
Study of low frequency Quasi-Periodic Oscillations in accreting black hole binaries

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1 Introduction

1.1 X-ray binaries (XRBs)

X-ray binaries (XRBs) are a class of binary stars that are luminous in X-rays. They are double systems formed by a stellar remnant that has collapsed to a compact object (a black hole or a neutron star) and has remained gravitationally bound to its companion. The X-rays are produced by matter falling from the companion star (donor) to the compact object (accretor). This accretion flow from the donor to the accretor results in an *accretion disk* around the compact object, where the angular momentum of matter is transported outwards and the gravitational potential energy is converted in kinetic energy and radiation.

Depending on the type of compact object, XRBs can be either BHBs (black hole binaries) or NSBs (neutron star binaries). XRBs can also be classified on the donor mass [see *Fig. 1*] -

- **Low mass XRBs (LMXBs)** : In LMXBs the companion star has evolved to fill its *Roche lobe*¹ and is transferring materi (see *Fig. 1*)al through the inner *Lagrangian point*², L_1 , onto the compact object. Such mass transfer is only stable if the donor star is less massive than the compact object. Due to this, LMXBs are optically faint although they are bright in X-rays.
- **High mass XRBs (HMXBs)** : In HMXBs the material for transfer onto the compact object is provided by a powerful *stellar wind* from an early-type, massive star (usually an O an B type star). A fraction of the stellar wind of the massive normal star is captured by the compact object, and produces X-rays as it falls onto the compact object. Optically, the high mass companion star dominates because it is extremely luminous.

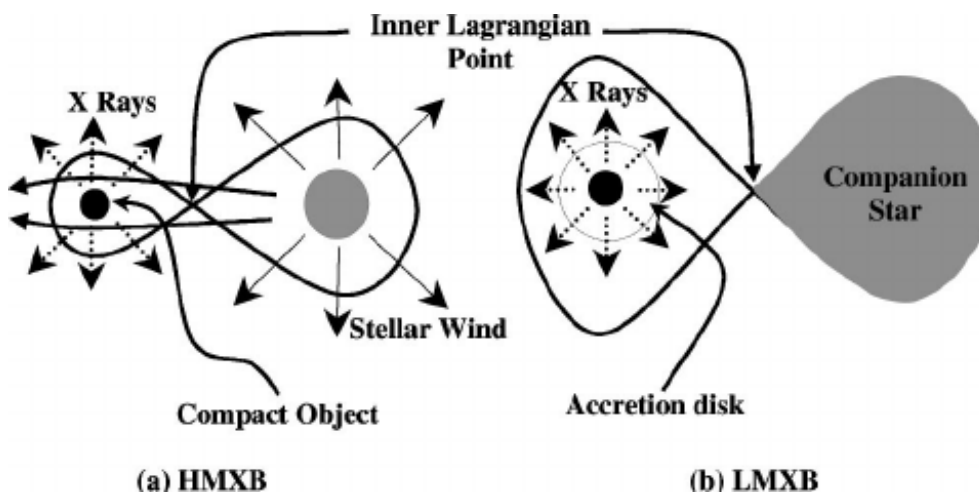


Figure 1: LMXBs vs HMXBs

¹The region around a star in a binary system within which orbiting material is gravitationally bound to that star. It is an approximately tear-drop-shaped region.

²Positions in an orbital configuration of two large bodies, wherein a small object, affected only by the gravitational forces from the two larger objects, will maintain its position relative to them.

1.2 Transient states in XRBs

Only a few BHBs are persistent sources. Almost all other XRBs are transient systems. They spend most of the time in a low accretion regime (with low count rate). The accretion rate onto the central objects increases by orders of magnitude and the sources go into outburst for a time that can range from a few days to several months. When the long-term evolution of an outburst is represented in a *Hardness-Intensity Diagram*³ (HID), strong regularities emerge. In most BHBs, four different canonical states are found to correspond to different branches of a q-shaped HID pattern [see *Fig. 2*]. The states are -

- **Low hard state (LHS)** : Emission is dominated by a strong *Comptonized*⁴ component, occasionally accompanied by a cool and faint thermal component associated to a truncated disk. Variability is high.
- **High soft state (HSS)** : Emission is dominated by a strong *thermal* component (black-body radiation), associated to an accretion disk whose radius can extend down to the Innermost stable circular orbit (ISCO). Variability is low.
- **Low intermediate state (LIMS) and High intermediate state (HIMS)** : Both components are present. Variability can vary a lot.

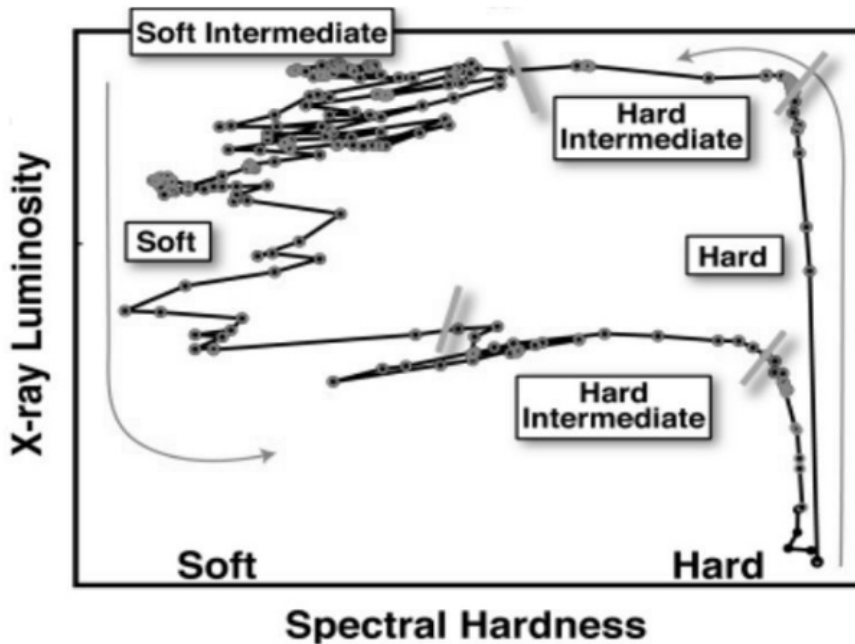


Figure 2: Typical Hardness-Intensity Diagram of XRBs

³X-rays with high photon energies (above 510 keV) are called hard X-rays, while those with lower energy are called soft X-rays. The ratio of counts in two separate bands roughly gives the hardness of a spectrum.

⁴Inverse Compton scattering involves the upscattering of low energy photons to high energies by relativistic electrons so that the photons gain and the electrons lose energy.

1.3 Quasi-periodic oscillations (QPOs)

BHBs can also show variability in much smaller time scales. Fourier analysis is used for this *fast-time variability*. Fast (aperiodic and quasi-periodic) variability is generally studied through the inspection of power density spectra (PDS). For a discrete time series x_t , $t = 0, 1, 2, \dots, N - 1$, the discrete Fourier transform (DFT) is given as -

$$y_f = \frac{1}{\sqrt{N}} \sum_{t=0}^{N-1} x_t e^{\frac{2\pi i t f}{N}}, \quad f=0, 1, 2, \dots, N - 1$$

and the PDS is given as $P_f = |y_f|^2$.

Different features can be observed in the PDS of BHBs, like broadband noise (present in all frequencies) and much narrower peaks - *quasi-periodic oscillations*(QPOs). Periodic oscillations would appear as single frequency peaks in the PDS. However, QPO peaks are broader and take a *Lorentzian* shape.(QPOs). A Lorentzian (Cauchy distribution) is the distribution of the ratio of two independent normally distributed random variables if the denominator distribution has mean zero. It is given as -

$$h(f) = \frac{1}{2\pi} \left[\frac{K \cdot \sigma}{(f - f_0)^2 + (\sigma/2)^2} \right]$$

where f_0 is the centroid of the peak, σ is the full-width half-maximum (FWHM) of the peak and K is the scaling factor.

The exact origin of QPOs is not very well understood, although there have been various models proposed. They are thought to provide information on the accretion processes involved. They are divided into two main branches - Low frequency QPOs (few mHz to below 50 Hz) and High frequency QPOs (above 100 Hz to a few kHz). In this project, only LFQPOs are encountered.

Low frequency QPOs (LFQPOs) : LFQPOs are divided into three main types based mainly on QPO centroid frequency and width (also energies and phase lags) [see *Fig. 3*]. They are as follows :

- **Type A :** Weak and broad peak at 6 – 8 Hz. Subharmonic and harmonic⁵ peaks are usually not present.
- **Type B :** Relatively strong and narrow peak around 6 Hz or 1 – 3 Hz. Weak harmonic peak is usually present, sometime along with a subharmonic peak.
- **Type C:** Strong, very narrow and variable peak at 0.1 – 15 Hz. Subharmonic and harmonic peaks are often present, sometimes with a third harmonic peak.

⁵For fundamental frequency f , the frequencies $f/2, f/3, \dots$ are its subharmonics, and $2f, 3f, \dots$ are its harmonics. They arise in the PDS due to the discrete Fourier transform (DFT) and are mostly false peaks.

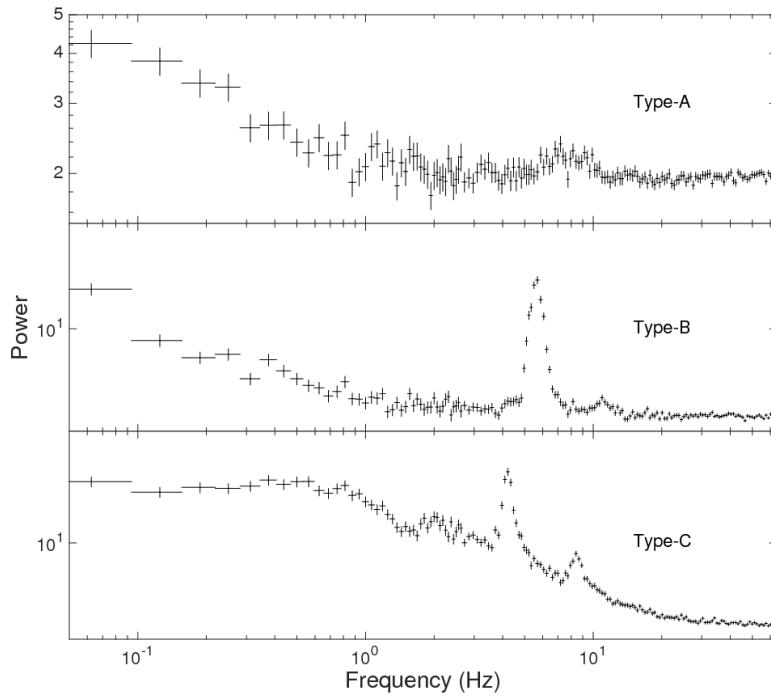


Figure 3: Main types of LFQPOs

In a paper by *S. Motta et al. (2011)*, LFQPOs have been classified based on the Total fractional rms⁶ vs. QPO centroid frequency plot. This has been done for various observations of the source GX 339-4 over a few years [see *Fig. 4*].

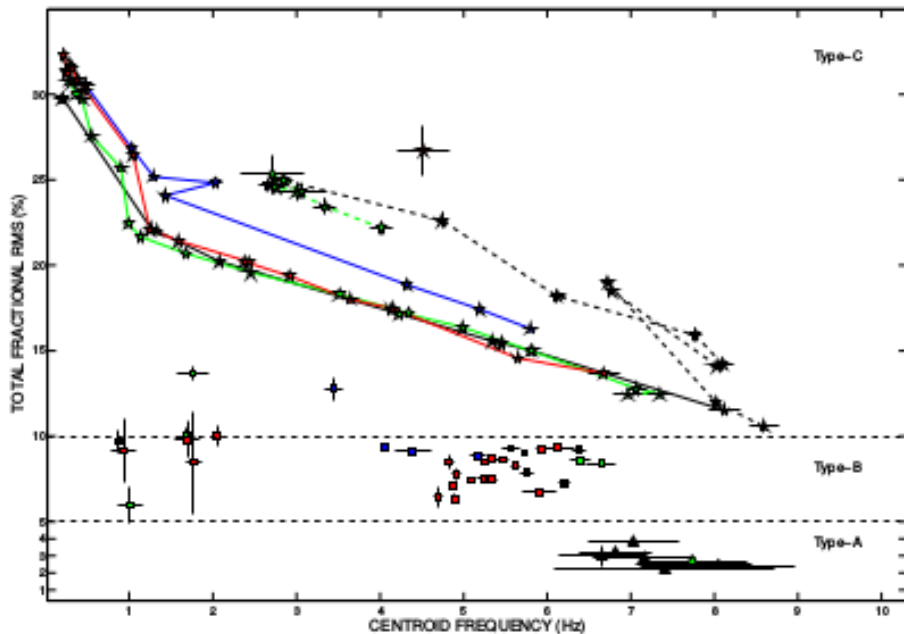


Figure 4: Total fractional rms vs. QPO centroid frequency plot (different symbols refer to different observations)

⁶Flux of an observation is the integral under its PDS (minus broadband noise). Fraction rms is given as $\sqrt{\frac{F \cdot C}{(C - B)^2}} \times 100\%$, where F is flux, C is mean source count rate, B is mean background count rate.

1.4 X-ray telescopes

There are many telescopes which probe the X-ray sky - Chandra X-Ray Observatory (CXO), Rossi X-Ray Timing Explorer (RXTE), Neil Gehrels *Swift* Observatory, XMM-Newton to name a few. However, in this project, data from two telescopes have been used - Astrosat LAXPC and NuSTAR.

- **Astrosat LAXPC** : Astrosat is India's first dedicated multi-wavelength space observatory. It performs observations covering spectral bands from radio, optical, IR, UV, and X-ray wavelengths. The scientific payload contains six instruments, one of which is LAXPC (Large Area X-ray Proportional Counter). Astrosat covers X-ray timing and low-resolution spectral studies over a broad energy band (380 keV) with a cluster of 3 co-aligned LAXPCs.
- **NuSTAR** : NuSTAR (Nuclear Spectroscopic Telescope Array) is the eleventh mission of NASA's Small Explorer satellite program and the first space-based direct-imaging X-ray telescope at energies beyond those of the Chandra X-ray Observatory and XMM-Newton. It consists of two co-aligned high-energy X-ray optic units with two shielded detectors. NuSTAR detects X-rays with energies between 3 and 80 keV.

1.5 Software and programs

For this project, two software have been used - GHATS and XSPEC.

- **GHATS** : General High-Energy Aperiodic Timing Software (GHATS) was written in the Interactive Data Language (IDL) by Dr. Tomaso Belloni for aperiodic timing analysis. Initially written for the analysis RXTE PCA (Proportional Counter Array) data, it has been extended for NuSTAR and Astrosat as well. The program itself accumulates its own light curves and discards them at the end. Timing analysis based on Fourier Transforms is essentially based upon two separate steps. The first is the production of Power Density Spectra (PDS) or Fast Fourier Transforms (FFT). The second is the analysis of the products.
- **XSPEC** : XSPEC is a command-driven, interactive, X-ray spectral-fitting program, designed to be completely detector-independent so that it can be used for any spectrometer. It was developed by NASA's The High Energy Astrophysics Science Archive Research Center (HEASARC) as a part of the HEASoft software. XPEC can be used to analyze data from RXTE, Chandra, XMM-Newton, Swift, NuSTAR, Astrosat to name a few. It has various models and functions which can be used to fit the PDS of observed data.

The programming language used in this project is IDL, which is popularly used in particular areas of science, such as astronomy, for data analysis.

2 My project

2.1 Objective

To perform fast-timing analysis of signals from BHB SwiftJ1658, produce PDS for different observations and analyze (and classify) the resulting LFQPOs.

2.2 Procedure overview

The general procedure for the analysis is as follows:

1. Astrosat LAXPC data is in the form of *.fits* files and NuSTAR data in the form of *.evt* files. These files are read using GHATS commands.
2. The corresponding *.pds* files are generated by specifying various parameters. Now, the light curve and the PDS can be extracted.
3. The PDS of each observation is imported to XSPEC for fitting various models, which are described later.
4. Using XSPEC, fitted model parameters and errors are saved in files. These values are used for analyzing the spectrum.
5. Various parameters are plotted against each other, analyzed and conclusions are made.

The above procedure is explained in great detail in the subsequent sections.

2.3 GHATS - Obtaining PDS and light curve

After installation, the GHATS environment is launched in the terminal using the command `ghats`⁷. The processes for obtaining the PDS of Astrosat LAXPC and NuSTAR data are not the same, but extremely similar. The GHATS command `gh_laxpc_misra` is used for the former, and the command `gh_nustar` for the latter. The command parameters include filename - *.fits* or *.evt* file, or a file containing the list of files to be read. The various prompts and parameters are described below :

- **Astrosat LAXPC data :**

```
Ghats> gh_laxpc_misra, gti=filename
```

Here, *filename* refers to the file containing the 'good time intervals' of the observation. At this point, a window pops up and the user is required to select the respective *.fits* file or a file containing the list of *.fits* files. After choosing the file, parameter values need to be specified.

⁷For detailed information about various commands, refer to the GHATS manual.

Choose channels for accumulation

ALL: All channels

RANGE: Continuous range of channels

UNIT: Separate range for LAXPC units

ENERGY: energy range in keV. If negative, channels will be computed from DRM. If po

(ALL) -> :

ALL is the default value, which selects data from all energy bands. To choose specific energy bands (for example 3-10 keV or 10-30 keV), the *ENERGY* option is chosen. In this project, most of the analysis is done in all the bands.

Choose type of accumulation

POWER: Power spectra (PDS file)

FFT: Fourier spectra (FFT file)

(POWER) -> :

The default option *POWER* is to obtain the PDS. To obtain the FFT, the other option is chosen.

Units to accumulate : 123

Enter units -> :

Layers to accumulate : 12345

Enter layers -> :

Default output filename : level2.event.fits.pds

Enter output filename -> :

The output file name has to be specified. The extension of the file is either *.pds* or *.fft*, depending on the analysis.

Available time resolution: 9.9999998e-06 seconds

Enter rebinning factor in time (1) -> : 50

% Compiled module: NINT.

Default # of points per FFT 16384 (8.1919998 seconds)

Enter # of points per FFT-> : 16384

% Compiled module: MU_POWER_OF_TWO.

% Compiled module: PRINO.

The time resolution is 10^{-5} s, which corresponds to a frequency resolution of 10^5 Hz. We don't expect anything for such a high frequency, except noise. Thus, a rebinning factor

of 50 results in a frequency resolution of 2000 Hz. The Nyquist frequency⁸ is now 1000 Hz, which seems optimum (well above the expected LFQPO frequencies). The number of points used for one FFT is 16384, which corresponds to 8.192 s (one point corresponds to 0.5 ms after rebinning).

- **NuSTAR data :**

```
Ghats> gh_nustar
```

At this point, a window pops up and the user is required to select the respective *.evt* file or a file containing the list of *.evt* files. After choosing the file, parameter values need to be specified.

```
Overview of available channels: all channels 0-4095
```

```
Choose channels for accumulation
```

```
ALL: All channels
```

```
RANGE: Continuous range of channels
```

```
(ALL) -> :
```

```
Choose type of accumulation
```

```
POWER: Power spectra (PDS file)
```

```
FFT: Fourier spectra (FFT file)
```

```
(POWER) -> :
```

```
Default output filename : AB.pds
```

```
Enter output filename -> :
```

```
Available time resolution: 0.0020000001 seconds
```

```
Enter rebinning factor in time (1) -> : 1
```

```
Default # of points per FFT 8192 (16.384001 s)
```

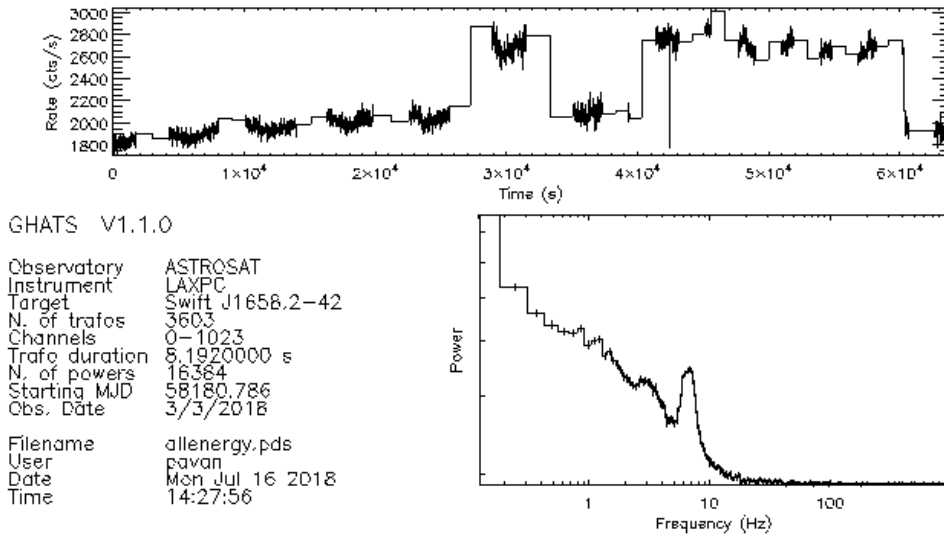
```
Enter # of points (I) or time length (R) per FFT-> : 8192
```

The explanation is very similar here. In this case, the time resolution is only 2 ms, which corresponds to a frequency resolution of 500 Hz and a Nyquist frequency of 250 Hz. There is no requirement to reduce this further. The number of points used for one FFT is 8192, which corresponds to 16.384 s (one point corresponds to 2 ms).

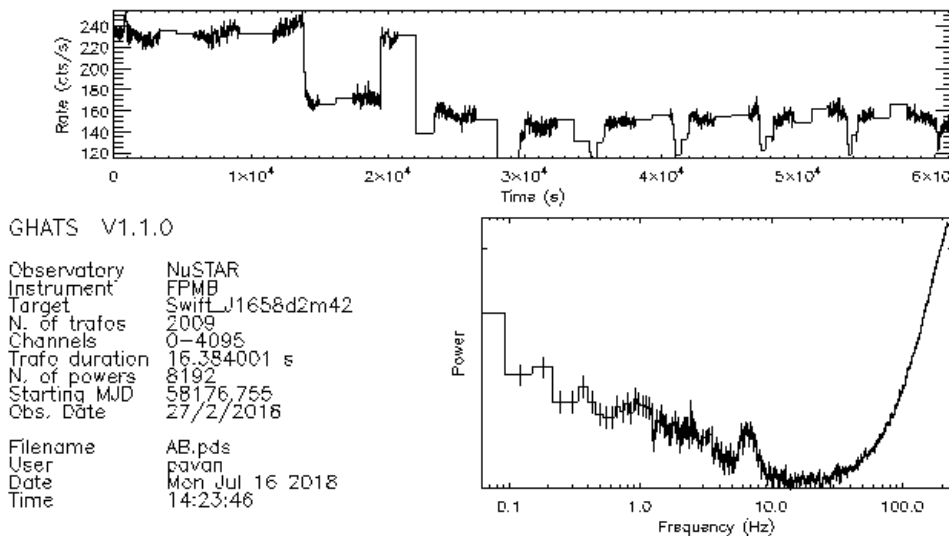
⁸The highest frequency that can be coded at a given sampling rate in order to be able to fully reconstruct the signal. It is half of the sampling rate of a discrete signal processing system. Undersampling can result in aliasing, which refers to the distortion that results when the signal reconstructed from samples is different from the original continuous signal

The output is now ready to be analyzed. The command `ghats_all` can be used to get the overview - the light curve, the PDS, information about the observation (date, instrument, etc.), all in a single window. From this, one can easily observe the differences in sensitivities between the two instruments [see *Fig. 5*]. The light curves reveal that LAXPC count rates (1500 – 3000 /s) are much higher than NuSTAR count rates (50 – 150 /s). The PDS reveal that NuSTAR data tends to have increasingly high noise above 30 Hz (approximately), whereas Astrosat data does not. Thus, it is necessary to truncate the data to an optimal limit.

In this project, **two LAXPC** observations (**Feb 20** and **Mar 3**) and **six NuSTAR** observations (**Feb 16**, **Feb 27**, **Mar 4**, **Mar 11**, **Mar 15** and **Mar 26**) have been analyzed and compiled together. All observations were made in 2018, and were within 40 days of each other.



(a) LAXPC Obs 2 (Mar 3)



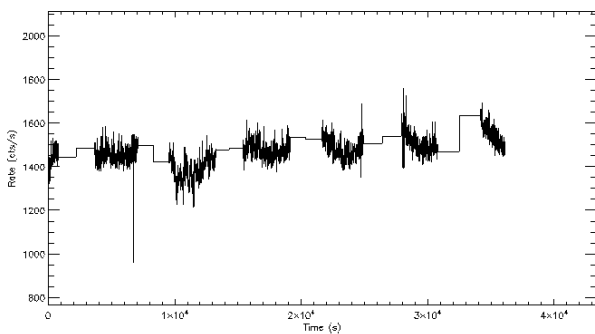
(b) NuSTAR Obs 2 (Feb 27)

Figure 5: Difference in instrument count rates and high frequency behaviour

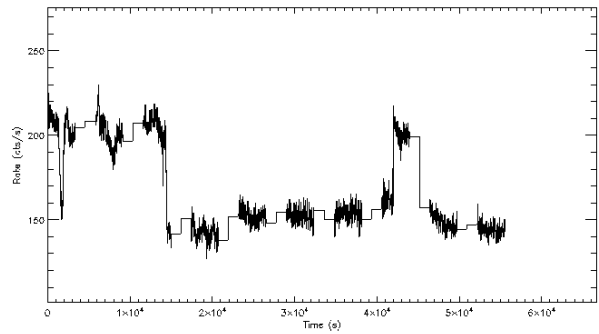
To extract the light curve parameters, the command `gh_licu` is used.

```
Ghats> gh_licu,pdsfile,time,rate
Ghats> gh_plot_licu,time,rate
```

Here, *pdsfile* refers to the file from which data is to be extracted. The light curve values are stored in two arrays called (in this case) *time* (time values) and *rate* (count rate values). These arrays can be manipulated, and the light curve can be plotted using the `gh_plot_licu` command. The light curve of each observation looks different, with certain regions having lower counts and others having higher counts [see *Fig. 6*].



(a) LAXPC Obs 1 (Feb 20) - one level



(b) NuSTAR Obs 3 (Mar 4) - two levels

Figure 6: Light curves of different observations indicating different 'states'

To extract the PDS parameters, the command `ghx` is used.

```
Ghats> ghx,pdsfile,freq,pow,pow_e,time=[starttime,endtime]
Ghats> gh_reb,freq,pow,pow_e,-100,rebfreq,rebpow,rebpow_e
Ghats> gh_plot_power,rebfreq,rebpow,rebpow_e
```

Here, *pdsfile* refers to the file from which data is to be extracted. The PDS values are stored in three arrays called (in this case) *freq* (frequency values), *pow* (power values) and *pow_e* (power error values). The *starttime* and *endtime* values are real numbers which refer to the time interval for which PDS extraction is being done. The `gh_reb` command is used to rebin the data into new arrays *rebfreq*, *rebpow* and *rebpow_e*. Positive values refer to linear bins while negative ones refer to logarithmic bins⁹ [see *Fig. 7*]. A factor of -100 results in each bin being 1% larger than the previous one. These arrays can be manipulated, and the PDS can be plotted using the `gh_plot_power` command.

⁹Since the PDS plots are logarithmic, rebinning is also usually done logarithmically. No rebinning results in unnecessarily large number of data points at higher frequencies, which do not matter much anyway.

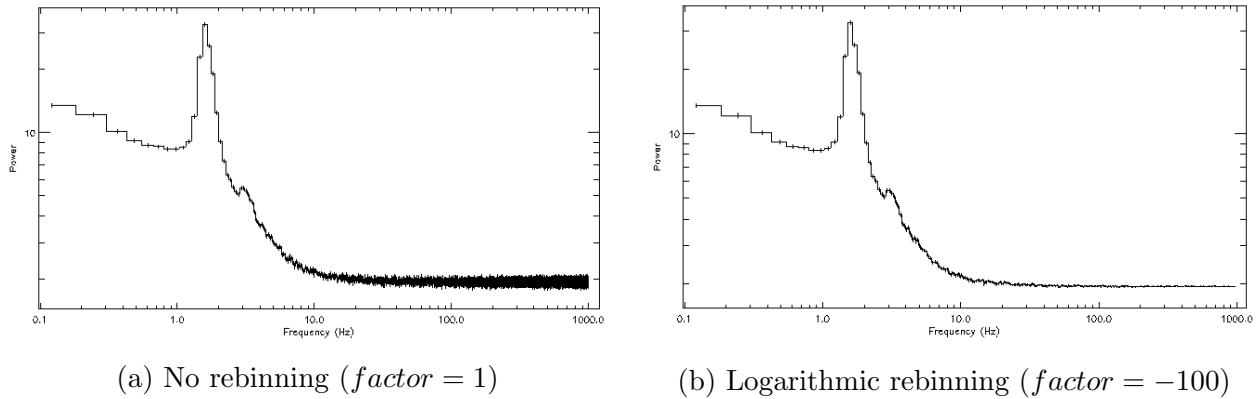


Figure 7: PDS of LAXPC Obs 1 (Feb 20) with different rebinning factors

This process is repeated for different time intervals of different observations. The 'high count' and 'low count' regions are dealt with separately to see how the PDS varies. This can be seen in the next section.

Next, the PDS have to be exported to XSPEC for spectral fitting. The command `gh_xspec` is used for this purpose.

```
Ghats> gh_xspec, rebfreq, rebpow, rebpow_e, output
```

Here, `rebfreq`, `rebpow` and `rebpow_e` arrays (described previously) are the inputs. There are two outputs for this command - the `.pha` (spectral data file) and the `.rmf` (response file). Now, the data is ready to be fitted.

2.4 XSPEC - Fitting PDS with models

After installation of HeaSOFT, XSPEC (Version 12) is launched in the terminal using the command `xspec`¹⁰. The inputs to the fitting module are the `.pha` and the `.rmf` files mentioned previously.

```
XSPEC12> cpd /xs
XSPEC12> setplot energy
```

Here, `cpd` (change plotting device) opens a pgplot Windows X-server `xs` (in this case) plot window to view data and models. By default, data is plotted against channel number. The command `setplot` changes the plot parameter to energy¹¹.

```
XSPEC12> data fitfile
XSPEC12> plot data
```

¹⁰For detailed information about various commands, refer to the XPEC manual.

¹¹XSPEC was originally designed for fitting energy spectra (counts vs. energy). In this project, PDS (counts vs. frequency) are fitted. Thus, in this case, *energy* actually refers to *frequency*.

Here, *fitfile* refers to the common name of the *.pha* and the *.rmf* files (same as *output* of *gh_xspec*). The `plot` command is used to plot the input data.

The functions used for fitting PDS are described below :

- **Power law** : A power law profile is given as -

$$A(E) = K \cdot E^{-\alpha}$$

where α is the photon index and K is the scaling factor.

The PDS of a BHB contains broad-band noise, which is approximately the same at all frequencies. A power law component of photon index of approximately 0 (i.e. constant noise) is hence incorporated.

- **Lorentzian** : A Lorentzian profile is given as -

$$A(E) = \frac{1}{2\pi} \left[\frac{K \cdot \sigma}{(E - E_L)^2 + (\sigma/2)^2} \right]$$

where E_L is the line energy, σ is the FWHM of the peak and K is the scaling factor.

QPO peaks, as mentioned previously, have a Lorentzian profile. Also, the PDS of a BHB tends to have broad Lorentzian component centered around 0.

As mentioned before, so-called energy parameters in the functions are actually frequency parameters.

In XSPEC, a model is added using the `model` command, followed by the function (*(lorentz)*, *powerlaw*, etc.).

```
XSPEC12> model powerlaw
```

```
1:powerlaw:PhoIndex>
```

```
2:powerlaw:norm>
```

This is an example of a powerlaw model. *PhoIndex* and *norm*, refer to the parameters α and K described previously. If these tentative parameter values are not supplied, the default values are chosen.

```
XSPEC12> model lorentz
```

```
1:lorentz:LineE>
```

```
2:lorentz:Width>
```

```
3:lorentz:norm>
```

This is an example of a Lorentzian model. *LineE*, *Width* and *norm*, refer to the parameters E_L , σ and K described previously. If these tentative parameter values are not supplied, the

default values are chosen.

The `help` command can be used any time for information about models or commands. A few other important commands are given below :

- `addcomp` appends extra components.
- `delcomp` removes unwanted components.
- `ignore` rejects bad data points (or a range of points).
- `notice` does the inverse of `ignore`.
- `newpar` changes individual parameter values.
- `freeze` fixes the value of a parameter during fitting.
- `thaw` does the inverse of `freeze`.

After suitable number of components are added, bad data ignored and parameter values tweaked, a final best fit can be performed using the `fit` command. Fitting continues until either the minimum χ^2 is attained or the process is stopped by the user. The 'goodness of fit' or χ^2 test minimizes

$$\chi^2 = \sum_{i=1}^n \frac{(O_i - E_i)^2}{E_i}$$

where, O_i and E_i are the observed and expected (as per model) data values respectively. The previously mentioned `plot` command can be used to plot a lot of things - *data*, *ldata* (logarithmic data), *model*, *chi* (fitting errors), *ufspec* (unfolded spectrum and model), etc.

The fit can be further refined by using the `error` command, which minimizes the error of each component individually, within a user defined limit. Finally, the best fit can be saved to a file for future reference.

```
XSPEC12> save all datafile
XSPEC12> @datafile
```

Here, `save all` saves the parameter values, along with the commands required to obtain the model. The output *datafile* is of the format *.xcm*. The same model can be reused using the prefix `@` followed by the filename.

The flux (area under the PDS spectrum) can be easily obtained using the `flux` command. Before doing this, the power law component must be removed (using `delcomp`) to get the actual flux (without noise). To calculate the fractional rms, background count rate is required. For LAXPC, background is available, and the rate can be obtained from XSPEC by loading the background *.pha* and *.rmf* files. The command `show rate` displays the background count

rates. NuSTAR data is assumed to have negligible background. Now, the fractional rms is calculated using the formula

$$\sqrt{\frac{F \cdot C}{(C - B)^2}} \times 100\%$$

where F is flux, C is mean source count rate, B is mean background count rate.

By comparing average count rates of both instruments, it is evident that LAXPC rates are approximately 12-13 times those of NuSTAR. Thus, NuSTAR count rates of ~ 150 /s and ~ 200 /s correspond to ~ 2000 /s and ~ 2500 /s respectively for LAXPC. This is clearly observed in the corresponding light curves.

As described in the introduction, various 'types' of QPOs can be identified just by observation [see *Fig. 8* and *Fig. 9*].

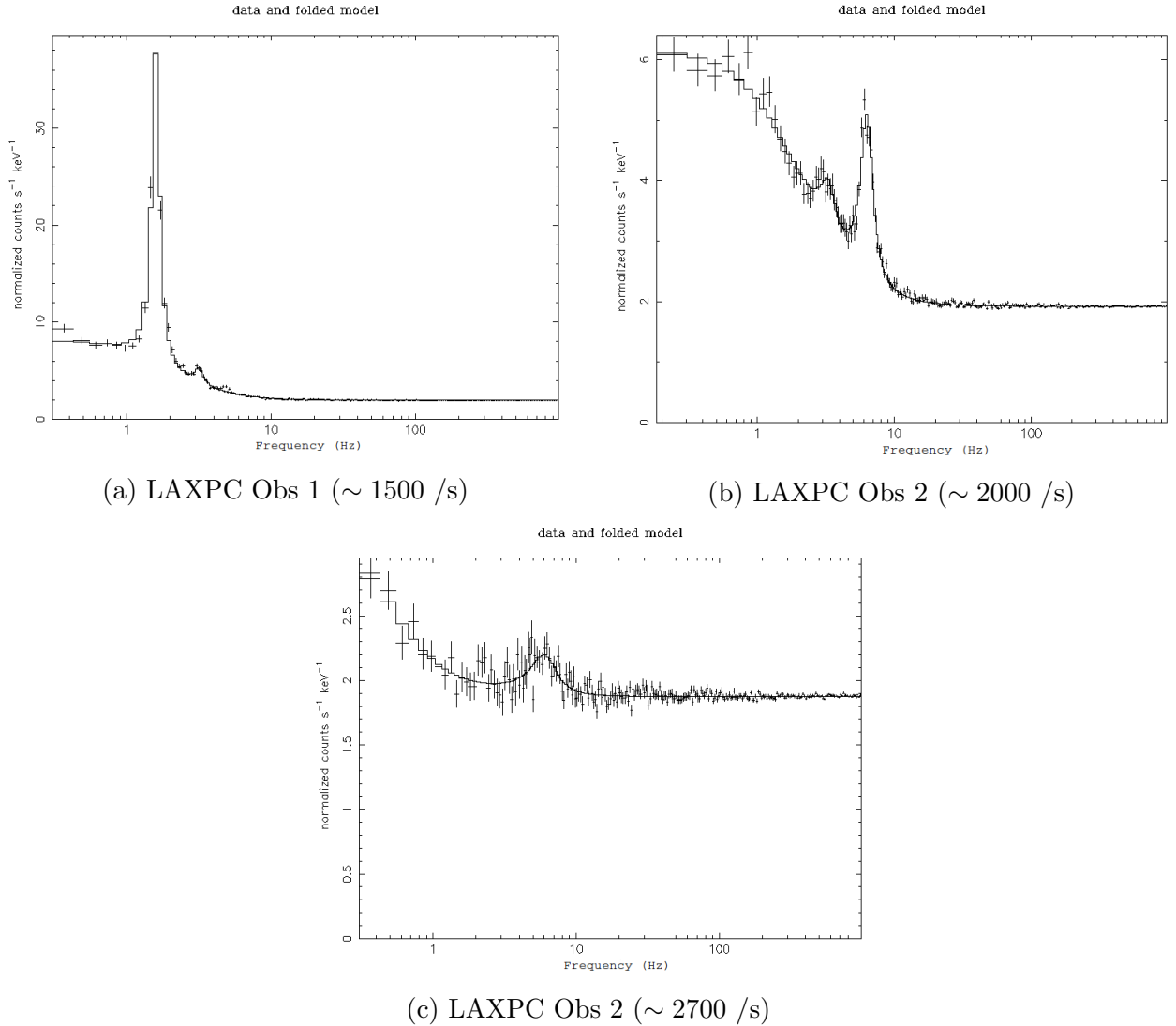
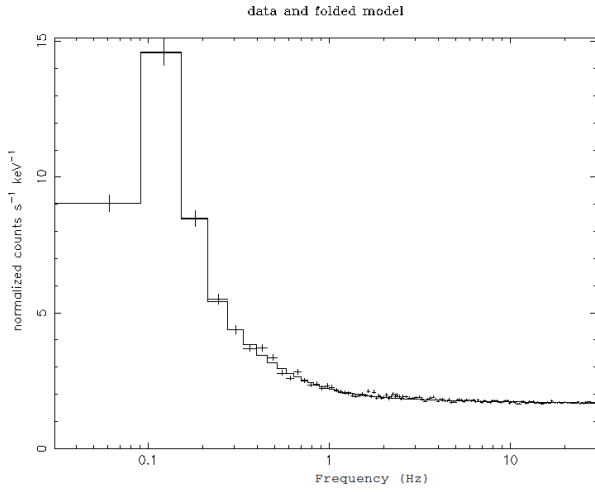
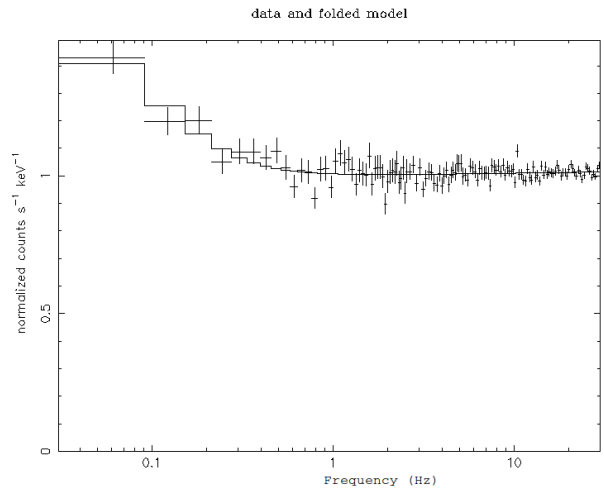


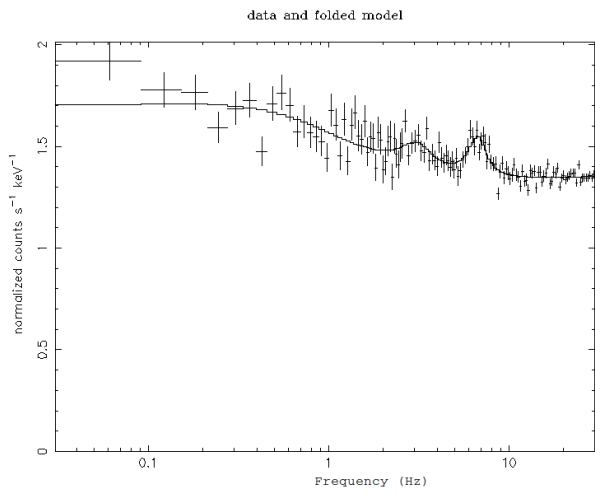
Figure 8: PDS of LAXPC Observations of different count rates (in parantheses)



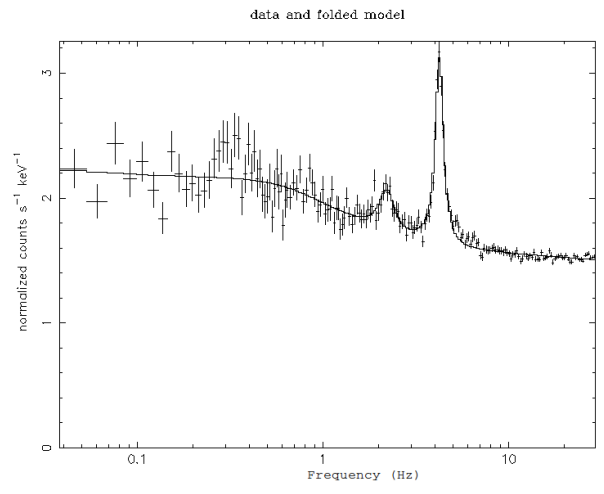
(a) NuSTAR Obs 1 (~ 70 /s)



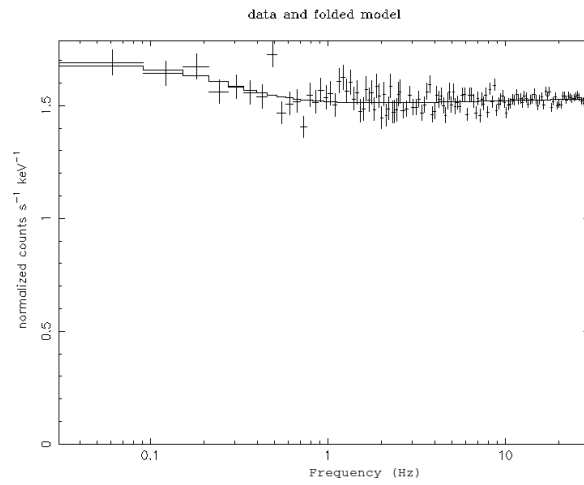
(b) NuSTAR Obs 2 (~ 230 /s)



(c) NuSTAR Obs 2 (~ 150 /s)



(d) NuSTAR Obs 3 (~ 110 /s)



(e) NuSTAR Obs 6 (~ 90 /s)

Figure 9: PDS of NuSTAR Observations of different count rates (in parantheses)

2.5 Analyzing the data

The fractional rms vs. QPO (fundamental) frequency plot is extremely similar [see *Fig. 10*] to the plot of the source GX 339-4 given in the paper by *S. Motta et al. (2011)*, as shown in the introduction section.

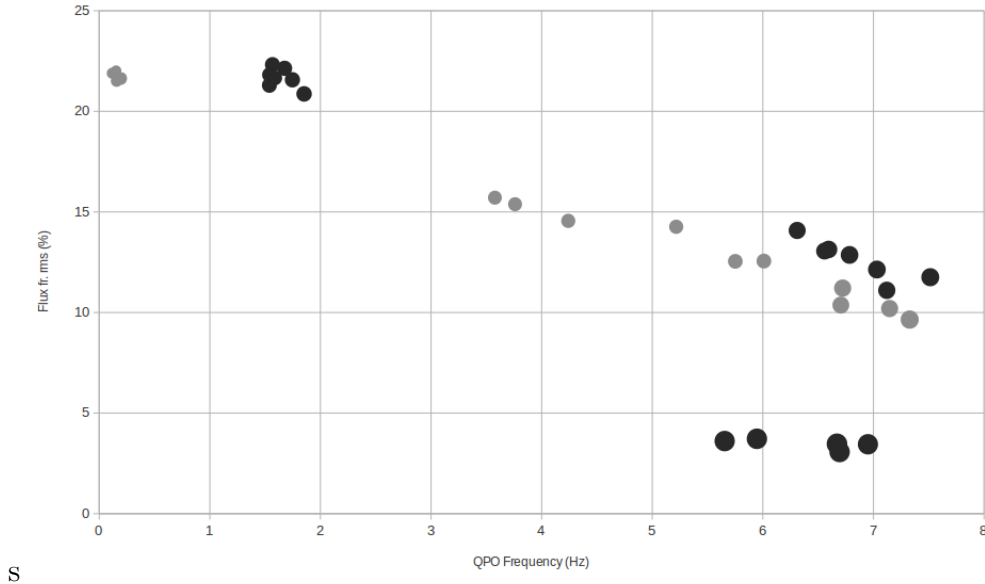


Figure 10: Total fractional rms vs. QPO centroid frequency plot (**gray bubbles** : NuSTAR data, **black bubbles** : LAXPC data); bubble sizes indicate relative count rates (NuSTAR data are multiplied by a factor 12.5 to compensate for instrument sensitivity variation)

The plot clearly separates Type A and Type C QPOs. Type B QPOs are not observed in this plot. The data bubble sizes, indicating the relative count rates, show the type transitions. The plot is described in detail below :

- The highest count rate regions in LAXPC data (~ 2700 /s) have very low fractional rms of less than 5 %, and QPO frequencies in the range 5 – 7 Hz. These QPO peaks are low and broad. This is typical of **Type A** QPOs. Corresponding high count regions in NuSTAR data (~ 230 /s) do not seem to have observable peaks (large relative errors). But it is very likely that they fall in this region as well.
- In the observations with the highest count rates, regions with relatively lower count rates in LAXPC (~ 2000 /s) and NuSTAR (~ 150 /s) are also observed. Fractional rms are in the range 10 – 15 % with fundamental QPO frequencies of 6 – 8 Hz. These QPOs are neither narrow nor peaked, but they are prominent. Both LAXPC and NuSTAR data points seem to correlate very well, forming the tail part of the **Type C** QPO region.
- There are a few NuSTAR observations with intermediate count rates (100 – 120 /s), fractional rms of ~ 15 % and intermediate QPO frequencies of 3 – 6 Hz. These QPO peaks are narrow and peaked, and are evidently of **Type C**. There is no corresponding data in LAXPC.

- The lowest count regions in NuSTAR data (~ 70 /s) have the highest fractional rms of more than 20 %, and very low QPO frequencies of 0.1 – 0.2 Hz. These QPO peaks are extremely narrow and peaked. There is no corresponding data in LAXPC. These form the topmost part of the **Type C** QPO region.
- The lowest count regions in LAXPC data (~ 1500 /s) also have very high fractional rms of more than 20 % and low QPO frequencies of 1 – 2 Hz. These QPO peaks are also very narrow and peaked. There is no corresponding data in LAXPC. These form the top part of the **Type C** QPO region.
- One set of NuSTAR observations having count rates of ~ 90 Hz are somewhat ambiguous. With such low count rates, these QPOs are expected to be of Type C, but they do not exhibit any observable QPOs at all. In fact, only a broad Lorentzian component is visible. These points need to be reanalyzed.

To summarize, the **Type C** region consists of QPOs with fractional rms in the range of 10 – 25 % and frequencies 0.1 – 8 Hz. Both ranges are quite broad, with the data points forming a linear region with negative slope i.e. there is a negative correlation between fractional rms and QPO frequency. On the other hand, the **Type A** QPOs seem to have similar fractional rms of 3 – 4 % but varying QPO frequencies of 5 – 7 Hz. There does not seem to be any correlation.

As mentioned before, **Type B** QPOs are not observed. Most probably, high-low transition regions, which have not been analyzed, exhibit Type B QPOs. Or maybe, in the observation duration of around 40 days, there were no Type B QPOs. This can only be confirmed by further analysis of data with longer durations of observation.

3 Acknowledgements

Firstly, I would like to thank my supervisor Dr. Tomaso Belloni for guiding me through this project, and being extremely friendly and accommodating. I learnt a lot, not only about the basic theory of black hole and neutron star binaries, but also timing and spectrum analysis.

A hearty thanks to the residents of the guest house at OAB, especially Federico, for helping me adjust temporarily in a new country. I am thankful that I was able to converse with them in English.

I loved the travels around Europe and the fact that I could cross borders with minimal effort. Thanks to this, I have been able to visit more places outside Italy than inside.

Finally, I am grateful to my family and friends who kept in touch with me. I have learnt that it is very necessary for a person in a foreign place to communicate with someone familiar.

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