe overflow through the inner Lagrange point which is the cause of sustainable accretion on the neutron star.[3]

2.2 Eddington luminosity

Most material accreted by the neutron star from its companion star is hydrogen, but it may still contain a significant amount of helium in its burst. The point at which x-ray bursts are thought to happen is near or at the Eddington limit (this can both mean luminosity and flux) , but will never exceed this point. The Eddington limit can conceptually be explained as the point where the outward radiation pressure will overcome the gravitational potential of the compact object. Mathematically, the point at which the radiation force F_{rad} balances the gravitational force F_g is

$$F_{rad} + F_g = 0 \tag{1}$$

$$\frac{\sigma_0 L_{Edd}}{4\pi R^2 c} = G\frac{M m_p}{R^2} \tag{2}$$

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_0} \tag{3}$$

where G is the universal constant of gravitation, M is the mass of the neutron star (canonical value is 1.4 solar masses), R is the radius of the neutron star (canonical value 10 km), m_p is the mass of the particle in question, c is the universal speed of light and σ_0 is the Thomson cross section.

[3]http://astronomy.swin.edu.au/cosmos/R/Roche-lobe+Overflow

Instead, this formula can be expressed in terms of the Eddington flux F_{Edd} as follows

$$L_{Edd} = 4\pi d^2 F_{Edd} = \frac{4\pi G M m_p c}{\sigma_0} \tag{4}$$

$$F_{Edd} = \frac{G M m_p c}{\sigma_0 d^2} \tag{5}$$

Of course, this expression of the Eddington flux is dependent on the distance to the source in question.

However, note that these formulae of the Eddington luminosity and flux, respectively, do not take into account any burst anisotropy or any gravitational redshift which indeed are fundamental parameters, but nevertheless extremely difficult accurately to determine and therefore neglected in the expression of the Eddington limit.

Further investigating the expression of the Eddington limit you quickly realise it is entirely independent of the radius of the neutron star. Since most neutron stars seem to be quite close to the canonical value of 1.4 solar masses the Eddington limit can essentially be defined in terms of composition of the accreting material from the companion star in an x-ray binary. Therefore, it is really important to know the composition of the accreting matter to get a more accurate value of the Eddington luminosity of the neutron star.

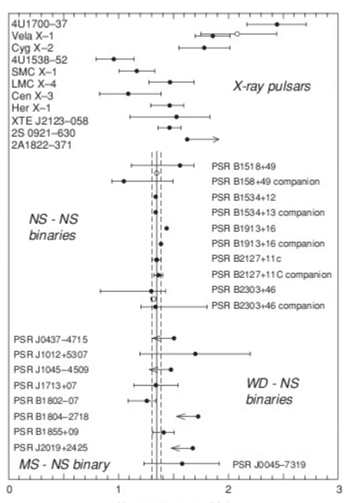


Figure 2.2 shows how measured masses of neutron stars in the different x-ray binaries actually are quite close to the canonical value of 1.4 solar masses. Therefore, the composition of the accreting matter on the neutron star is the principal factor for determining the Eddington luminosity of x-ray bursters.(1)

2.3 Distance determination

Distance determination is an important aspect in many branches of astronomy. Since some x-ray bursts can act as a standard candle[4] it is possible to determine the distance to the neutron star. Mathematically, the distance can be calculated knowing the luminosity and flux of a given object. The flux F of an object is the luminosity L divided by the spherical area A at which the given object radiates

$$F = \frac{L}{A} = \frac{L}{4\pi d^2} \tag{6}$$

Rearranging this equation for the distance d yields

$$d = \sqrt{\frac{L}{4\pi F}} \tag{7}$$

However, as we later will see some x-ray bursts occur right at the Eddington limit (photospheric radius expansion) whereas some do occur somewhere below the Eddington limit, but will never exceed this value. Consequently, we can derive an upper limit to the neutron star

$$d \leq \sqrt{\frac{L_{Edd}}{4\pi F_p}} \tag{8}$$

where L_{Edd} is the Eddington luminosity and the F_p is the measured flux at the peak of the x-ray burst.

Normally, it is always possible to measure the flux of a given object, however, you do not generally know the value of the luminosity. Therefore, it is quite complicated to provide a reasonable estimate of the distance to a variety of the objects in the Universe.

My thesis will show that it is possible to determine the distance to x-ray bursters[5] when they exhibit a photospheric radius expansion (PRE) during an x-ray burst, since they all are seemingly really close to the Eddington luminosity. By knowing both the luminosity and the flux from the neutron star, it will be considered a standard candle since you will be able to determine quite precisely the distance to the neutron star. An accurate description of x-ray bursts as standard candles due to photospheric radius expansions will be discussed in the next section.

[4] A standard candle is an object for which it is possible accurately to determine the distance between Earth and the object

[5] An x-ray burster is a neutron star on which x-ray bursts occur

2.4 Photospheric radius expansion - PRE

Photospheric radius expansions are important features of x-ray bursts because it seems that they actually all reach the Eddington limit. Physically, the photospheric radius expansion will occur at exactly the Eddington limit, since the Eddington limit represents the point at which the outward radiation pressure overcomes gravity. This has significant implications as it will allow you to determine an accurate distance to the neutron star and hence be considered a standard candle.

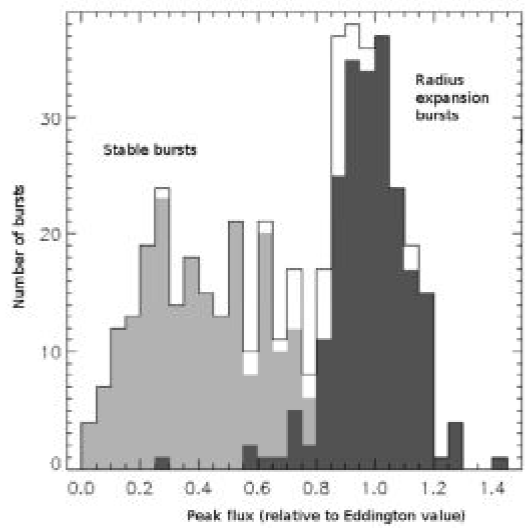


Figure 2.4 shows the relationship of the measured peak fluxes of a variety of bursts observed by RXTE/PCA relative to the calculated Eddington flux. This clearly shows that x-ray bursts exhibiting photospheric radius expansions empirically are the ones close to the Eddington limit which justifies the assumption that all x-ray bursts showing photospheric radius expansions reach the Eddington limit.(1)(2)

The calculations of the Eddington flux are made possible for a number of x-ray bursters due to the RR Lyrae variable stars in globular clusters for which the distance can be accurately calculated due to the period-luminosity relationship. Exploiting the distance determinations by means of RR Lyrae, it is in fact possible to provide a reasonable Eddington limit for x-ray bursters in globular clusters. This is clearly shown in the work of Kuulkers et al from 2002.(3)

2.5 Accretion disc

X-ray bursts only occur in LMXB's, however, it turns out they will just occur in specific types of LMXB's. At this point the state of the accretion disc and the accretion rate are crucial to comprehending the characteristics of x-ray bursts. An interesting feature of x-ray bursts is the well established fact that it is a recurrent process, but it still remains a problem predicting the recurrence time for x-ray bursts properly. It turns out that the recurrence time is not constant at all which indicates that the accretion of matter on the neutron star indeed is dynamic. Changes in flux from the accretion disc are clearly measurable which, for this reason, appropriately could be called accretion emission that is commonly known as persistent flux in the literature. You can derive a simple relationship between the accretion rate, M_{acc} and the recurrence time Δt_R to illustrate, how they may relate to one another

$$\Delta t_R = \frac{M_b}{\dot{M}_{acc}} = \frac{E_b}{\epsilon \dot{M}_{acc}} \tag{9}$$

where ϵ is the burning efficiency and E_b is the burned energy. Instead, you can express the recurrence time of bursts as a function of the accretion luminosity L_{acc} as:

$$\Delta t_R = \frac{E_b}{\epsilon \dot{M}_{acc}} = \frac{E_b \eta c^2}{\epsilon L_{acc}} \tag{10}$$

The equations 9 and 10 both show that the burst recurrence time is inversely proportional to the accretion rate $\Delta t_R \propto \dot{M}_{acc}$(or the accretion luminosity $\Delta t_R \propto L_{acc}$), i.e higher accretion rate/luminosity should result in shorter burst recurrence times. Physically, it makes sense that more accretion should mean shorter recurrence times. (This relation has been shown for a particular burster by Galloway et al. 2003(4)). However, things cannot be put that simple. At too low accretion rates the recurrence time is too high so that almost no x-ray bursts should occur, but at too high accretion rates it turns out that there will almost be no x-ray bursts at all. Therefore, accretion rates on neutron stars close to the Eddington limit in LMXB's, which are called Z-sources in the literature, are not expected to exhibit any x-ray bursts(Cyg X-2 is a rare exception). Consequently, only in LMXB's where the accretion rate is constrained to a certain range (typically 0.01-0.2 m_{Edd} for most Atoll sources(1)) you will likely frequently observe x-ray bursts that are significantly below the Eddington rate. Such x-ray binaries are commonly called Atoll sources in the literature. Generally, the relationship between the burst recurrence time and the accretion rate therefore seems only to be expected to be present within a narrow range of the accretion rate.

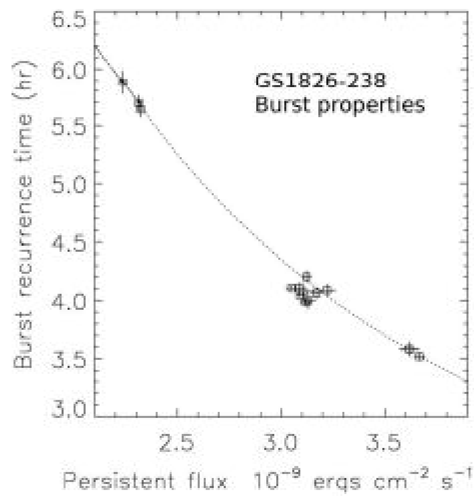


Figure 2.5 shows an example of a particular source where the burst recurrence time is inversely proportional to the accretion luminosity consistent with what I derived in 10. (Based upon a diagram created by Galloway et al. 2004)

An important aspect for determining and predicting the properties of x-ray bursts is the burning composition of the accreted material. It has turned out that the ratio of the accretion fluence and the burst fluence is a good indicator of the burning composition. The fluence is defined as the energy produced from a given area. In terms of the burst and accretion flux (F_b and F_a), the burst and accretion fluences (E_b and E_a) can be written as

$$E_a = \int_{t_i}^{t_j} F_a dt = F_a \Delta t_a \tag{11}$$

$$E_b = \int_{t_i}^{t_j} F_b dt = \sum_{i=1}^{n} F_{b,i} \Delta t_{b,i} \tag{12}$$

where Δt_a is the accretion time duration from one burst to the next subsequent burst, $\Delta t_{b,i}$ is the burst duration of each time interval during the burst (Typically Rise, Peak, Decay1 and Decay2) and $F_{b,i}$ is the flux of each burst time interval. Therefore, the dimensionless parameter α (5) can be defined as

$$\alpha = \frac{E_a}{E_b} = \frac{F_a \Delta t_a}{\sum_{i=1}^{n} F_{b,i} \Delta t_{b,i}} \tag{13}$$

Importantly, the fluxes used have to be bolometric in order to take into account the whole electromagnetic spectrum. Moreover, in the calculations made in my thesis (both in this report and the catalogue) I have primarily made use of the unabsorbed bolometric flux to avoid any corrections of, say, the Eddington luminosity when estimating the distance to the neutron stars.

3 Methods - NuSTAR, NuSTARDAS and time resolved spectral analysis

This section will give a brief introduction to NuSTAR, the software developed for NuSTAR called NuSTARDAS (NuSTAR Data Anaysis Software), the models used for the spectral analyses of the x-ray bursts and accretions prior to the x-ray bursts that can be found in the x-spec manual which provides a tool for analysing x-ray spectra(6) and a description of how the time resolved spectral analyses are made. The scripts nupipeline, nuproducts and the x-spec scripts used in my thesis can be found in appendix B. Furthermore, the absorption columns used throughout my thesis are found in appendix A with references included.

3.1 NuSTAR

NuSTAR is to date the first orbiting high energy (3-79 keV) focussing x-ray satellite that efficiently observes the sky of hard x-rays/soft gamma rays. The main advantage of NuSTAR is its deployed focussing optics instead of coded apertures that by nature have limited sensitivity and which yields opportunities to observe new things that otherwise would not be possible.(7)

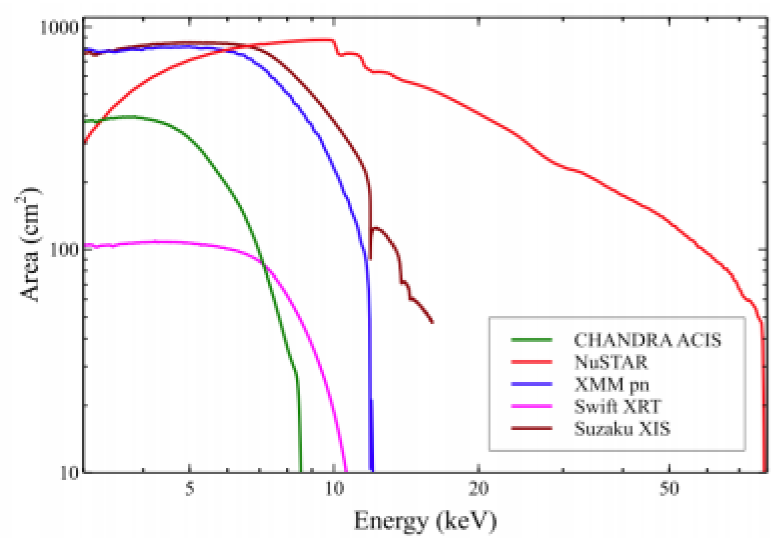


Figure 3.1 shows the energy range at which NuSTAR is able to observe. Comparing NuSTAR with the other x-ray focussing satellites it is evident that NuSTAR is revolutionary when it comes to x-ray focussing sateliites.(8)

NuSTAR is a LEO (Low Earth Orbit) satellite with a small inclination in order to avoid too many passages through the SAA (South Atlantic Anomaly) that is a region of high concentrations of charged particles which extends down to the many LEO orbit satellites passing this region. It has the advantage of being quite well protected from any influence of solar activity, proton and electron belts of high concentrations of charged particles. NuSTAR has a nearly circular orbit at heights of only 600 km which implies that its period around the Earth solely is a little more than 1.5 hours. This means that there are many gaps when observing a particular object due to the fact that the Earth is crossing the focus of view of NuSTAR.

Importantly, NuSTAR has two identical modules (FPMA and FPMB) which makes it ideal to do the xspec analysis as we now have twice as much data making it easier to do statistics.

Moreover, NuSTAR observes a variety of different sources and events which emit large amounts of soft/hard x-rays like supernovae, AGN's and x-ray binaries etc. My thesis will exclusively focus on the systematic analysis of all type 1 x-ray bursts in LMXB's in which the compact object is a neutron star with a low mass companion star. This is the reason why we have only observed a limited amount of x-ray bursts since the launching of NuSTAR.

3.2 NuSTAR Software and methods

Since NuSTAR was sent into orbit in 2012 it has collected data from a variety of different patches of the x-ray sky. All observations made by NuSTAR have been grouped into different OBSID (observation identifications). As the scientific objectives of NuSTAR are diverse, only limited time is spent on observing x-ray bursters where x-ray bursts occur. Therefore, only 73 type 1 x-ray bursts have been observed on 13 different x-ray bursters with NuSTAR since the day of launch in June 2012 until August 2016.

The NuSTAR team has developed special software (NuSTARDAS) for processing the raw data that NuSTAR receives during its observations of the x-ray sky that I have used for my thesis. Roughly, NuSTARDAS (NuSTAR Data Analysis Software) comprises three stages which can be summarised by the following image

Figure 3.2 shows the different steps the raw data has to pass through before being ready for the x-spec analysis. (6)

For my thesis two different scripts developed by NuSTARDAS to be executed on the sets of data of the x-ray bursts were utilised. The first script is called *nupipeline* which goes through the first two stages, namely data calibration and data screening, and the second one is called *nuproducts* that is used to extract a region of the x-ray sky which for the purpose of my thesis is the x-ray burster in question found in the respective OBSID that can be found on HEASARC (High Energy Astrophysics Science Archive Research Center). The main purpose of using nupipeline is to provide detailed information of the events observed by NuSTAR where you will get new types of data like **good quality data** (01), **Earth occultaion** (02), **slew** (03), **SAA pasages** (04), **calibration source in view** (05) and the **dubious attitude reconstruction** (06).

The script nuproducts is used to extract the x-ray burster. From the nupipeline the necessary clean and calibrated event files were created, however, in principle you can look at all the six kinds of different clean event files, but only a couple of them is of any interest to me. These clean event files are **good quality data** (01) and **dubious attitude reconstruction** (06). Good quality data (01) is obviously the good data to be worked with, but it turns out that 06 data in fact contains many x-ray bursts. Therefore, it is very important to separate the raw data into different data types since you are mostly interested in good quality data.

On the given list I was provided the exact epoch at which the x-ray burst occured and the data type (01 or 06) in which it was to be found. Since the purpose of the nuproduct script is to extract the region of interest it is necessary to open the clean event file. For all OBSID's you will need to make both a source region file (src file) and a background region file (bkg file), because you want to subtract the background contribution of counts from the source to obtain more accurate results. (9)

At first, it is sufficient to do the extraction for the FPMA module because both modules (FPMA and FPMB) are identical and therefore not expected to exhibit any significant differences. Therefore, I have only divided the bursts into a number of consecutive time intervals (Typically Rise, Peak, Decay1 and Decay2) for data type A, but nevertheless you can preferably do the extraction for both modules (FPMA and FPMB) from the very beginning since you will need to run the nuproducts (only for the time interval chosen) again when all time intervals are time resolved into (typically) Rise, Peak, Decay1 and Decay2. This has to be done with both modules FPMA and FPMB.

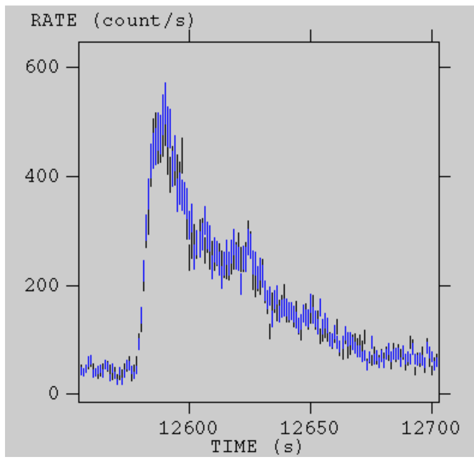


Figure 3.2 shows the ligthcurves produced by modules FPMA (Blue) and FPMB (Black) plotted on the same graph of the first x-ray burst of the source 1RXS J180408.9-342058 in OBSID 80001040002. This clearly illustrates that it makes no significant difference whether you time-resolve the bursts (Typically Rise, Peak, Decay1 and Decay2) with the lightcurves produced by FPMA or FPMB.

3.3 Models of the x-spec manual

The x-spec manual comprises a huge collection of different models for doing spectral analyses of x-ray/gamma spectra for many different sources of x-ray emission, including x-ray binaries, AGN's, supernovae, galaxy clusters etc, however, only a small fraction of them is of any interest for describing the spectra of x-ray bursts and the accretion disc prior to the burst in question. Hereinafter, I will present all the additive models (**bbodyrad**, **po**, **bknpower** and **bkn2po**) and the multiplicative absorption model **Tbabs** that I have used for the spectral analysis.

The model used for fitting x-ray bursts is **bbodyrad** (x-spec manual: 6.2.6). This model is mathematically expressed as

$$A(E) = \frac{N \cdot 1.0344 \cdot 10^{-3} E^2 dE}{exp(E/kT) - 1} \tag{14}$$

where A(E) is the normalised blackbody spectrum as a function of the temperature E in keV and N is the norm that is defined as

$$N = \frac{(R/1km)^2}{(d/10kpc)^2} \tag{15}$$

where R is the radius of the neutron star and d is the distance between Earth and the neutron star in question.

The model **bbodyrad** utilised for all x-ray bursts has the advantage of providing *physical* parameters that can be interpreted. Firstly, you will get a value of the temperature during the stages of the x-ray bursts (typically Rise, Peak, Decay1 and Decay2), but you will get a value of the norm which means that if you know the distance to the neutron star you will be able to estimate the radius of the neutron star and vice versa.

The models used for fitting the accretion emission prior to the x-ray burst are **po** (power law), **bknpower** (broken power law) and **bkn2po** (double broken power law) together with its multiplicative model Tbabs.

Firstly, the power law (po) spectrum A(E) as a function of the energy E is according to the x-spec manual (x-spec manual: 6.2.74) defined as

$$A(E) = KE^{-\alpha} \tag{16}$$

where α is a dimensionless photon index of the power law and K is the norm expressed at 1 keV as $photons/keV/cm^2/s$.

Secondly, the broken power law (bknpower) A(E) versus the energy E is according to the x-spec manual (x-spec manual: 6.2.9) defined as follows

$$A(E) = \begin{cases} KE^{-\Gamma_1} & E \leq E_{break} \\ KE_{break}^{-\Gamma_1-\Gamma_2}(E/1kev)^{-\Gamma_1} & E > E_{break} \end{cases}$$

where Γ_1 and Γ_2 are power law photon indices 1 and 2, respectively, E_{break} is the break energy and K is the norm in units of $photons/keV/cm^2/s$.

Thridly, the double broken powerlaw (**bkn2po**) A(E) against the energy E is according to the x-spec manual (x-spec manual: 6.2.10) expressed as

$$A(E) = \begin{cases} KE^{-\Gamma_1} & E \leq E_{break,1} \\ KE_{break,1}^{-\Gamma_1-\Gamma_2}(E/1kev)^{-\Gamma_1} & E_{break,1} \leq E \leq E_{break,2} \\ KE_{break,1}^{-\Gamma_1-\Gamma_2}E_{break,2}^{-\Gamma_2-\Gamma_3}(E/1kev)^{-\Gamma_3} & E_{break,2} \leq E \end{cases}$$

where Γ_1 and Γ_2 and Γ_3 are power law photon indices 1, 2 and 3, respectively, $E_{break,1}$ and $E_{break,2}$ are the break energy and K is the norm in units of $photons/keV/cm^2/s$.

Finally, the absorption model **Tbabs**, having the one input parameter *equivalent hydrogen column*, takes all absorption by both light and heavy elements as if it were solely due to hydrogen absorption.

All models are formed by implementing a multiplicative absorption model, Tbabs, together with an additive model (bbodyrad, po, bknpower, bkn2po). The model used for the spectral analysis of the burst is **Tbabs(bbodyrad)** and the models for the spectral analysis of the accretion disc were either **Tbabs(po)**, **Tbabs(bknpower)** or **Tbabs(bkn2po)**.

The model Tbabs(bbodyrad) is examined in the energy spectrum 3-20 keV as a rule of thumb, however, some of them do not fit properly in this energy band. Therefore, I have constrained the energy band to 3-15 keV for many burst intervals (one burst interval is even constrained to 3-10 keV). Since x-ray bursts are most powerful at around 3 keV, taking into account only blackbody radiation, it makes sense the blackbody model does not quite well with the observed emission at energies around 15-20 keV. In principle, you could fit the burst spectrum in the whole energy band 3-79 keV, but 3-20 keV is chosen as a rule of thumb because x-ray bursts only emit little radiation above 20 keV.

Fundamentally, the reason why I have used the different power laws is that they are simple models. All models contain power law photon indices, but they do not tell you anything about the physics of the accretion disc. However, since the purpose of my thesis is to provide the accretion (persistent) flux prior to all x-ray bursts I have only used the simple power law models for the accretion emission. Nonetheless, it would have been interesting to acquire knowledge of processes taking place in the accretion disc, e.g. the temperature, size and structure of the inner and outer discs, comptonization etc. I have tried the diskbb (x-spec manual: 6.2.28) and compTT (x-spec manual: 6.2.24) on some of accretion emission parts, however, I did not obtain any reliable results, probably due to lack of data in some of the intervals I chose to examine.

The blackbody *bbodyrad* used for doing the spectral analyses of the bursts turns out to fit quite well to most bursts. The advantage of this model is that it gives you some physical parameters which in fact physically tell you something about the bursts e.g. the temperature and norm of each stage of the burst. Consequently, even if a power might have fitted sufficiently well to some of the bursts the blackbody model is the desirable one to use since it has the advantage of providing parameters that can be physically interpreted.

3.4 Time resolved spectral analysis

In principle, there is no true way of dividing the burst and accretion emissions. It entirely depends on what kind of information you want to extract from the x-ray burst or the accretion disc, however, you generally want to follow the evolution of the x-ray burst and the accretion disc. As a rule of thumb, I have always tried to divide the bursts into the following categories: **Rise**, **Peak**, **Decay1** and **Decay2**. In general, the x-ray burst have a sharp rise, a peak and a subsequent steady decay which is why I have chosen to strive to dividing the decay into **Decay1** and **Decay2**, but it turns out that the time intervals were not adequate for sufficiently descibing the evolution of the x-ray burst. As another rule of thumb I tried to divide the burst time intervals starting from 25% of the peak value in $counts/s$ and then stopping at 25% of the peak value.

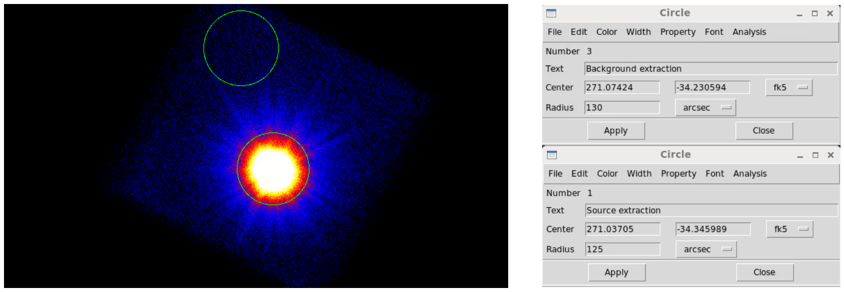
Sometimes I found it more appropriate to add a **Flat** because at times the burst seemed to have a steady count rate during its decay phase which happened between the first decay phase, Decay1, and the second decay phase Decay2. Occasionally, there were exceptionally long bursts ($\sim$ 80 s) for which I consequently made a **Decay3**. On one occasion I chose both to include a Flat and a Decay3. All time intervals Flat and Decay3 only appeared in the source 1RXS J180408.9-342058 due to its long bursts.

Some x-ray bursters exhibited many bursts of fairly short duration ($\sim$ 10 s). Therefore, dividing the time intervals Rise, Peak, Decay1 and Decay2 was really difficult. Consequently, I included only one decay interval Decay1, ie for short bursts I included Rise, Peak and Decay1.

Two x-ray bursts had had extremely peculiar shapes for which it was nearly impossible to divide the burst into several time intervals. For those bursts I only made one time interval.

For all bursts I have extracted the accretion emission prior to the bursts in order to obtain the accretion flux, however, sometimes it was not possible. At some instances there was a data gap which, of course, makes it impossible to extract the accretion flux before the burst. Occasionally, the accretion flux was too weak or the time interval was not long enough to make a good fit of the data. In these cases, I examined whether the accretion flux is persistent or not throughout the interval by looking at the count rate. This being the case, I have extracted a large interval of time for the flux. If the accretion flux was not persistent throughout the interval I had to find out where the flux was at approximately the same level as right before the burst.

The spectral analyses of the burst and the accretion disc were made by **x-spec** from which you would be able to see how well the data fit to your chosen model. Essentially, this was the main criterium for the burst and the accretion spectral analyses.



(a) Source and background extractions (b) Extration information

Figures (a) and (b) show the product extraction of burst 1 of source 1RXS J180408.9-342058 in OBSID 80001040002. From these source and background extractions you will now be able to produce all the needed lightcurves, energy spectra etc. As you can see the source extraction is chosen so that it covers the region of many counts to get light curves, energy spectra etc. of the full burst, yet, I have chosen not to extract too much (ie. to take too much of the background) in order to avoid too much noise.

4 Analysis and Results

The NuSTAR software (NuSTARDAS), the models of x-spec utilised and the method of time resolved spectral analysis, have now been introduced. My catalogue contains 73 x-ray bursts of which have been conducted thorough time resolved spectral analyses, thus my thesis could in principle comprise several hundred pages with all kinds of various detailed calculations. However, I only intend to present a few concrete examples of how my results can be used and then explain the prospects of my catalogue for future use.

4.1 Concrete example of analysing x-ray bursts - 1

This subsection will deal with x-ray burst 1 of the source 1RXS J180408.9-342058 (OBSID 80001040002). The nupipeline script has grouped the NuSTAR data into the different data types (01, 02, 03, 04, 05 and 06). The x-ray burst of source 1RXS J180408.9-342058 can be found in the 01 data type from which you can extract the background and source regions of both FPMA or FPMB modules. In my thesis I have only extracted the source and background regions by means of a circle because that was the most simple tool to be used. Other simple tools to be used are ellipses, boxes, polygons etc., however, I found the circle to be the most appropriate tool to be applied. Figures (a) and (b) show the results of my source and background extractions from the FPMA module for my choice of x-ray burst.

The nuproducts script provides the requisite light curves and energy spectra to be used. The task is now to do the time resolved spectral analysis where the choices of time intervals for this burst are Rise, Peak, Decay1, Flat and Decay2 in this order.

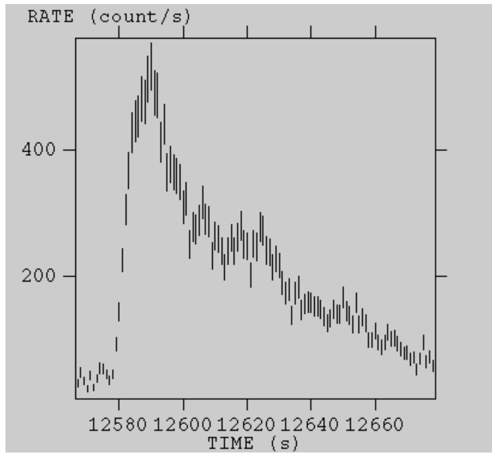


Figure 4.1 shows the first burst by FPMA from the source 1RXS J180408.9-342058 in OBSID 80001040002. This burst has been time resolved into the following time intervals: Rise, Peak, Decay1, Flat and Decay2.

For this burst, however, I have chosen to make an extra time interval Flat between the two decay intervals (Decay1 and Decay2) because the count rate reaches a nearly constant value for some time before further decaying. For comparison, I have for some other bursts (all of them from the same source 1RXS J180408.9-342058) chosen to make a Decay3 burst time interval, because some bursts are quite long (longer than 60 seconds).

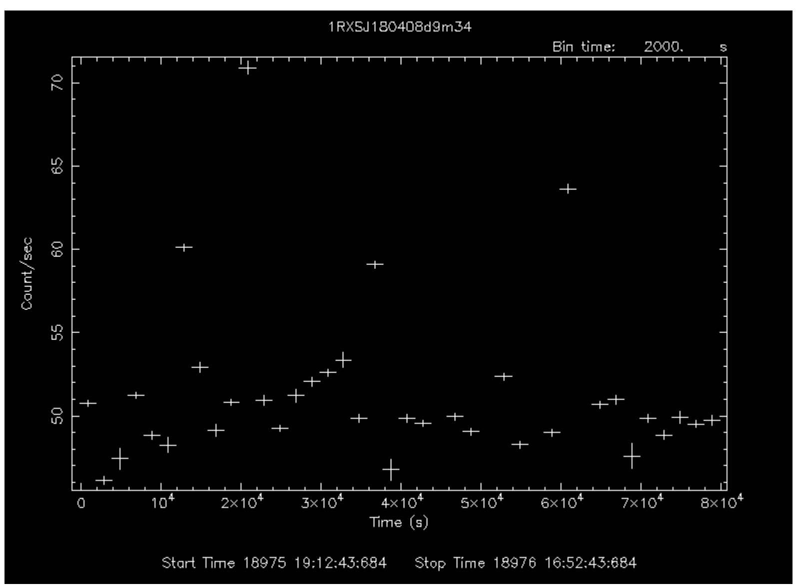


Figure 4.1 shows the light curve of 1RXS J180408.9-342058 in OBSID 80001040002 after it has been rebinned. The large count rates (above 55 c/s) are due to bursts, and the others

are contributions mainly by the accretion disc. This figure shows that the accretion flux is nearly persistent, however, the flux in general is not necessarily persistent. Thus, it really matters which time interval you choose. This is essentially why I find the use of accretion flux more appropriate than persistent flux in order to describe the flux from the accretion disc.

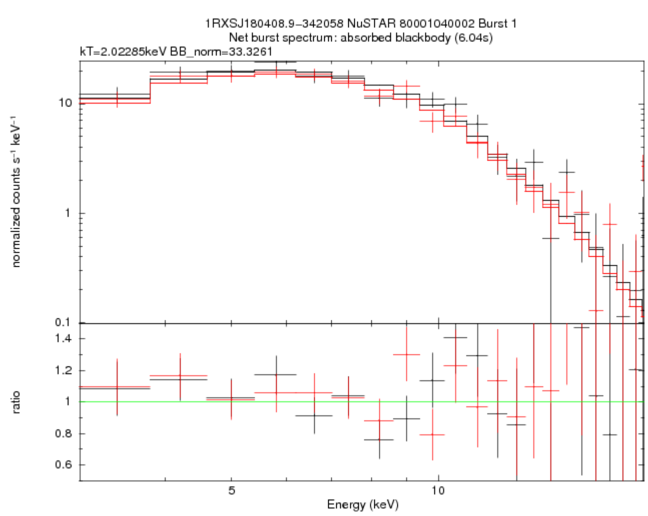
The spectral analysis of this x-ray burst has yielded no clear evidence of a photospheric radius expansion which means that we can only estimate an upper limit to this source. The unabsorbed bolometric flux of the peak of this x-ray burst was calculated to be $F_p = 1.5 \cdot 10^{-8} ergs/cm^2/s$ which gives the following estimate of the upper distance to this source, assuming the Eddington luminosity is $L_{Edd} = 2.0 \cdot 10^{38} ergs/s$

$$d \leq \sqrt{\frac{L_{Edd}}{4\pi F_p}} \tag{17}$$

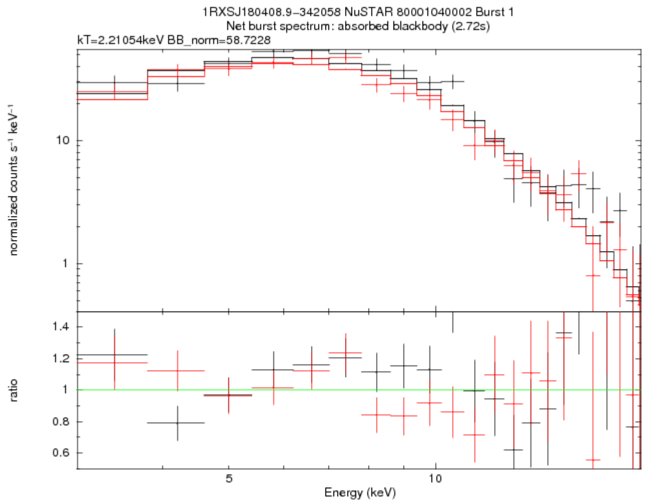
$$d \leq 11 kpc \tag{18}$$

For the calculation of the Eddington luminosity I have assumed that the accreting material is hydrogen rich since the burst is rather long ($\approx 60s$) as can be seen at figure 3.2. Consequently, I have chosen the value of the Eddington luminosity to be $L_{Edd} = 2.0 \cdot 10^{38} ergs/s$ (10).

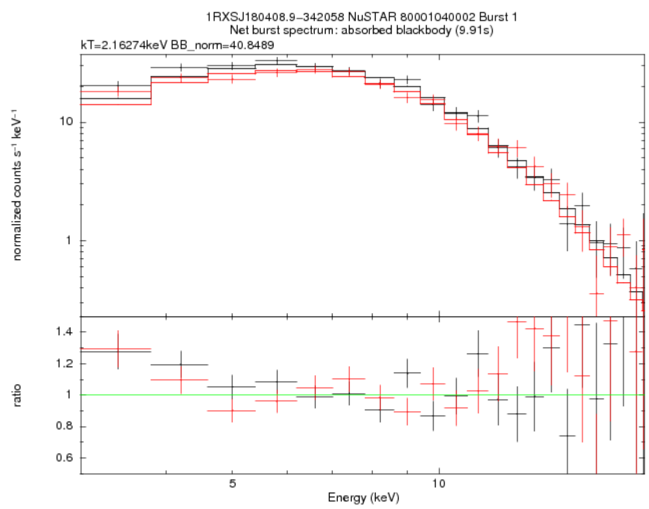
The results of my time resolved spectral analyses for this source are presented in the following plots that essentially show that the spectra of the time intervals of the x-ray burst follow quite well the blackbody spectra.



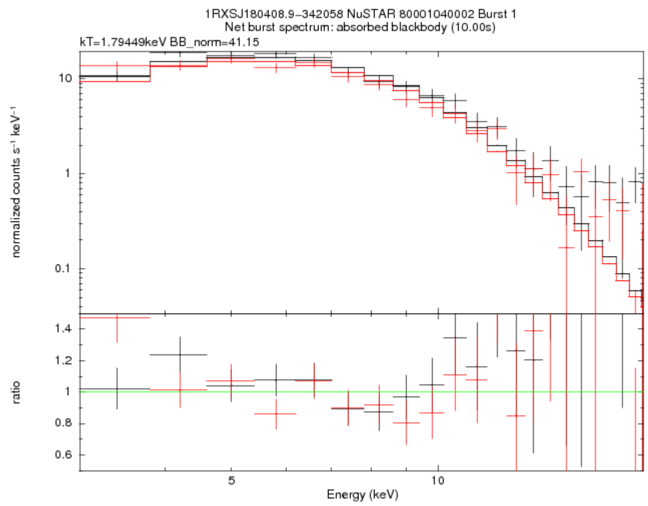
Rise spectrum of 1RXS J180408.9-342058



Peak spectrum of 1RXS J180408.9-342058



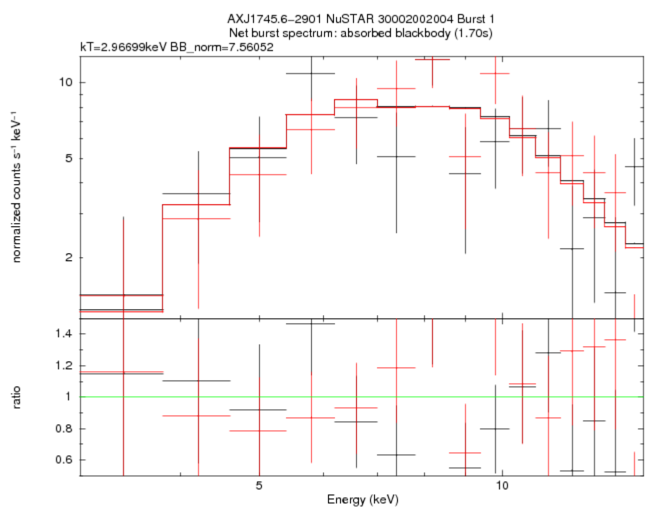
Decay1 spectrum of 1RXS J180408.9-342058



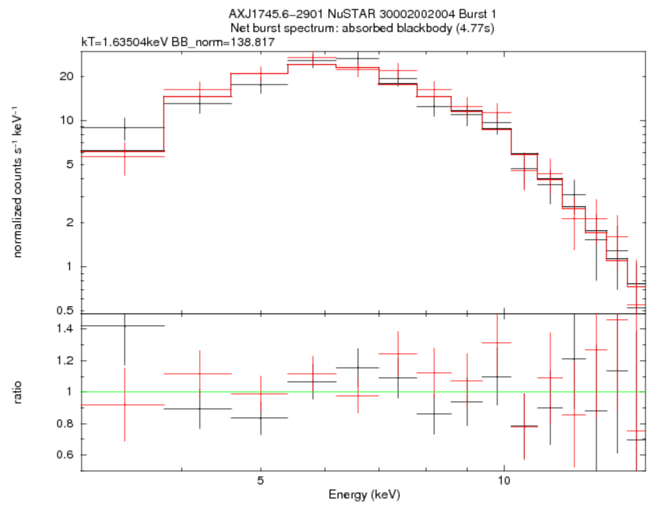
Decay2 spectrum of 1RXS J180408.9-342058

4.2 Concrete example of analysing x-ray bursts - 2

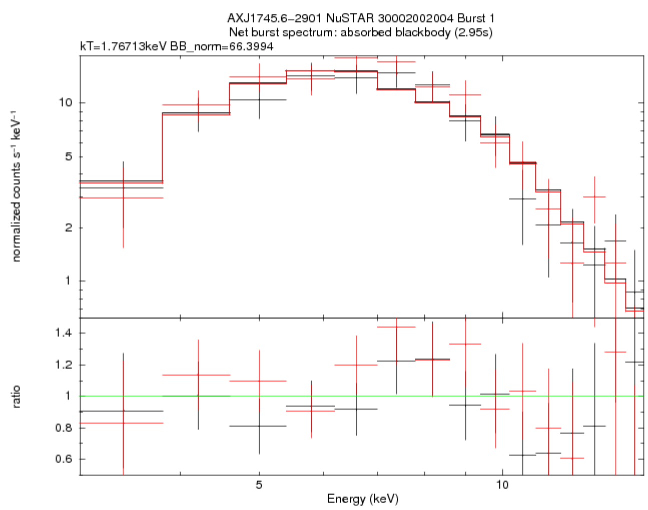
In this example I will just show the results of the time resolved spectral analyses of burst 1 from source AX J1745.6-2901 in OBSID 30002002004. Hereinafter, I want to describe the photospheric radius expansion that occurs during this x-ray burst. The results of my time resolved spectral analyses are shown in the following images



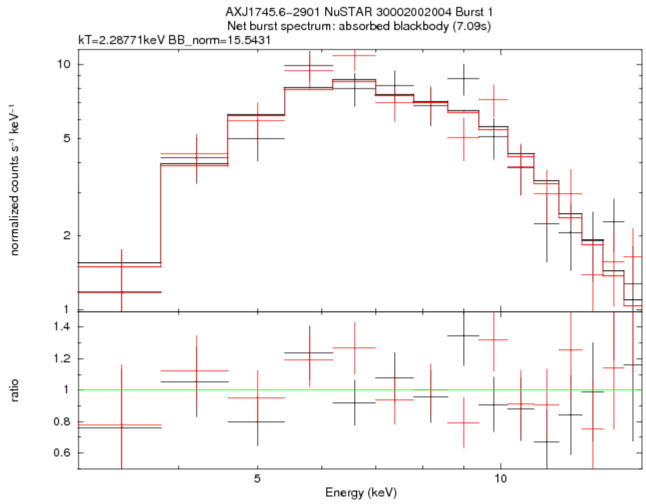
Rise spectrum of AX J1745.6-2901



Peak spectrum of AX J1745.6-2901

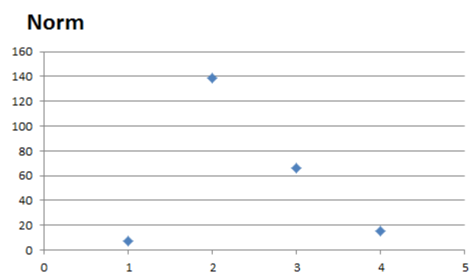


Decay1 spectrum of AX J1745.6-2901

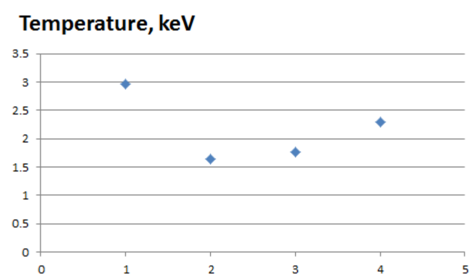


Decay2 spectrum of AX J1745.6-2901

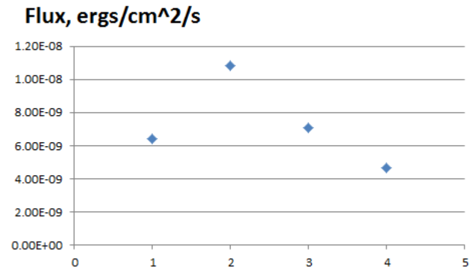
This source shows clear indications of a photospheric radius expansion that allows us to estimate the distance more accurately which can be seen in the following figures



This figure shows the evolution of the burst from AX J1745.6-2901 in OBSID 30002002004: **Rise(1)**, **Peak(2)**, **Decay1(3)** and **Decay2(4)** as a function of the norm



This figure shows the evolution of the burst from AX J1745.6-2901 in OBSID 30002002004: **Rise(1)**, **Peak(2)**, **Decay1(3)** and **Decay2(4)** as a function of the temperature



This figure shows the evolution of the burst from AX J1745.6-2901 in OBSID 30002002004: **Rise(1)**, **Peak(2)**, **Decay1(3)** and **Decay2(4)** as a function of the flux

Photospheric radius expansions indicate that the Eddington luminosity has been reached which means that the distance to AX J1745.6-2901 can be estimated by the following expression

$$d = \sqrt{\frac{L_{Edd}}{4\pi F_{Edd,p}}} \tag{19}$$

where $F_{Edd,p} = 1.1 \cdot 10^{-8} ergs/cm^2/s$ this time is the measured flux in where it reaches the Eddington flux. The distance to this source is estimated to (assuming $L_{Edd} = 2.0 \cdot 10^{38} ergs/s$ (10))

$$d = 12kpc \tag{20}$$

The coordinates of this source in galactic coordinates are $(359.9203, -00.0420)$[6] which is extremely close to the galactic center. Therefore, the burst is most likely not 12 kpc away from the Earth. Since the distance to the galactic centre is approximately 8 kpc, the distance to the source should not exceed this value significantly. As is explained in Degenaar et al. from 2008(10) the x-ray binary where AX J1745.6-2901 is located is an eclipsing x-ray binary which means that the inclination must be very close to 90 degrees. This may have an enormous effect on the possible anisotropy due to a possible thick accretion disc. Taking into account a possible anisotropy of the burst can be done in the fashion of Fujimoto, 1988 and Galloway et al. 2017(11). The formula used is

$$d_\xi = \sqrt{\frac{L_{Edd}}{4\pi F_{Edd,p} \xi_b}} \tag{21}$$

[6] http://simbad.u-strasbg.fr/simbad/sim-id?Ident=AX+J1745.6-2901

where d_ξ is the distance taking into account the burst anisotropy. Relating d=12 kpc and d_ξ we will get the following

$$d_\xi = d\xi_b^{-\frac{1}{2}} = 12kpc\xi_b^{-\frac{1}{2}} \tag{22}$$

Assuming that AX J1745.6-2901 is at the galactic centre (8 kpc), the value of the anisotropy burst must be

$$\xi_b = \left(\frac{d}{d_\xi}\right)^2 \tag{23}$$

$$\xi_b = 2.4 \tag{24}$$

Hence, the anisotropy factor indicates that the radiation primarily directed away from the Earth. My result indicates that anisotropy can play a significant role in determining the distance to eclipsing x-ray binaries.

4.3 Concrete example of analysing x-ray bursts - 3

In the last concrete example I will look at the relation between the recurrence time of x-ray bursts and the accretion flux. I have examined this relation for the source 1RXS J180408.9-342058 in OBSID 80001040004 since it has a total of 10 x-ray bursts. The graph shows this relationship assuming there are no x-ray bursts in gaps

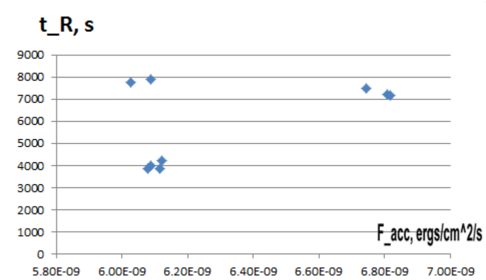


Figure 4.3 shows the relation between the recurrence time of bursts (10 bursts in total) for 1RXS J180408.9-342058 in OBSID 80001040004 and the accretion flux just before the next burst will occur. However, it seems that it does not harmonise with the the inversely proportionality between t_R and F_{Acc} assuming there are no bursts in the gaps.

This relation has been often shown by others to be true for many sets of bursts (Galloway et al. 2003(4)), but it seems not to be true for this source. However, I believe that it is (mainly) due to missing bursts in the gaps that this relation is not true for these bursts. As you look at the graph it is worth noting that the recurrence time for the bursts around $F_{acc} = 6.1 \cdot 10^{-9} ergs/cm^2/s$, either has a recurrence time of about 4000 seconds or 8000 seconds that might be due to the gaps, which then may be an indicator of missing bursts in the gaps. At $F_{acc} = 6.8 \cdot 10^{-9} ergs/cm^2/s$ the recurrence time is somewhere around 7200 seconds(2 hrs), however, this value may also be somewhat less (a factor of approximately 2) due to the missing bursts in the gaps. Consequently, I cannot exclude the possibility that the recurrence time is inversely proportional to the accretion flux for these bursts, but this will require that all the 5 ”missing”(If they really occured) bursts do exist. This may be possible to prove if other x-ray satellites have observed this source at the same time as NuSTAR. All this does in fact show that this is one disadvantage of NuSTAR that it has so many gaps because it is a LEO satellite. In the picture below there is an image of the 10 bursts to get a clearer view of how the ”missing” bursts may exist

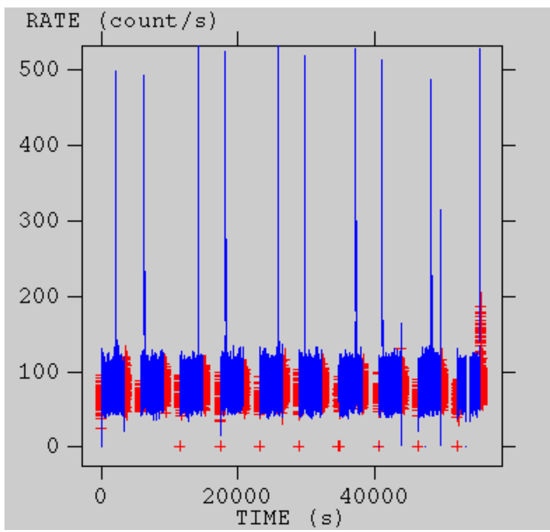


Figure 7 shows 01 data (blue) plotted together with 06 data for the source 1RXS J180408.9-342058 in OBSID 80001040002. This graph indicates that there may be some missing bursts in the gap.

Finally, I will show α values calculated for 1RXS JJ180408.9-342058 in OBSID 80001040004 and explain the meaning of them. I have calculated the first possible α value, α_{first}, and the last one possible, α_{last}, that by use of equation 13 gives the following values:

$$\alpha_{first} = 53 \tag{25}$$

$$\alpha_{last} = 110 \tag{26}$$

However, as I mentioned before there are most likely some missing bursts in the gaps. One of them should occur in between the last and the second last observed. Therefore, the burst recurrence time between the last and the second last burst is probably half the observed one. Hence, α_{first} and α_{last}, respectively, probably are

$$\alpha_{first} = 53 \tag{27}$$

$$\alpha_{last} = 55 \tag{28}$$

These two values indicate a mixed hydrogen/helium burning which is triggered by thermally unstable helium ignition.(12). The *alpha* values give a unique opportunity to estimate the composition of the accreted material which in turn can be used for estimating the Eddington luminosity more accurately and hence also the distance to the neutron star in question during an x-ray burst.

5 Discussion

This section will discuss the applicability and prospects of the catalogue I have produced.

As one of my results may have indicated even though you reach the Eddington luminosity due to a photospheric radius expansion the distance you can measure by equation 19 may not be true. Since the source AX J1745.6-2901 is almost right at the centre (359.9203,-00.0420) it is very unlikely it is somewhere on the other side of the galactic center. As this source was an eclipsing x-ray binary(10) it is very likely that some anisotropy is present.(13) Therefore, this has yielded an opportunity to calculate a value of the burst anisotropy factor for this burst, assuming this source is not further away than the centre of our galaxy (8 kpc(14)).

Taking into account the anisotropy factor (Fujimoto 1988), we will make the following correction:

$$F_B = \frac{L_B}{4\pi d^2 \xi_B} \tag{29}$$

In an article by Chenevez et al. from 2015(5) one of the bursts exhibited a photospheric radius expansion in which the distance to the source GS 1826-24 was estimated, however, a possible(if present) anisotropy was included in the formula.

where the ξ_B is the burst anisotropy factor. From this equation it is clear that ξ_B=1 defines burst isotropy. Values of the anisotropy factor $\xi_B < 1$ imply that the burst flux increases and hence most of the burst radiation is directed towards us whereas values of $\xi_B > 1$ imply the exact opposite (Galloway et al. 2017(11)). Yet, distance estimates due to anisotropy may still cause uncertainties in the distance determinations to sources which therefore would make it ideal for next generation telescopes like NICER (which is scheduled to be launched later this year 2017) and ATHENA to be sent into space (Likely in the late 2020's(15).

Another important issue is whether the assumption that the accretion emission is constant during the bursts and which has been my assumption throughout my thesis, however, it turns out that this may not always be true as explained by Degenaar et al. in 2016(16).

Occasionally, there were some deviations from the blackbody model which indicates that other processes do occur. The spectrum of Rise of the burst in AX J1745.6-2901 from OBSID 30002002004 showed some significant deviations which might be due to comptonisation of photons is a hot plasma around the neutron star as shown by Nakamura et al., 1989(17)

In reality, the effects of the gravitational redshift z cause that some of the values we observe on Earth is not what the correct value, but only the observed value. However, I have chosen not consider the effects of any gravitational redshift even though it might not be that difficult imposing Schwarzild metric is applicable and assuming a value of the gravitational redshift. Hence, all things that can be calculated without taking into account a gravitational redshift is a value we observe from the frame of reference of the Earth.

An interesting aspect about the models of the accretion discs used is that several phenomenological models could be implemented to fit the accretion spectra(3-50 keV) whereupon fluxes were extracted. I always started by using the simple power law model, but is was sometimes insufficient to fit the spectra. Generally, I often got better fits by using the broken power law(bknpower) and the double broken power law(bkn2po) instead of the simple power law(po).

6 Conclusion

The main goal of creating a new catalogue of all observed x-ray bursts by August ultimo has been achieved. By providing concrete examples I have shown how this new catalogue can be used to calculate upper limits, distances based upon photospheric radius expansions and some of the relations between recurrence time of x-ray bursts and the accretion flux prior to the x-ray bursts. The absorped blackbody model (tbabs(bbodyrad)) proved to fit quite well in the energy band 3-20 keV (or 3-15 keV) for most time intervals of the bursts. Moreover, the three phenomenological absorbed power laws, power law(tbabs(po)), broken power law(tbabs(bknpower)) and double broken power law(tbabs(bkn2po)) turned out to fit the accretion discs extremely well almost all the times.

This catalogue is huge and therefore all results cannot be presented in this report. Consequently, it is an encouragement to all people interested in this field to use this catalogue for the purpose of enriching the world of high energy astrophysics.

7 Acknowledgements

I would like to thank the NuSTAR team for giving me access to and letting me use available data and software(NuSTARDAS) for my catalogue. Furthermore, I would like to thank the people at DTU Space and at home for assisting me and giving valueable advise for my thesis.

Finally, I want to express my appreciation and my gratitude to my supervisor, senior scientist Jérôme Chenevez at DTU Space, for all assistance rendered me during my work on my thesis.

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Appendices

Appendix A

The intention of making the following appendices (A and B) is to let the reader get the opportunity to see where the absorption columns come from and to see the main scripts used throughout this thesis. The scripts are nupipeline, nuproducts by NuSTARDAS and two x-spec scripts are used where one of them is used for the absorption blackbody model and the other for the absorption powerlaw models.

Appendix A - Absorption columns

obsid	number	Source	Absorption x10^{22}	Reference Absorption
90002002002	1	4U1608-522	1.10	http://iopscience.iop.org/article/10.3847/0004-637X/823/2/131/pdf
30101024002	9	4U1636-536	0.19	http://iopscience.iop.org/article/10.3847/0004-637X/823/2/131/pdf
80001012002	4	4U1728-34	2.5	http://www.sciencedirect.com/science/article/pii/S1384107615001335
80001012004	3	4U1728-34	2.5	http://www.sciencedirect.com/science/article/pii/S1384107615001335
30101051002	3	4U1728-34	2.5	http://www.sciencedirect.com/science/article/pii/S1384107615001335
80001034003	1	AqlX-1	0.36	http://iopscience.iop.org/article/10.3847/0004-637X/823/2/131/pdf
30001002010	2	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
30002002002	1	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
30002002004	1	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
80002013018	4	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
80002013020	2	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
80002013022	2	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
80002013024	1	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
30001002008	1	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
30002002008	1	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
90101012002	1	AXJ1745.6-2901	21.8	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html
80001005002	1	GS1826-24	0.4	http://iopscience.iop.org/article/10.3847/0004-637X/818/2/135/pdf
80001005003	5	GS1826-24	0.4	http://iopscience.iop.org/article/10.3847/0004-637X/818/2/135/pdf
90101001002	1	IGRJ17511-3057	1.02	http://iopscience.iop.org/article/10.1088/0004-637X/755/1/52/pdf
90101013002	1	MXB1658-298	4.2	http://www.aanda.org/articles/aa/pdf/2014/04/aa22044-13.pdf
90001002002	8	SAXJ1748.9-2021	0.82	http://www.sciencedirect.com/science/article/pii/S1384107615001335
90102003002	1	SAXJ1808.4-3658	0.56	http://mnras.oxfordjournals.org/content/457/3/2988.full.pdf+html
30001013004	1	SERX-1	0.3	http://www.aanda.org/articles/aa/pdf/2016/04/aa27752-15.pdf
40031003002	1	GRS1741.9-2853	11.4	http://mnras.oxfordjournals.org/content/454/2/1371.full.pdf+html & Barrière+2015
80001040002	8	1RXSJ180408.9-342058	0.48	http://arxiv.org/pdf/1607.01780v1.pdf
80001040004	11	1RXSJ180408.9-342058	0.48	http://arxiv.org/pdf/1607.01780v1.pdf

Appendix B1 - nupipeline

```
#!/bin/sh
# usage: run_pipe.sh PATH/TO/OBSID

# syntax: run_pipe.sh INDIR
if [ $# != 1 ] ; then
    echo Syntax:  run_pipe.sh PATH_TO_OBSID
    exit 1
fi

# Note, PATH_TO_OBSID is assumed to be relative to the current
```

```
# directory:

INDIR=$1


# Set up your local NuSTAR science environment here:
#if [ -z "$NUSTARSETUP" ]; then
#echo "Need to set the NUSTARSETUP environment variable!"
#exit
#fi
# source $NUSTARSETUP

export CALDB=/home/jerome/Download/CALDB
. $CALDB/software/tools/caldbinit.sh

#export XSELECT_MDB=$CALDB/xselect_nustar.mdb



# Check to see if the TLE file exists. If not, then you need to get newer data:
for TLEFILE in $INDIR/auxil/*TLE*
do
    if [ ! -e $TLEFILE ];
    then
        echo Newer data are required! Please contact nustar-help@srl.caltech.edu
        exit
    fi
done


# Set the pfiles to point to $INDIR/PID_pfiles
# Assumes that INDIR is relative to the current directory
LOCPFILES=${PWD}/${INDIR}/$$_pfiles
if [ ! -d $LOCPFILES ]; then
mkdir $LOCPFILES
fi
#headas_locpfiles $LOCPFILES
export PFILES="$LOCPFILES;$HEADAS/syspfiles"

# Assume that INDIR will be the complete path, and we only want the last bit
# for the stem inputs:
STEMINPUTS=nu`basename ${1}`
OUTDIR=$INDIR/event_cl

if [ ! -d $OUTDIR ]; then
    echo $OUTDIR needs to be produced
```

```
    mkdir -m 750 $OUTDIR
#     chgrp nustar $OUTDIR
fi


logfile=$INDIR/$$_pipe.log

# Set the entry/exit stages here if you want to
# change it from the default of 1 and 2, respectively.
# Only set EXISTAGE=3 if you actually know what you're doing and have
# added correct keywords for effective area, grprmf, vignetting, etc below.

ENTRYSTAGE=1
EXITSTAGE=2

GTISCREEN=yes
EVTSCREEN=yes
GRADEEXPR='DEFAULT'
STATUSEXPR='DEFAULT'
CREATEATTGTI=yes
CREATEINSTRGTI=yes


echo
echo Running pipeline...

nupipeline \
    clobber=yes \
    indir=$INDIR steminput=$STEMINPUTS \
    outdir=$OUTDIR \
    entrystage=$ENTRYSTAGE exitstage=$EXITSTAGE \
    gtiscreen=$GTISCREEN \
    evtscreen=$EVTSCREEN \
    pntra=OBJECT pntdec=OBJECT \
    gradeexpr=$GRADEEXPR statusexp=$STATUSEXPR \
    createattgti=$CREATEATTGTI createinstrgti=$CREATEINSTRGTI >> $logfile 2>&1
```

Appendix B2 - nuproducts

```
#!/bin/sh
# usage: Call run_nuproducts.sh from inside OBSID directory


# syntax: run_nuproducts.sh OBSID FPM?
if [ $# != 2 ] ; then
```

```
    echo "Syntax:  $0 A|B xx ; where xx=obs_mode: 01, 02, 03, 04, 05, or 06"
    exit 1
fi

# Set up your local NuSTAR science environment here:
#if [ -z "$NUSTARSETUP" ]; then
#echo "Need to set the NUSTARSETUP environment variable!"
#exit
#fi
#source $NUSTARSETUP

export CALDB=/home/jerome/Download/CALDB
. $CALDB/software/tools/caldbinit.sh

#export XSELECT_MDB=$CALDB/xselect_nustar.mdb


# Set the pfiles to point to ./PID_pfiles
LOCPFILES=${PWD}/$$_pfiles
if [ ! -d $LOCPFILES ]; then
mkdir $LOCPFILES
fi
#headas_locpfiles $LOCPFILES
export PFILES="$LOCPFILES;$HEADAS/syspfiles"


# Set variables (about data location):
MOD=$1
srcregionfile=$1$2_src.reg
bkgregionfile=bkg$1$2_circle.reg
outdir=./out
OBSID=`basename $PWD`
INSTRUMENT=FPM$1
DATPATH=$PWD/event_cl
STEM=nu`basename $OBSID`
infile=${DATPATH}/${STEM}${MOD}$2_cl.evt


if [ ! -d $outdir ]; then
    echo $outdir needs to be produced
    mkdir -m 750 $outdir
#     chgrp nustar $outdir
fi


extended=no      # Point source
```

```
bkgextract=yes  # Bkg PHA file

runmkarf=yes
runmkrmf=yes
clobber=yes

logfile=nuprod.log

# Call to nuproducts:
nuproducts \
        indir=$DATPATH \
        infile=$infile \
        instrument=$INSTRUMENT \
        steminputs=$STEM \
        extended=$extended \
        bkgextract=$bkgextract \
        bkgregionfile=$bkgregionfile \
        srcregionfile=$srcregionfile \
        usrgtifile=./current_gti.fits \
        pilow=35 pihigh=999 \
        binsize=1. \
        lcenergy=10. \
        lcsrccorrfile=lcsrccorrfile.fits \
        outdir=$outdir \
        runmkarf=$runmkarf runmkrmf=$runmkrmf \
        clobber=$clobber \
        cleanup=yes \
        offaxishisto=DEFAULT \
> $logfile
#       srcra=277.3675 srcdec=-23.796944 \
#        pilow=30 pihigh=999 \
#        pilow=710 pihigh=1209 \
#        pilow=585 pihigh=1899 \
#        pilow=10 pihigh=709 \
#        pilow=710 pihigh=1899 \

# Prepare the output spectrum files:
outname=${STEM}${MOD}$2
cd $outdir
fthedit "${outname}_sr.pha[1]" ANCRFILE add ${outname}_sr.arf
fthedit "${outname}_sr.pha[1]" RESPFILE add ${outname}_sr.rmf
fthedit "${outname}_sr.pha[1]" BACKFILE add ${outname}_bk.pha

rm -R -f $LOCPFILES
```

Appendix B3 - Burst script

```
#Call by: xspec - auto_xspec
#Followed by: autorun dir_name Oid


proc autorun {Burst_nr intv.dir dataType} {
query yes
cd ${intv.dir}

set fileid [open fit_BB_net.dat w]
cpd /cps

  data nu80001040002A${dataType}_sr.pha, nu80001040002B${dataType}_sr.pha
  backgrnd ../Ae_Burst${Burst_nr}.out/nu80001040002A01_sr.pha,
 ../Ae_Burst${Burst_nr}.out/nu80001040002B01_sr.pha

  setplot energy
  ignore **:**-3. 20.-**

  abund wilm
  xsect bcmc
  weight churazov

 tclout expos 1
 set pex [scan $xspec_tclout "%f"]
 set exp [format "%.2f" $pex]

  setplot reb 20 20
  setplot com r y2 0.5 1.5
  setplot com label OT 1RXSJ180408.9-342058 NuSTAR 80001040002 Burst 1
  setplot com label top Net burst spectrum: absorbed blackbody (${exp}s)

  mo TBabs*(bbodyrad)
/*
  newpar 1 0.48 -1
  newpar 2 2.

#  statistic cstat
  fit

#  plot ldata ra
  log
  show
```

```
  err 2 3
  flux 2. 100. err

  tclout param 2
  set par1 [string trim $xspec_tclout]
  tclout err 2
  set err1 [string trim $xspec_tclout]
  puts $fileid "[lindex $par1 0] [lindex $par1 6] [lindex $err1 0]
 [lindex $err1 1]"
  tclout param 3
  set par2 [string trim $xspec_tclout]
  tclout err 3
  set err2 [string trim $xspec_tclout]
  puts $fileid "[lindex $par2 0] [lindex $par2 6] [lindex $err2 0]
 [lindex $err2 1]"
  tclout stat
  set chistat [string trim $xspec_tclout]
  tclout dof
  set d_o_f [string trim $xspec_tclout]
  puts $fileid "[lindex $chistat 0] [lindex $chistat 6] [lindex $d_o_f 0]
 [lindex $d_o_f 6]"
  tclout flux 1
  set fabs [string trim $xspec_tclout]
  puts $fileid "[lindex $fabs 0] [lindex $fabs 1] [lindex $fabs 2]"

  setplot com label file kT=[lindex $par1 0]keV  BB_norm=[lindex $par2 0]
  plot ldata ra

  dummyrsp 0.1 100.
  flux 0.1 100.
  newpar 1 0.
  flux 0.1 100.
#  response

  tclout flux 1
  set fbol [string trim $xspec_tclout]
  puts $fileid "[lindex $fbol 0]"
  close $fileid

  exec /bin/mv pgplot.ps net_XrB_spe.ps
  exec /bin/mv xspec.log A+B_xspec.log

exit
}

#autorun Peak.out
```

Appendix B4 - Accretion script

```
\\
\\
#Usage in xspec:
# source auto_xspec_net.xcm
# autorun-xspec dir_name A|B

proc autorun-xspec {Burst_nr intv.dir dataType} {

cd ${intv.dir}

query yes

set fileid [open fit_po_net.dat w]
cpd /xs

  data nu80001040002A${dataType}_sr.pha, nu80001040002B${dataType}_sr.pha
  backgrnd nu80001040002A${dataType}_bk.pha, nu80001040002B${dataType}_bk.pha

  setplot energy
  ignore 1:1 **-3. 50.-**
  ignore 2:2 **-3. 50.-**

  abund wilm
  xsect vern
  weight churazov

 tclout expos 1
 set pex [scan $xspec_tclout "%f"]
 set exp [format "%.2f" $pex]

  setplot reb 10 10
  setplot com r y2 0 2
  setplot com label OT NuSTAR accretion emission ${Burst_nr} 80001040002${dataTy
  setplot com label top Net persistent spectrum: absorbed PL (${exp}s)

  mo TBabs(po)
 /*
  newpar 1 0.48 -1
  fit

  pl ldata ra
  cpd /ps
```

```
  pl

  log
  show

flux 2. 100. err

tclout stat
  set chistat [string trim $xspec_tclout]
  tclout dof
  set d_o_f [string trim $xspec_tclout]
  puts $fileid "[lindex $chistat 0] [lindex $chistat 6] [lindex $d_o_f 0]
 [lindex $d_o_f 6]"
  tclout flux 1
  set fabs [string trim $xspec_tclout]
  puts $fileid "[lindex $fabs 0] [lindex $fabs 1] [lindex $fabs 2]"

  dummyrsp 0.1 100.
  flux 0.1 100.
  newpar 1 0.
  flux 0.1 100.
#  response

  tclout flux 1
  set fbol [string trim $xspec_tclout]
  puts $fileid "[lindex $fbol 0]"
  close $fileid

  exec /bin/mv xspec.log xspec_Ae.log

exit
}
```