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7 MARCH 2021

ANALYSIS OF THE LIGHT CURVES TO UNDERSTAND THE MYSTERY OF X-RAY PULSARS

A half day workshop on Hands-on X-Ray Astronomy was conducted on 28 February 2021, by Nehru Planetarium, Nehru Memorial Museum and Library, in collaboration with IISER, Mohali and Hansraj College, which allowed participants to arrive at a beginner learning about Neutron Stars and undertake some simple quantitative projects with X-Ray Astronomy data related to Neutron Stars.

Definitions:

a. Light Curve: A graph showing the variation in the light received over a period of time from a variable star (here, Neutron Star)
b. Power Density Spectrum: The power density spectrum (PDS) of the signal describes the power present in the signal as a function of frequency, per unit frequency.
c. Fast Fourier Transform: A fast Fourier transform (FFT) is an algorithm that computes the discrete Fourier transform (DFT) of a sequence, or its inverse (IDFT). Fourier analysis converts a signal from its original domain (often time or space) to a representation in the frequency domain. (Here, the original domain is time)
d. Log-Log Curve: Log–Log plot/ curve is a two-dimensional graph of numerical data that uses logarithmic scales on both the horizontal and vertical axes.

To perform the project, a number steps to be followed are:

Steps:

- Open the Google Collab file (View Code) and follow the further steps side by side.
- Execute the 1st cell and 2nd cell to import the required python libraries.
- In the 3rd cell, change the file name whose light curve is to be obtained (`with fits.open('file name') as hdul:`). Then execute the cell. This will take the data from the fits file and will print the exposure and time resolution of the light curve of given file name.
- Execute the 4th cell to plot the light curve, with the default time resolution.
- Execute the 5th cell with the desired bin-size/ time resolution and plot it by executing the 6th cell.
- Execute the 7th cell to perform the Fast Fourier Transform of the signal which converts a signal from the time domain to the frequency domain and Power density spectrum of the light curve can be obtained.
- Also, you can write *plt.yscale('log') plt.xscale('log')*, to the 7th cell to obtain the Log-Log Curve of the desired PDS.

(You can change the parameters like *xlim, xticks, ylim* etc. depending upon the requirement)

A Report comprising of Light Curves and Power Density Spectrum for a number of X-ray Pulsars is as follows:

HER X-1 RXTE

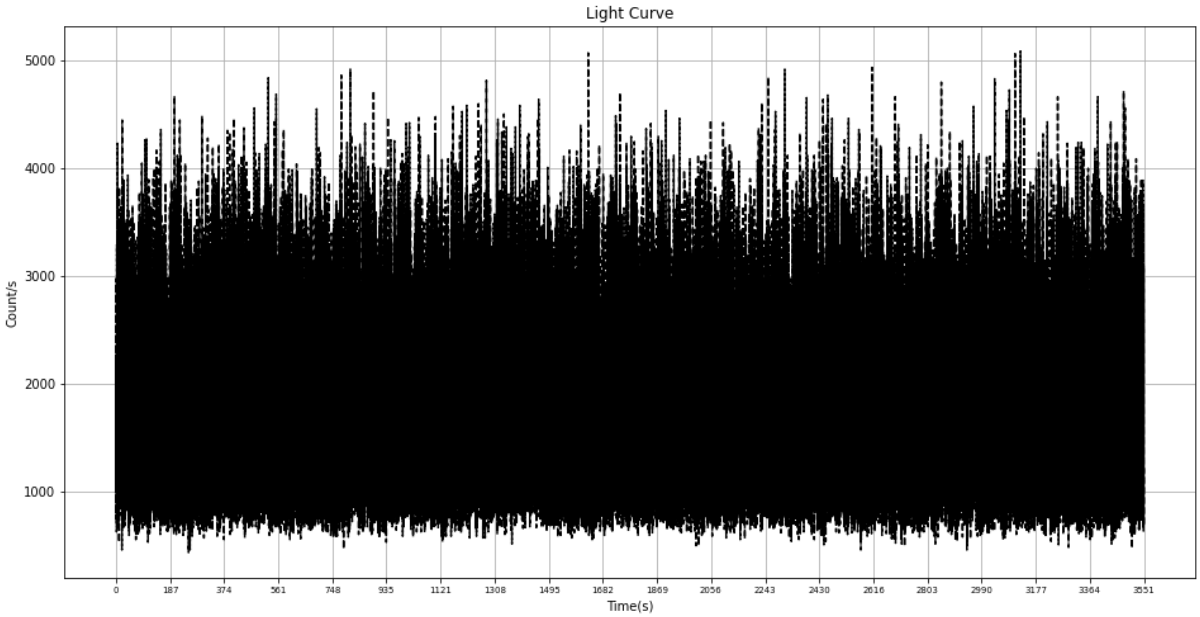

Figure 1: Light Curve of Her X-1 from the RXTE Mission with Exposure = 3550.875 seconds and Time Resolution = 0.125 sec

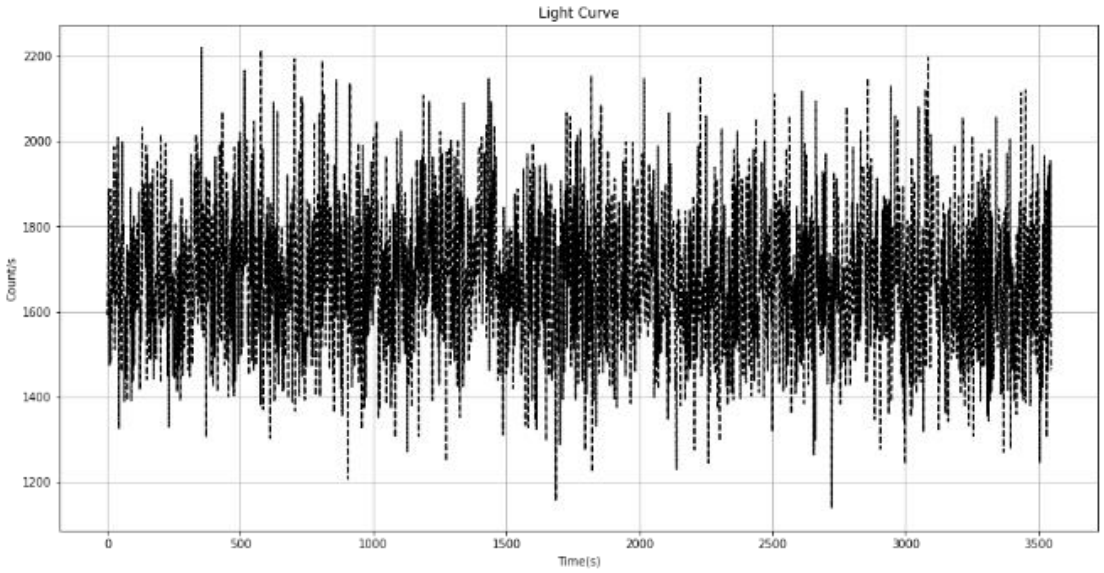

Figure 2: Light Curve of Her X-1 with Time resolution / Bin-size = 2 seconds

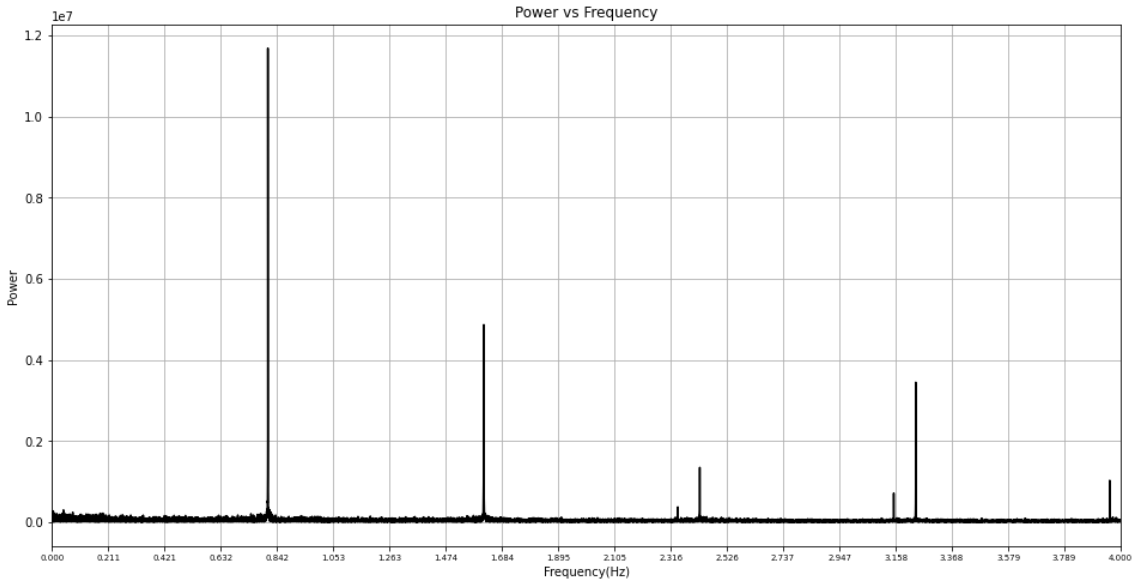

Figure 3: Power Density Spectrum for Her X-1 RXTE

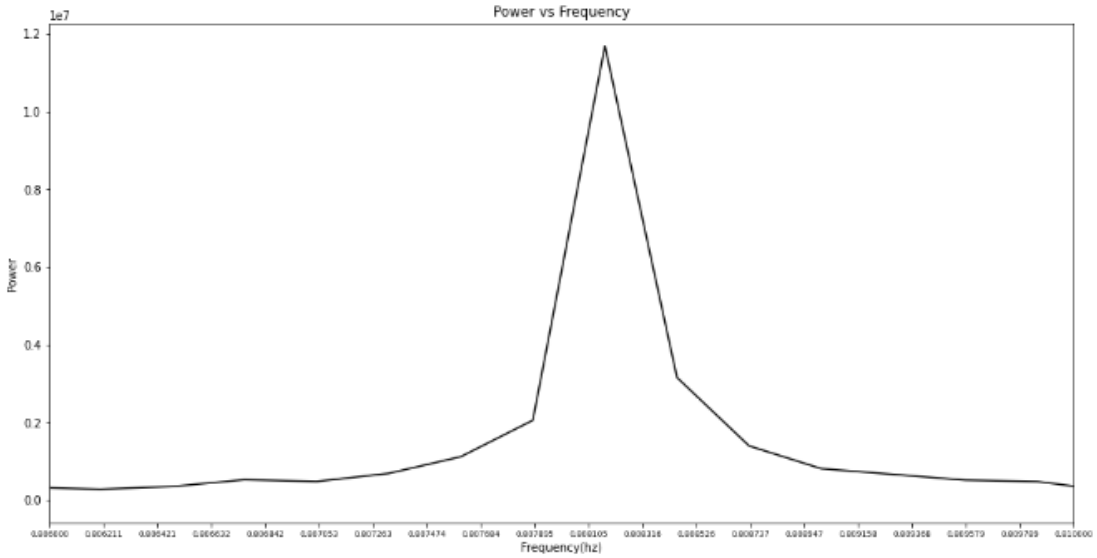

Figure 4: Zoom in of the peak frequency from PDS of Her X-1

Observations:

The peak frequency is observed at 0.808 Hz.

Hence, the Periodicity of the Pulsar Her X-1 = 1 / Peak frequency

= 1 / (0.808)

= 1.238 seconds

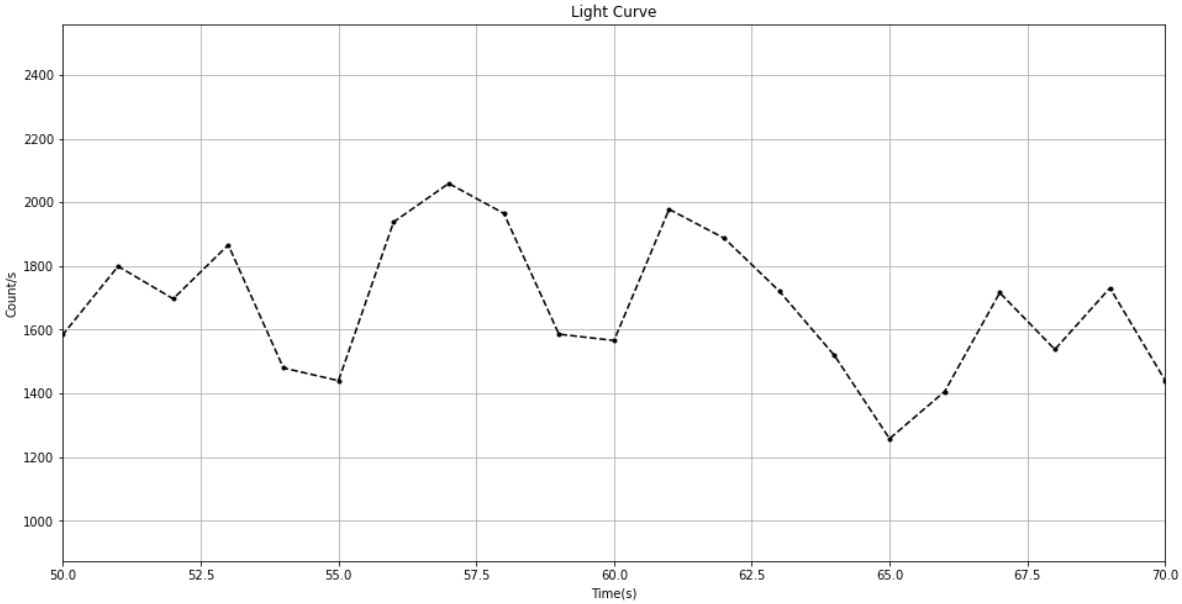

Figure 5: For bin size = 1, peaks in the light curve of Her X-1 corresponds to 1.238 sec (approximately).

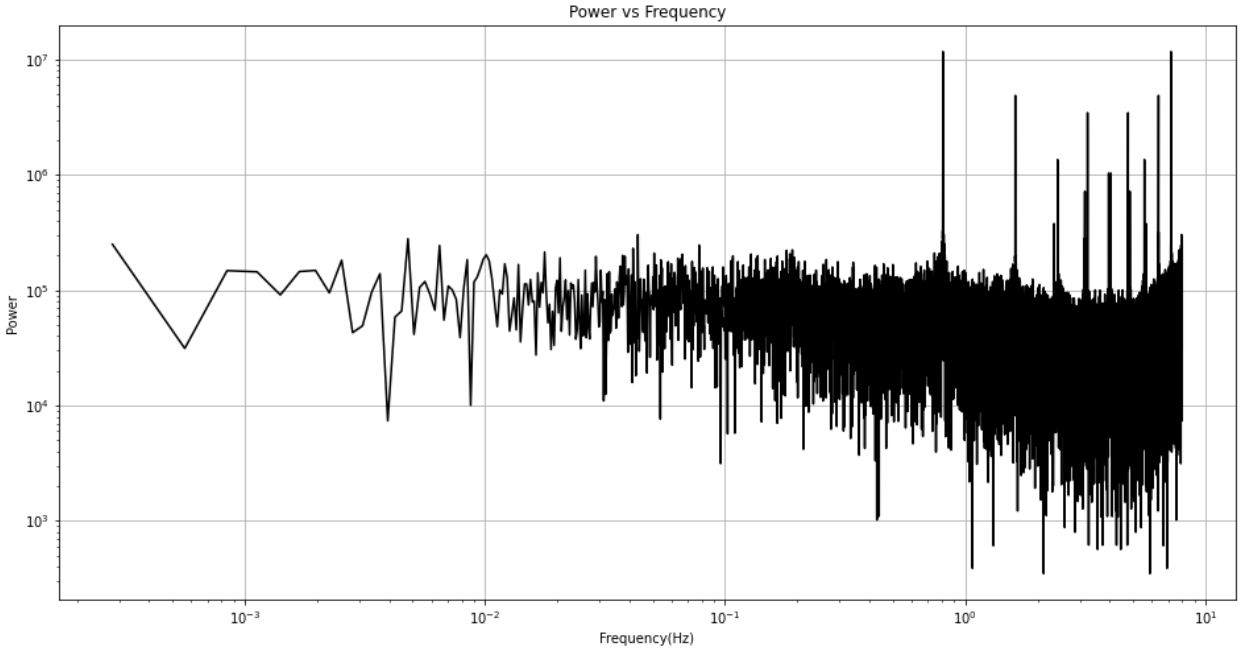

Figure 6: Log-Log Curve of PDS for Her X-1

CEN X-3

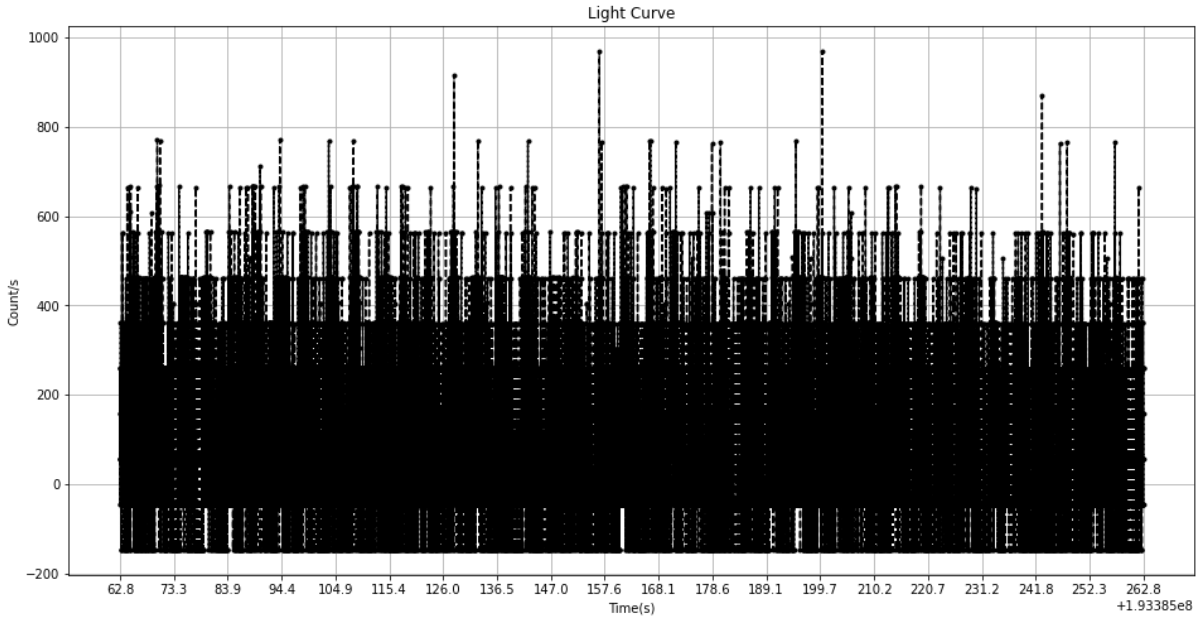

Figure 7: Light Curve of Cen X-3 with Exposure = 200.004 seconds and Time Resolution = 0.01 sec

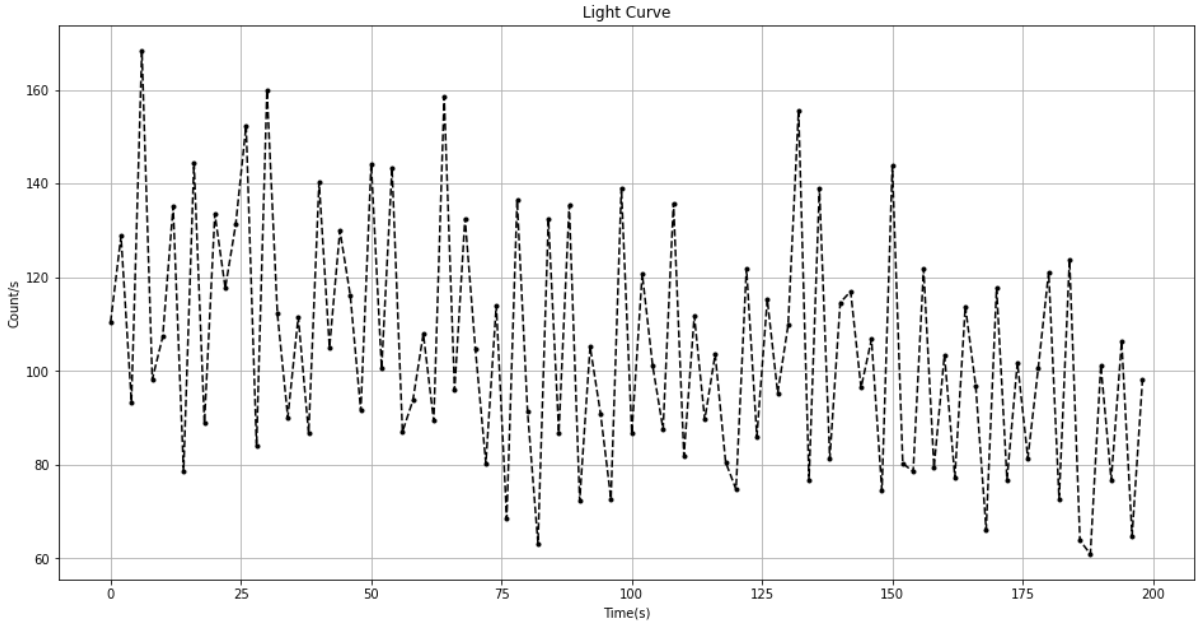

Figure 8: Light Curve of Cen X-3 with Time resolution / Bin-size = 2 seconds

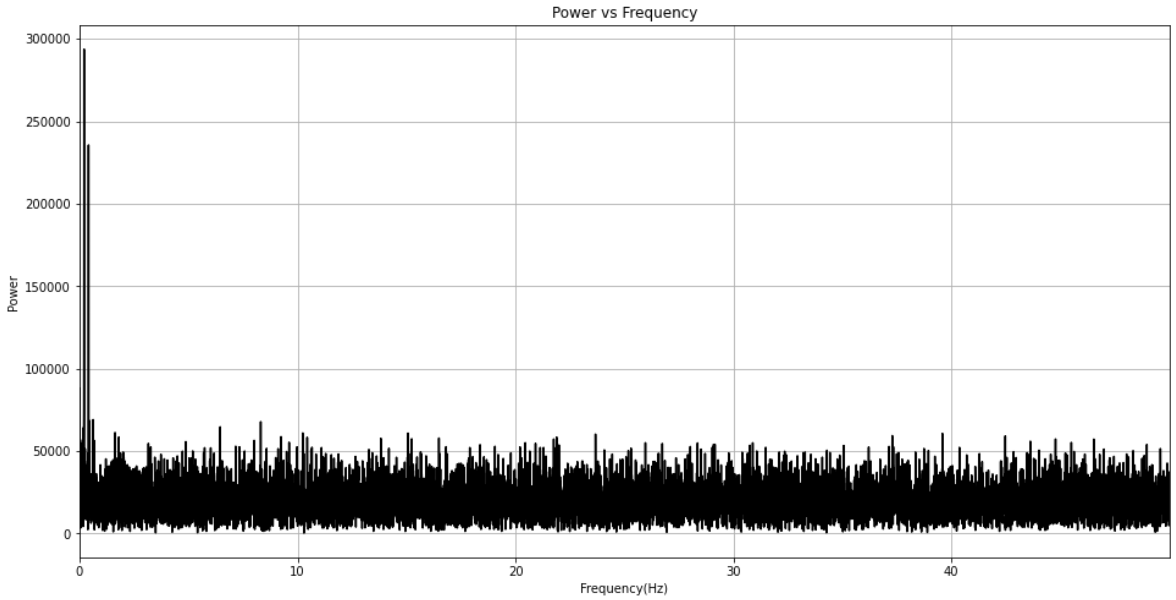

Figure 9: Power Density Spectrum of Cen X-3

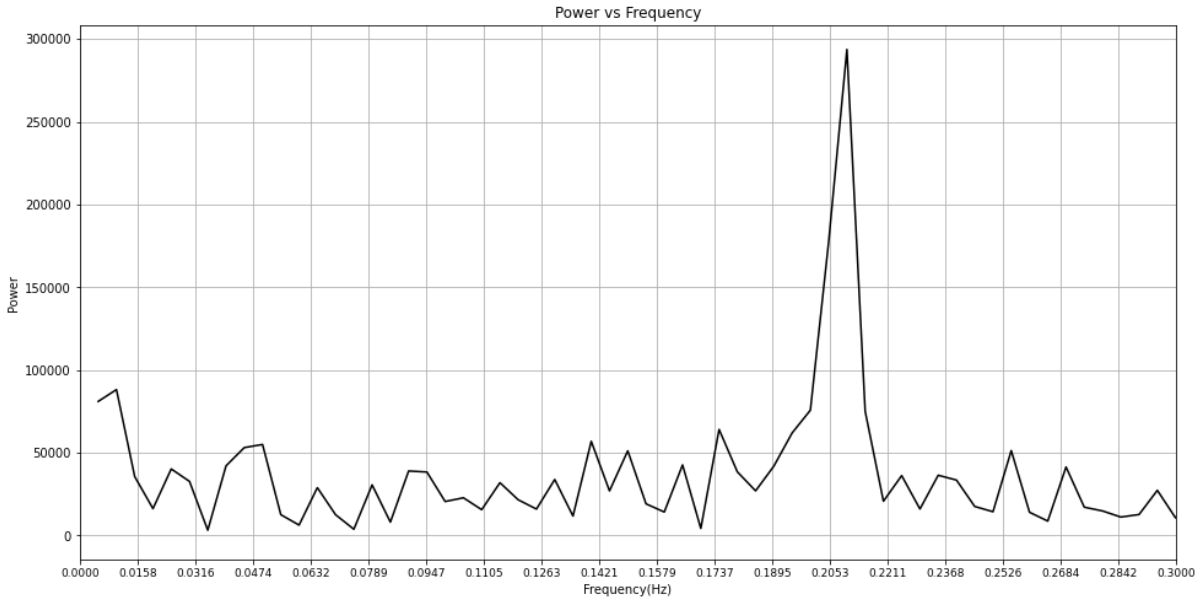

Figure 10: Zoom in of the peak frequency from PDS of Cen X-3

Observations:

The peak frequency is observed at 0.208 Hz.

Hence, the Periodicity of the Pulsar Her X-1 = 1 / Peak frequency

= 1 / (0.208)

= 4.808 seconds

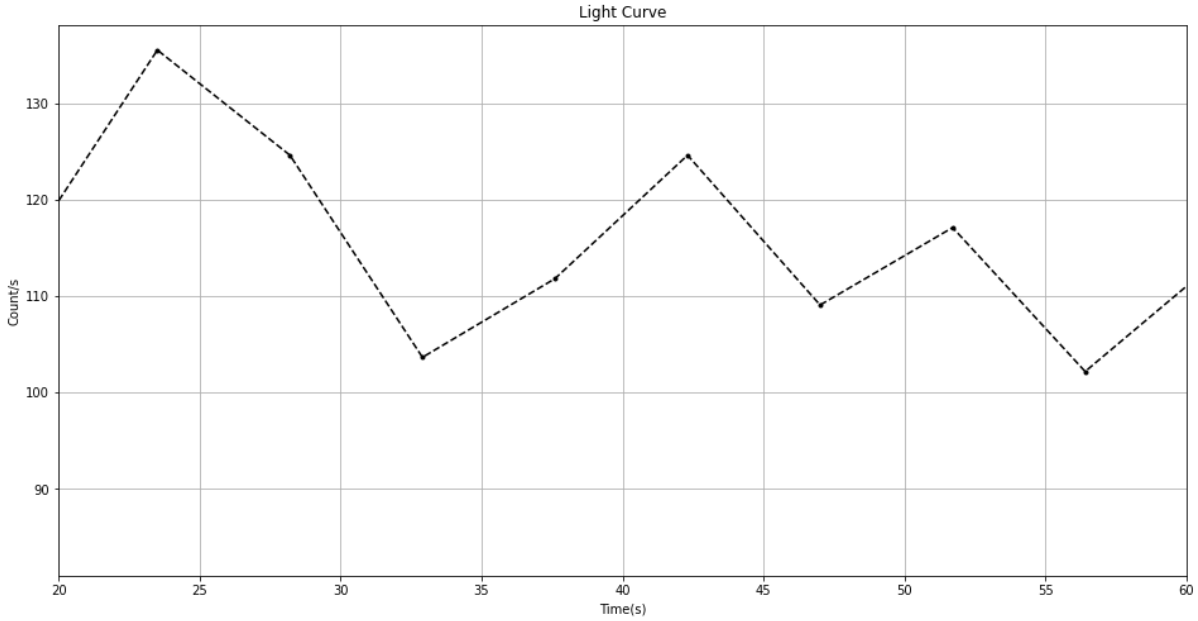

Figure 11: For bin size = 4, peaks in the light curve of Cen X-3 corresponds to 4.8 sec (approximately).

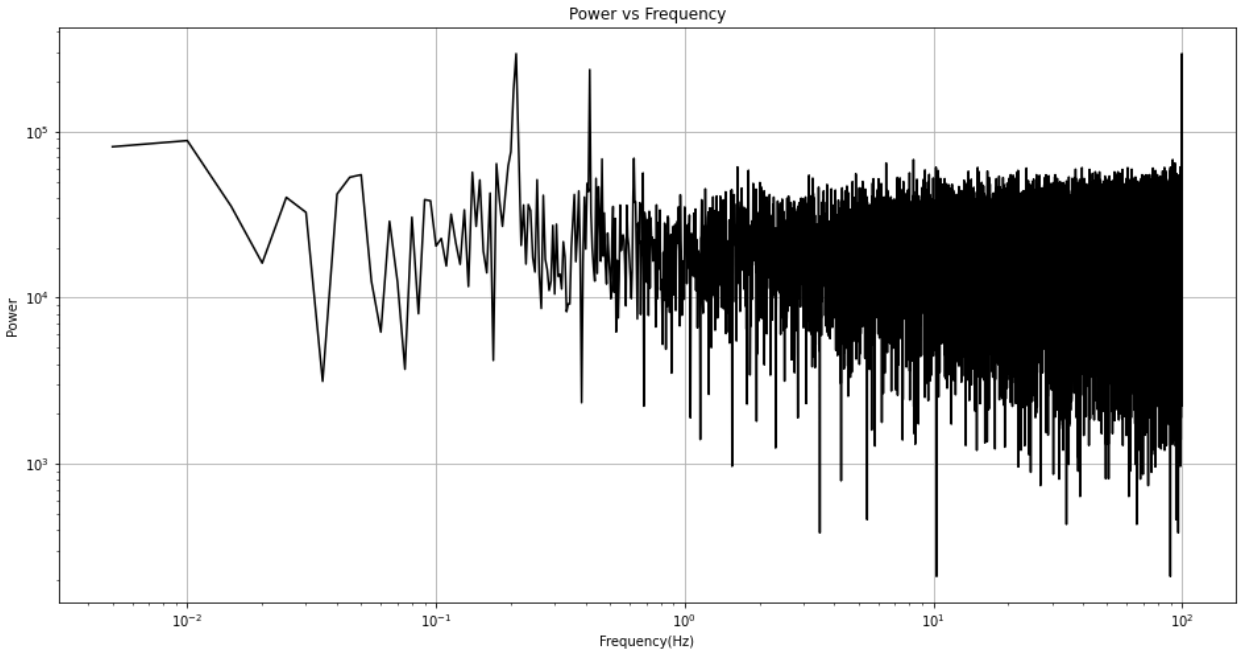

Figure 12: Log-Log Curve of PDS for Cen X-3

4U 1626

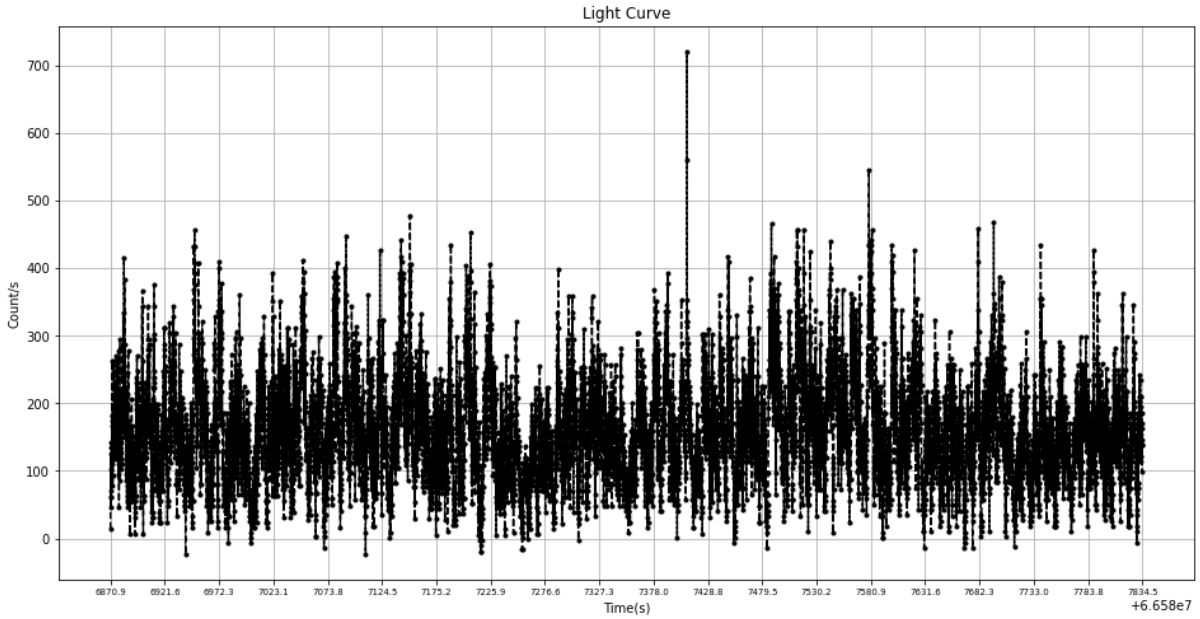

Figure 13: Light Curve of 4U1626 with Exposure = 963.558 seconds and Time Resolution = 0.125 sec

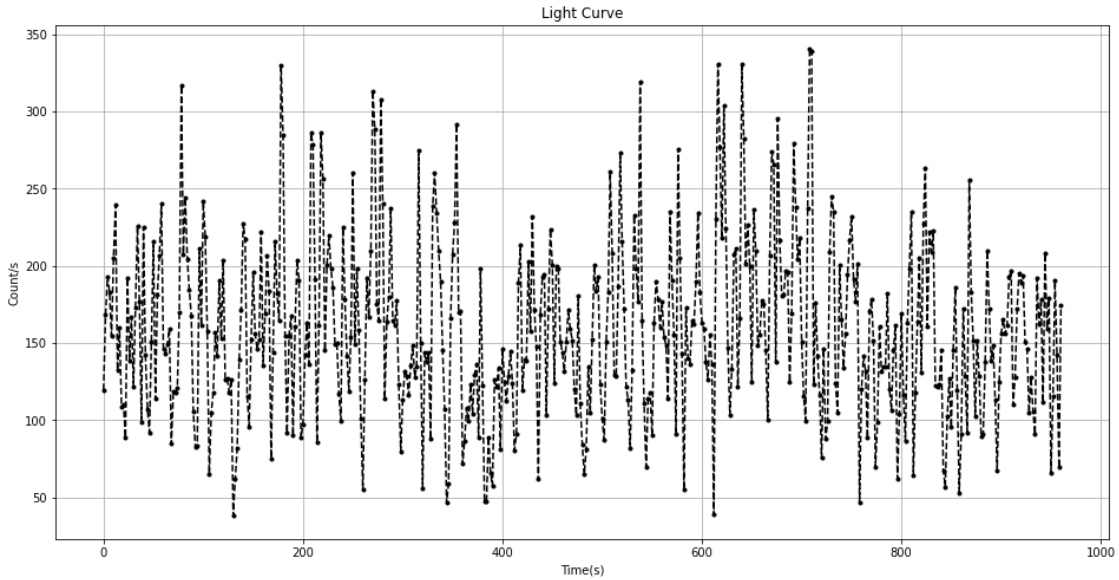

Figure 14: Light Curve of 4U 1626 with Time resolution / Bin-size = 2 seconds

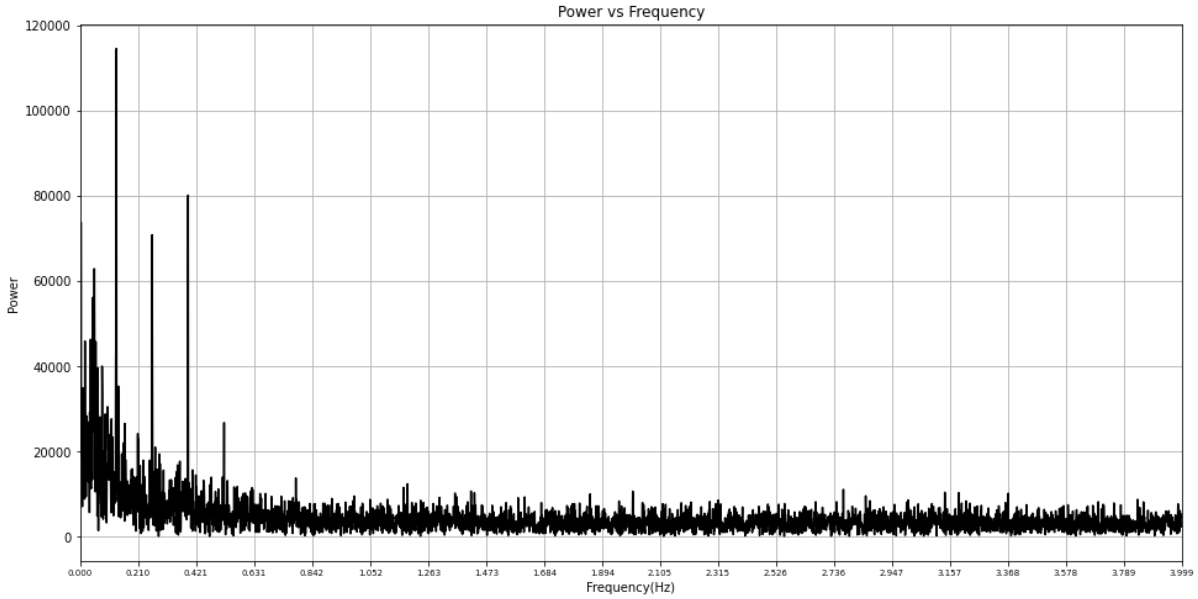

Figure 15: Power Density Spectrum of 4U1626

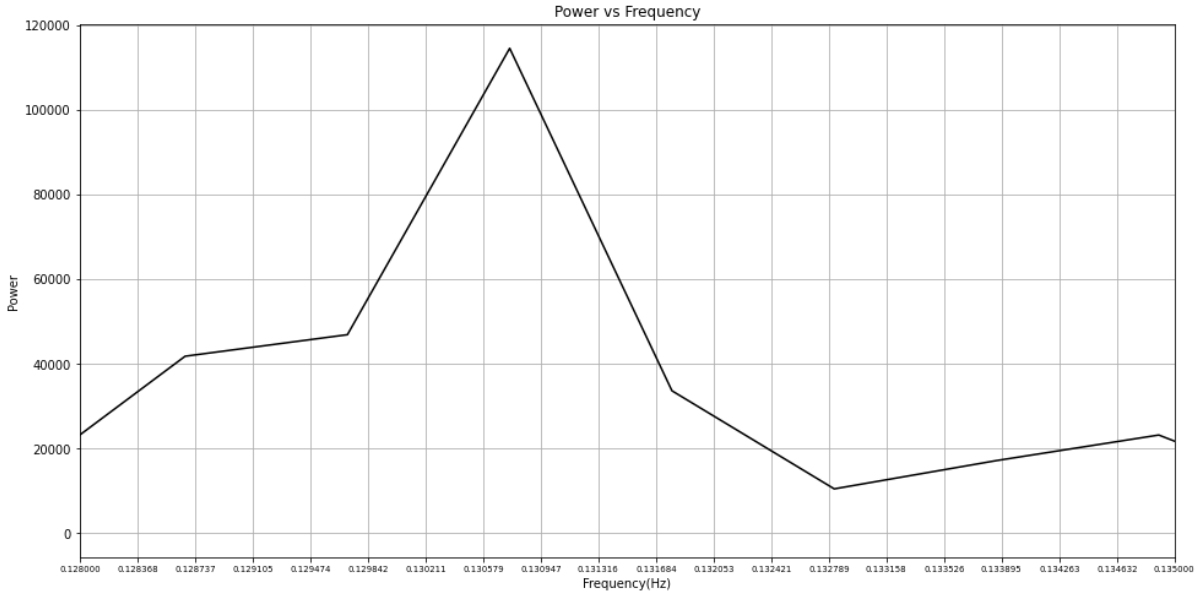

Figure 16: Zoom in of the peak frequency from PDS of 4U 1626

Observations:

The peak frequency is observed at 0.130 Hz.

Hence, the Periodicity of the Pulsar Her X-1 = 1 / Peak frequency

= 1 / (0.130)

= 7.692 seconds

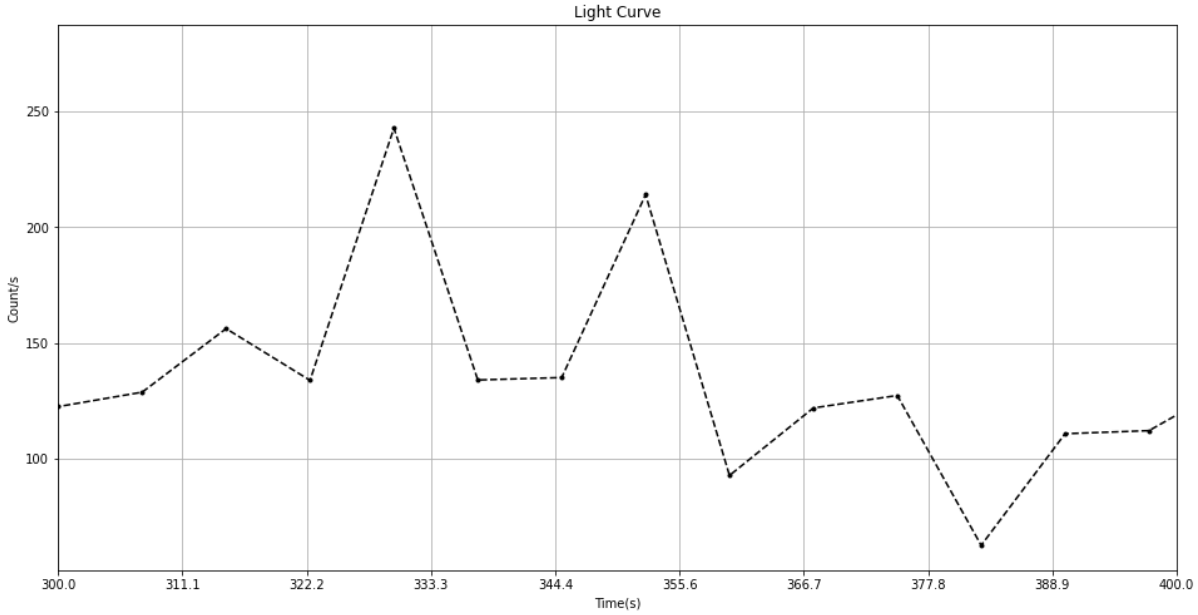

Figure 17: For bin size = 7.5, peaks in the light curve of 4U 1626 corresponds to 7.69 sec (approximately).

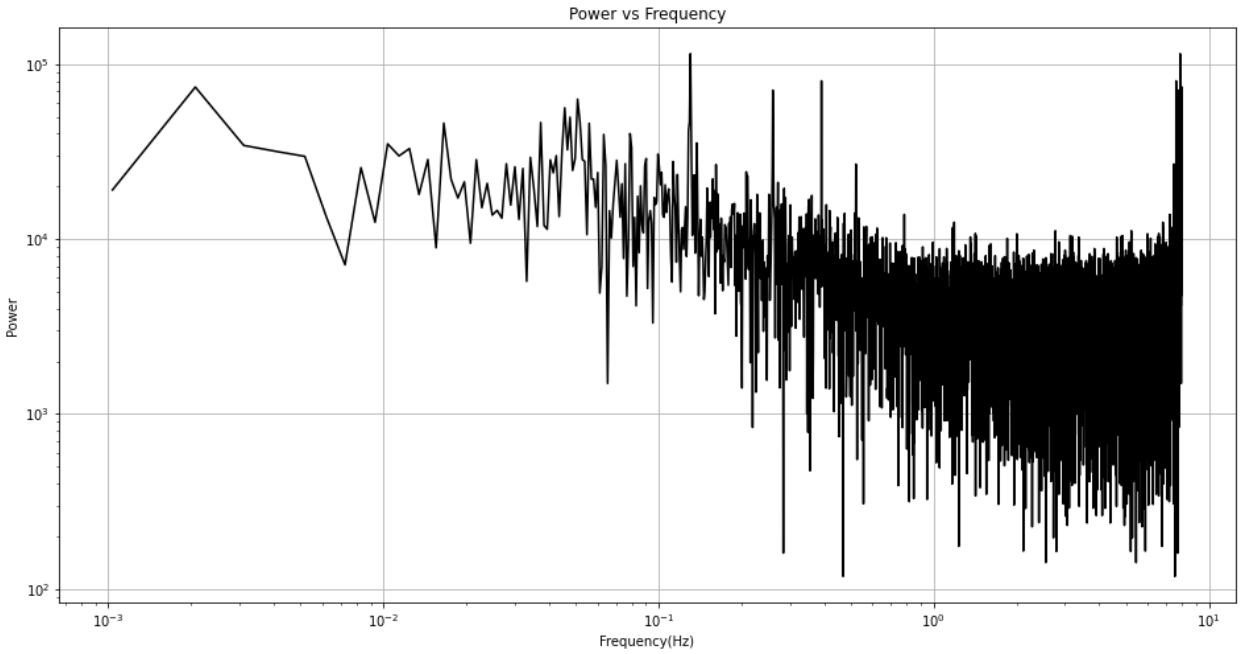

Figure 18: Log-Log Curve of PDS for 4U 1626

- 4U 1626 2010 FLARES

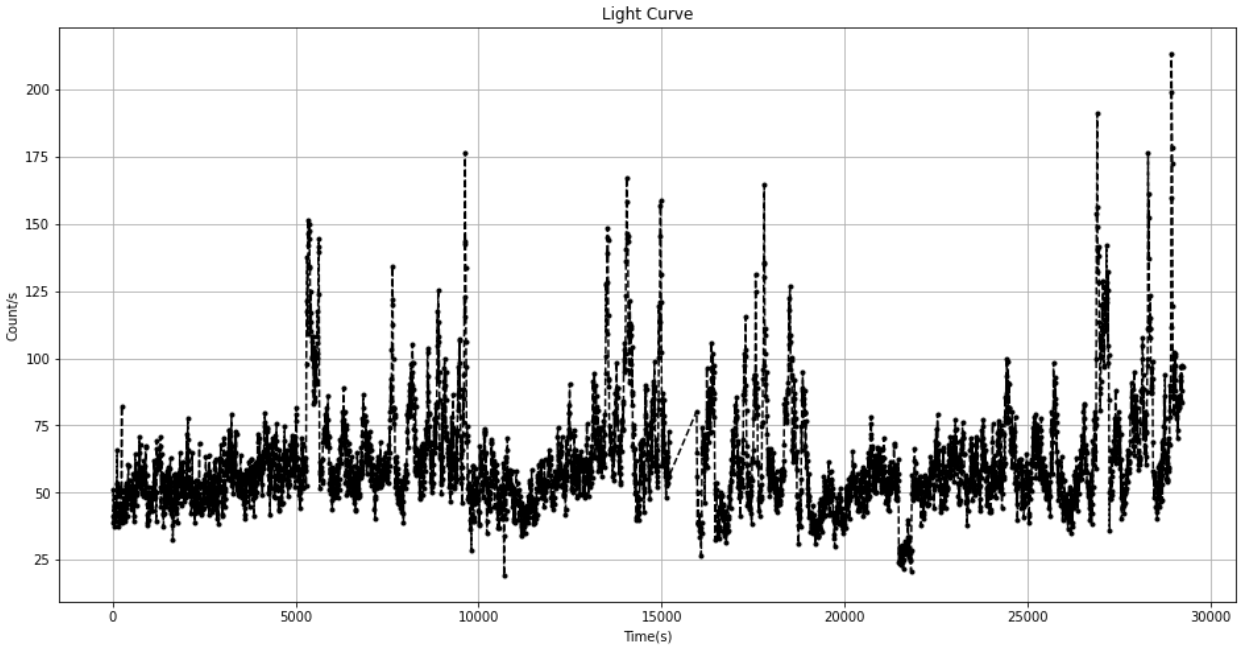

Figure 19: Shows the 'flaring state' of 4U 1626, which happens when there is a sudden increase in the amount of material accreting onto the surface of the neutron star resulting in larger X-ray radiation.

- 4U 1626 GINGA FLARES

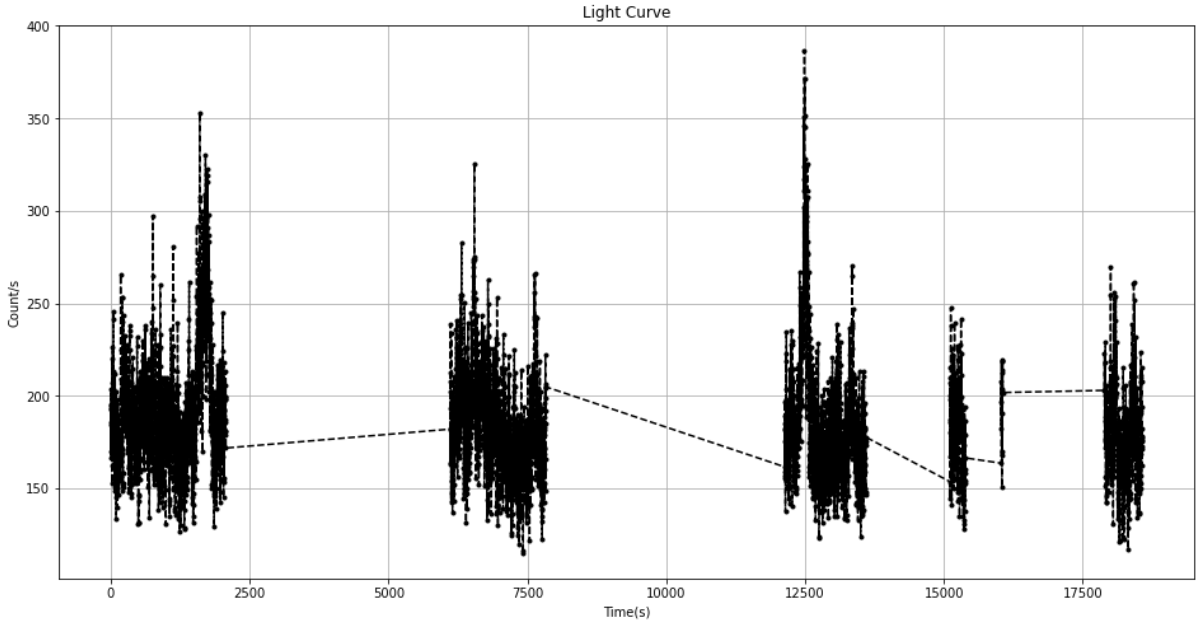

Figure 20: Shows the 'flaring state' of 4U 1626 from GINGA mission

LMC X-4

LMC X-4 is a two-star system consisting of a pulsar - a highly magnetized neutron star beaming X-rays - and a companion star. In this study, Dr. Aru Beri and Dr. Biswajit Paul from RRI examined characteristics of the X-ray signals emitted from LMC X-4, using signal processing techniques and analysis. The scientists observed three states in the intensity of X-ray emitted by the pulsar: ‘flaring’, ‘persistent emission’, and ‘eclipse’.

- LMC X-4 – PERSISTENT

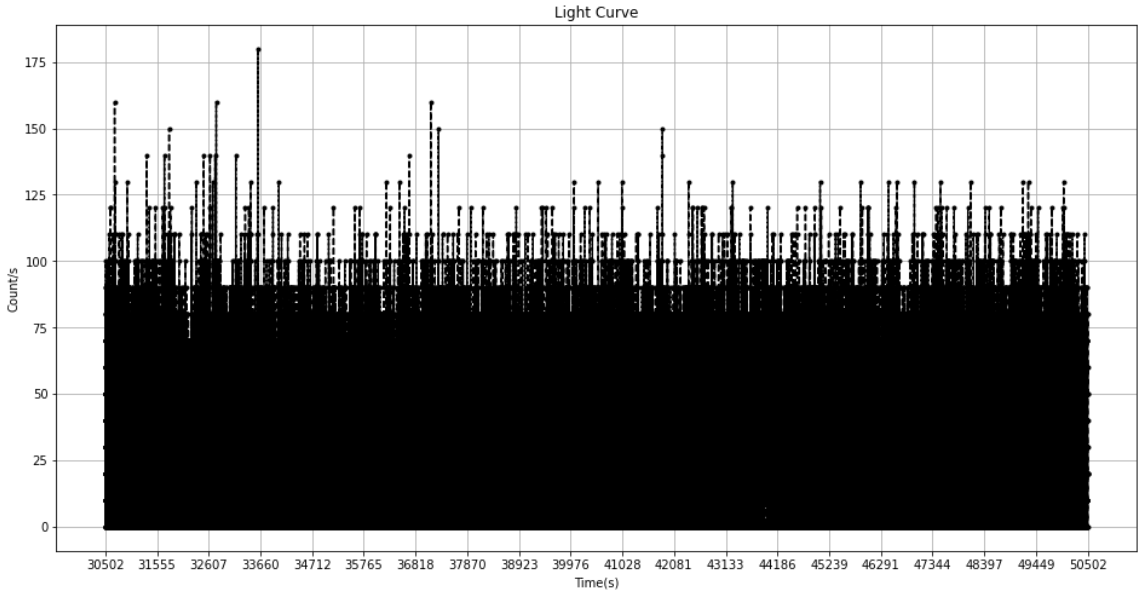

Figure 21: Light Curve of LMC X-4 during persistent emission with Exposure = 19999.900 seconds and Time Resolution = 0.1 sec

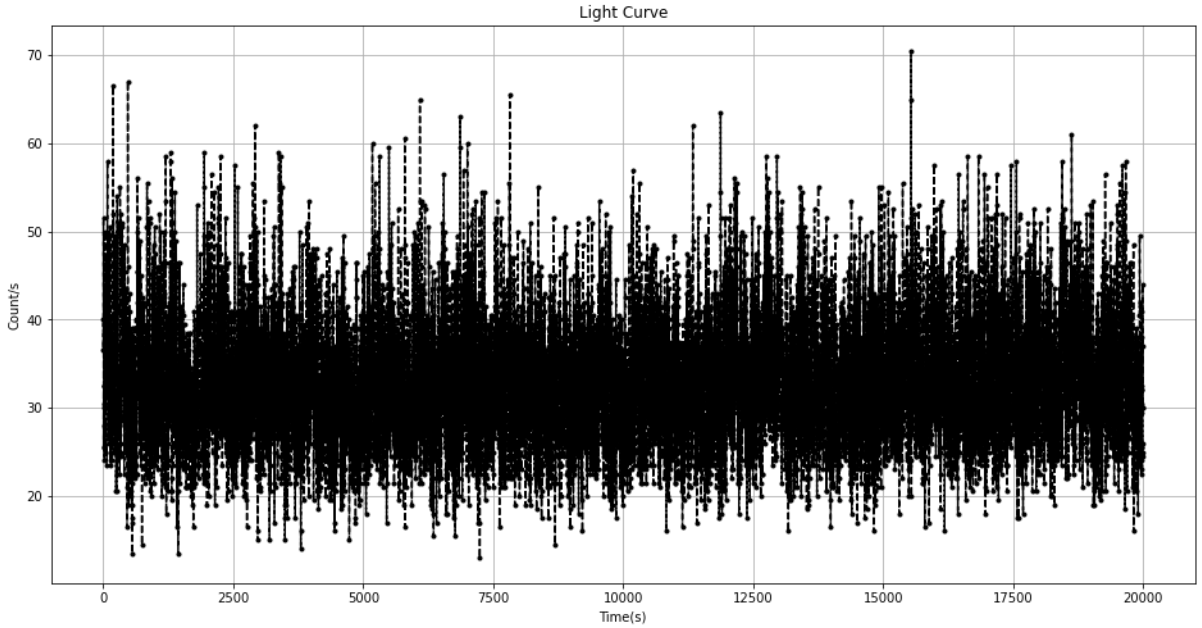

Figure 22: Light Curve of LMC X-4 with Time resolution / Bin-size = 2 seconds

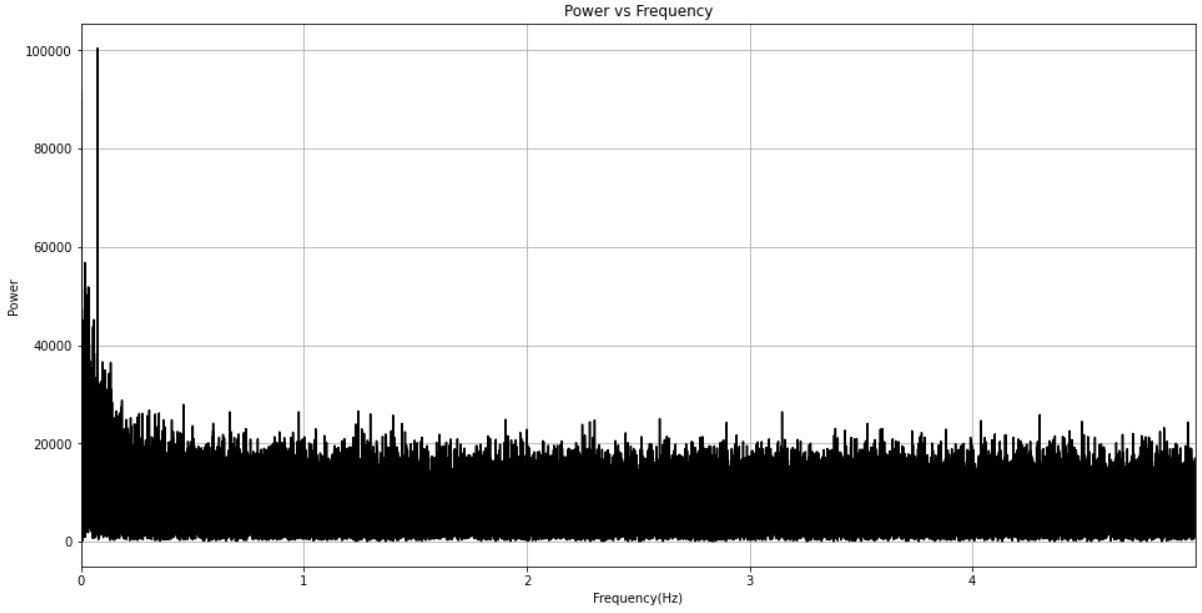

Figure 23: Power Density Spectrum of LMC X-4 during persistent emission

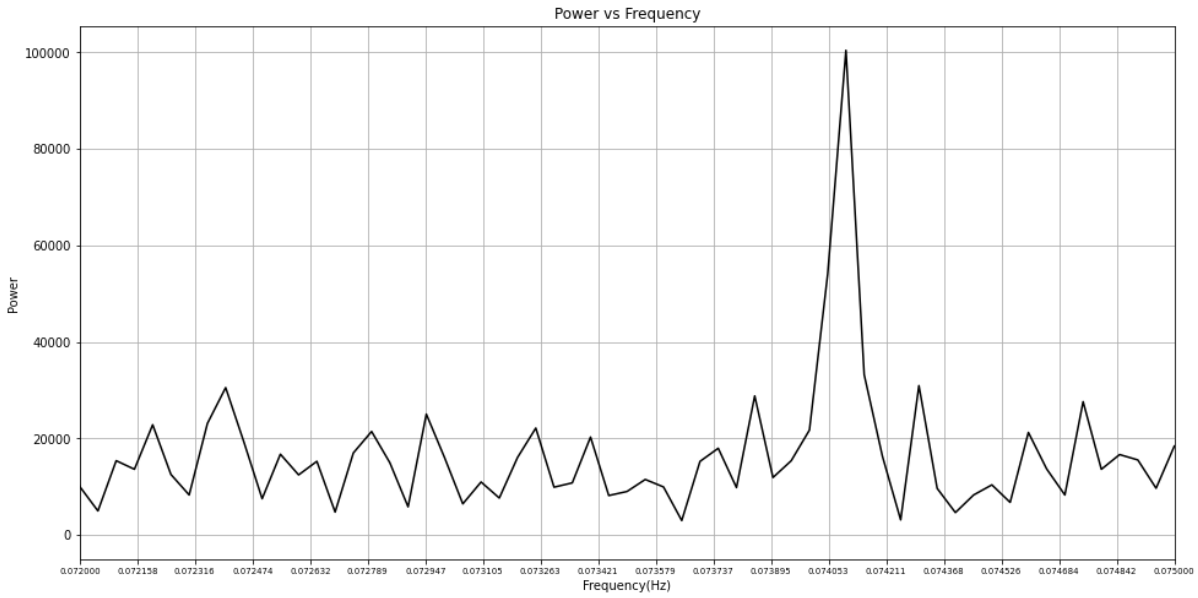

Figure 24: Zoom in of the peak frequency from PDS of LMC X-4

Observations:

The peak frequency is observed at 0.074 Hz.

Hence, the Periodicity of the Pulsar Her X-1 = 1 / Peak frequency

= 1 / (0.074)

= 13.513 seconds

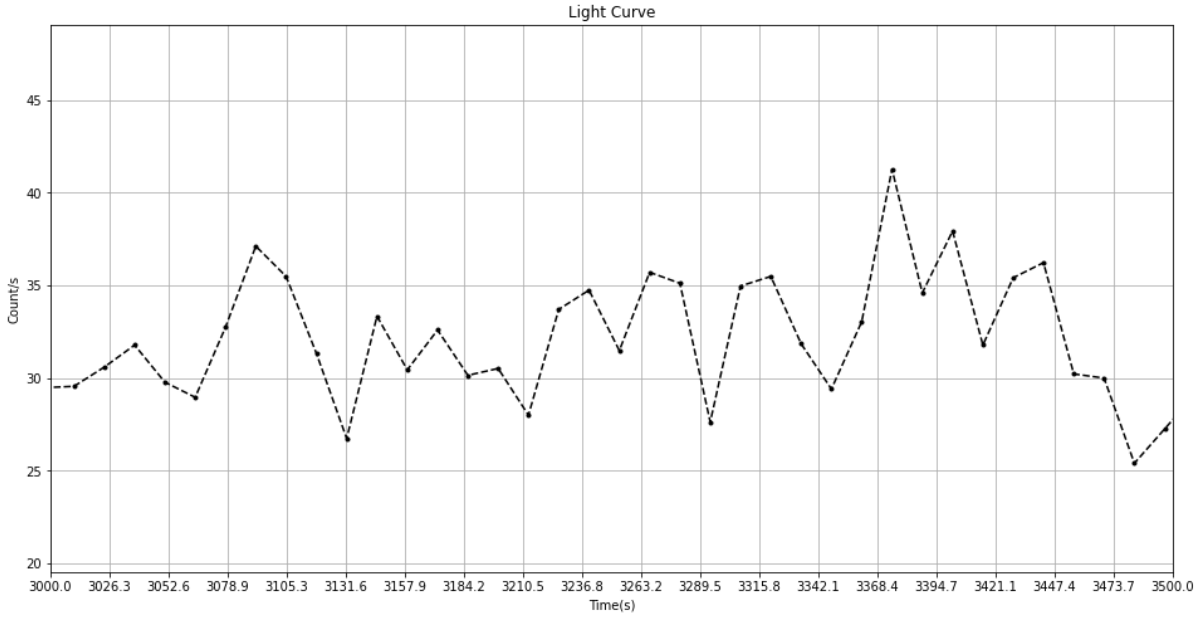

Figure 25: For bin size = 13.5, peaks in the light curve of LMC X-4 corresponds to 13.51 sec (approximately).

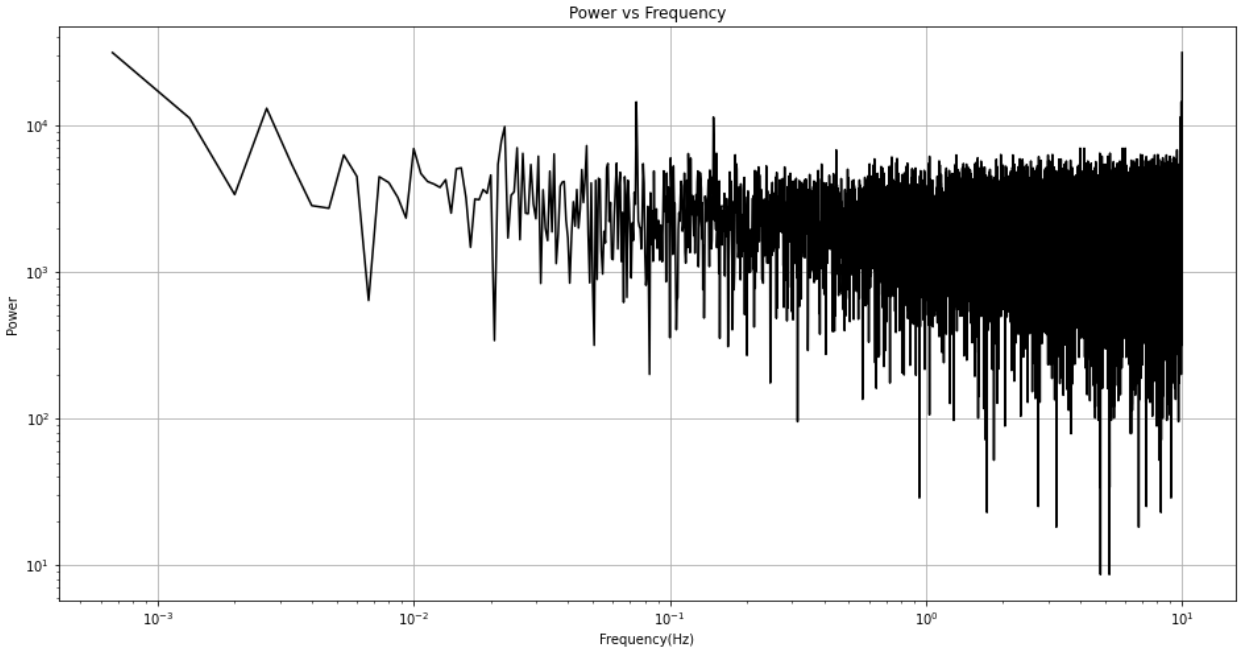

Figure 26: Log-Log Curve of PDS for LMC X-4

- LMC X-4 – FLARES

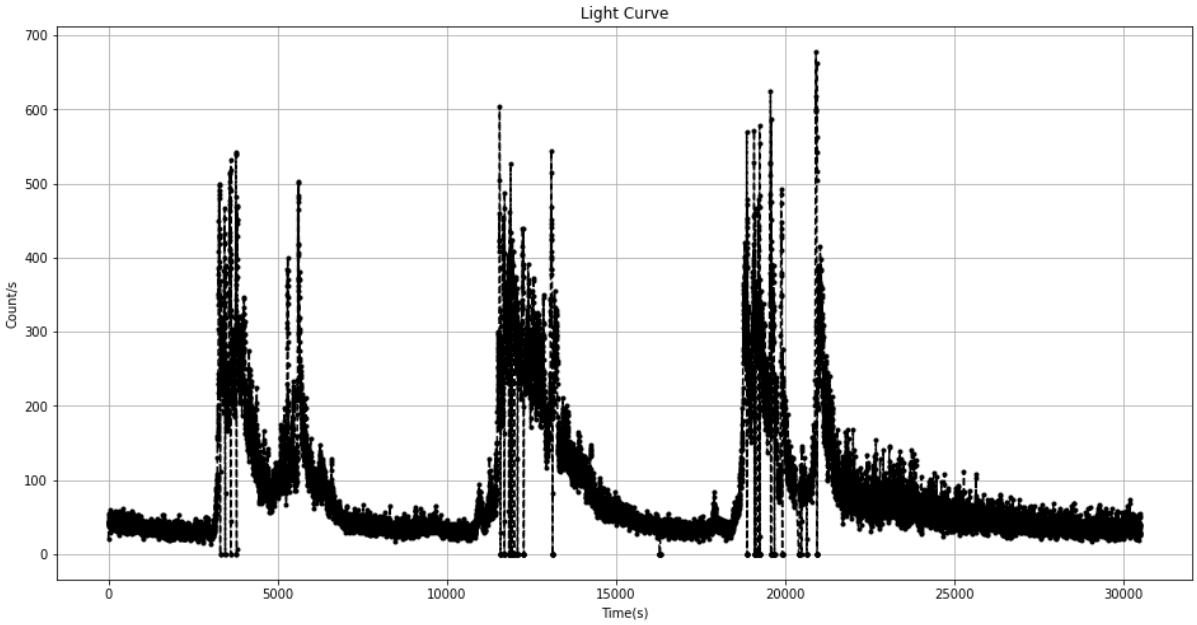

Figure 27: Shows the 'flaring state' of LMC X-4, which happens when there is a sudden increase in the amount of material accreting onto the surface of the neutron star resulting in larger X-ray radiation.

- LMC X-4 – ECLIPSE

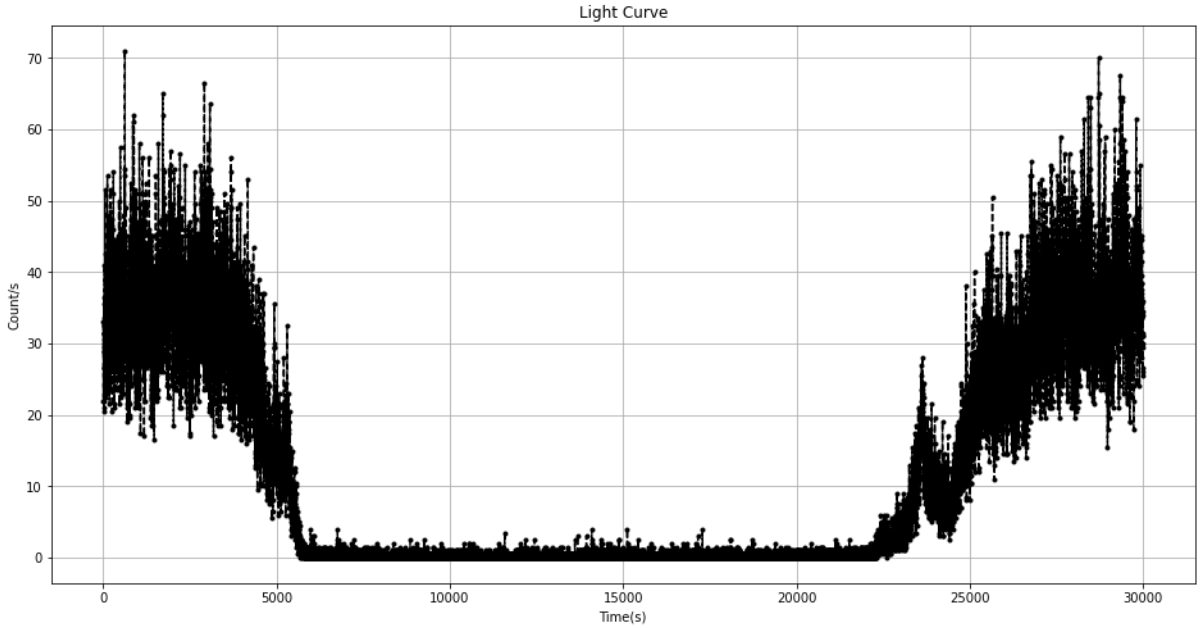

Figure 28: Shows the 'eclipse state' of LMC X-4, which happens when our view of the neutron star is blocked by its much larger companion and is identified by the absence of X-Rays

A simulation visualizing the Eclipse State of Neutron Star: Click Here

In the simulation, the blue sphere represents the neutron star and yellow sphere represents the companion star. Eclipse state of the neutron star happens when our view of the neutron star is blocked by its much larger companion star. So, in the simulation, the yellow sphere blocks our view of the blue sphere. This eclipse state is identified by the absence of X-Ray, i.e., we can see a dip in the light curve from approximately 5500 seconds to 22500 seconds, which means that the companion star blocks our view of the neutron star for about 17000 seconds.

Table 1: Shows the Peak Frequency and Periodicity of four X-Ray Pulsars

X-ray Pulsar	Peak frequency (Hz)	Periodicity (sec)
HER X-1	0.808	1.238
CEN X-3	0.208	4.808
4U 1626	0.130	7.692
LMC X-4	0.074	13.513

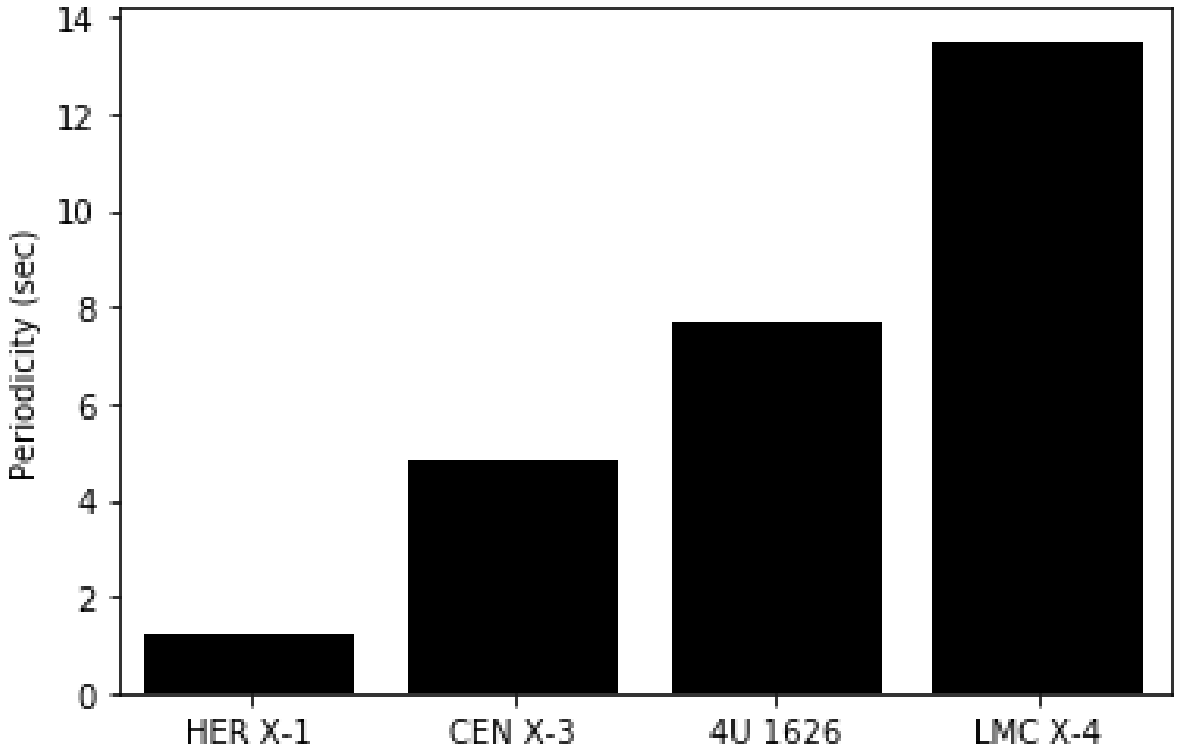

Figure 29: Shows the bar plot comparing the Periodicity of given X-Ray Pulsars

Conclusion:

Thus, observations from the light curves of four X-Ray Pulsars, HER X-1, CEN X-3, 4U 1626 and LMC X-4, gave a better insight of the behavior of the X-Ray Pulsars, their Companion Stars, their Periodicity and also the flaring and eclipse state of LMC X-4 and 4U 1626. The eclipse state of the LMC X-4 light curve shows us that for how long the companion star remains in front of the neutron star, i.e., around 17000 seconds, which gives us an idea of comparable size difference between the neutron star and its companion star. Binning of the light curves shows us about the variation of Count/s with a certain time resolution, let's say, for LMC X-4, the original bin-size was 0.1 seconds, which was increased to 2, which tells us the variation of Count/s for every 2 seconds, when the bin-size was changed to the periodicity of the neutron star,

it tells us the variation of Count/s after each rotation of the neutron star. The Log-Log curve of the Power Density Spectrum helps us to view the variation of Power for a wider range of frequencies compared to the linear curve, and also in identifying powerful signals.

Reference:

- Jaseem, Namitha, "What's cooking in the LMC X-4 binary star system", *Research Matters* (2018).
- Wikipedia

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