
Study of reprocessing of X-rays in environment of Neutron Stars

Kinjal Roy

Advisor: Professor Biswajit Paul



Raman Research Institute, Sadashivanagar, Bengaluru, Karnataka 560080, India

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to



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Certificate

This is to certify that the work submitted in the thesis titled '**Study of reprocessing of X-rays in environment of Neutron Stars**,' submitted by **Kinjal Roy** (Enrolment No. RRI/2020/001) to the Jawaharlal Nehru University for the award of the degree of **Doctor of Philosophy (Ph.D.) in Physical Sciences** is the bonafide record of the original research work carried out by Kinjal Roy under my guidance and supervision at **Raman Research Institute (RRI)**, Bengaluru, India. The results embodied in the thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

Prof. Tarun Souradeep

Director & Professor, RRI

Astronomy & Astrophysics Group

Raman Research Institute (RRI)

Bengaluru 560080, Karnataka, India

Prof. Biswajit Paul

Supervisor

Declaration

I, **Kinjal Roy** (Enrolment No. RRI/2020/001), declare that the work reported in this thesis titled '**Study of reprocessing of X-rays in environment of Neutron Stars**' is entirely original. This thesis has been composed by me at **Raman Research Institute (RRI)** under the supervision of **Professor Biswajit Paul** and is the result of my own work unless otherwise stated. I further declare that the subject matter presented in this thesis has not previously formed the basis for awarding any degree, diploma, membership, associateship, fellowship, or any other similar title of any university or institution. I also declare that this thesis has been checked using the plagiarism software DRILLBIT.

Prof. Biswajit Paul

Supervisor

Kinjal Roy

Candidate

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Abstract

Accreting X-ray Pulsars (XRP) are some of the brightest X-ray sources in the sky, with widely varying intensities reaching upto a few Crabs. XRP are binary stellar systems with a Neutron Star (NS) and a main sequence star. The NSs in these systems are highly magnetised ($B \sim 10^{12}\text{G}$) and are powered by matter accreted from the companion. Some details of the vicinity of the NS and the wider binary environment can be studied from the temporal and spectral properties of the X-ray emitted from these systems. In the first part of the thesis, results from an investigation of the binary environment in HMXB pulsar using fluorescent emission lines are presented. The strong iron fluorescent line in GX 301-2 is a tracer of the reprocessing environment. We look for temporal signatures in the iron fluorescence emission lines which can originate from any inhomogeneous and anisotropic matter distribution near the NS. The second part of the thesis is about the reprocessed emission from the shock forming region in the accretion column in X-ray binary pulsars, where the cyclotron lines are theorized to originate. Be-XRP, a subclass of XRP, are known to exhibit a wide range in luminosity providing an ideal system to study the luminosity dependence of cyclotron lines. We study CRSF features in multiple Be-XRP during their outburst phase to study how the line forming region in these systems depend on luminosity.

List of Publications

Publications [Part of This Thesis]

1. Studying the variability of fluorescence emission and the presence of clumpy wind in HMXB GX 301–2 using XMM-Newton,
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2. Changes in the distribution of circum-binary material around the HMXB GX 301–2 during a long spin-up episode of the neutron star,
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3. Science with the Daksha High Energy Transients Mission,
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4. Unveiling the intensity-dependent wake structure of Vela X–1 using MAXI /GSC,
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5. Detection of self-obscuration and evolving winds from MAXI J1803–298 during its 2021 outburst,
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Under review, *ApJ*.
6. XMM-Newton view of pulsating iron fluorescent emission from Centaurus X-3,

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List of Abbreviations

Acronym	Full form
ACIS	Advanced CCD Imaging Spectrometer
AGN	Active Galactic Nuclei
ARF	Ancillary Response File
ASCA	Advanced Satellite for Cosmology and Astrophysics
ASM	All Sky Monitor
BAT	Burst Alert Monitor
BH	Black Hole
CALDB	CALibration DataBase
CCD	Charge-Coupled Devices
CRSF	Cyclotron Resonance Scattering Feature
EM	Electro Magnetic
EPIC	European Photo Imaging Camera
ESA	European Space Agency
FITS	Flexible Image Transport System
FPM	Focal Plane Module
FRB	Fast Radio Burst
FWHM	Full-Width Half Maxima
GBM	Gamma-ray Burst Monitor
GIS	Gas Imaging Spectrometer
GRB	Gamma ray Burst
GSC	Gas Slit Camera
GTI	Good Time Interval
GW	Gavitational Wave
HEAO	High Energy Astrophysics Observatory
HEASoft	High Energy Astrophysics Software
HETG	High Energy Transmission Grating

Acronym	Full form
MAXI	Monitor of All-sky X-ray Image
HMXB	High Mass X-ray Binary
IMXB	Intermedite Mass X-ray Binary
INTEGRAL	INTErnational Gamma-Ray Astrophysics Laboratory
ISRO	Indian Space Research Organisation
IXPE	Imaging X-ray Polarimetry Explorer
LAXPC	Large Area X-ray Proportional Counter
LECS	Low Energy Concentrator Spectrometer
LMXB	Low Mass X-ray Binary
JEM-X	Joint European X-Ray Monitor
MECS	Medium Energy Concentrator Spectrometer
MS	Main Sequence
NASA	National Aeronautics and Space Administration
NICER	Neutron star Interior Composition Explorer
NPEX	Negative and Positive power-laws EXponential
NS	Neutron Star
NuSTAR	Nuclear Spectroscopic Telescope Array
OM	Optical Monitor
PCA	Proportional Counter Array
PF	Pulse Fraction
PHA	Pulse Height Amplitude
POLIX	Indian X-ray Polarimeter
PSD	Power Spectral Density
PSF	Point Spread Function
RGS	Reflection Grating Spectrometers
RXTE	Rossi X-ray Timing Explorer
RMF	Response Matrix File

Acronym	Full form
SAA	South-Atlantic Anomaly
SAS	Science Analysis System
SGXB	Super giant X-ray Binary
SNR	Signal to Noise Ratio
SSC	Solid-state Slit Camera
ToO	Target of Opportunity
TPCM	Two Pole Cyclotron line Model
UVOT	Ultraviolet-Optical Telescope
WD	White Dwarf
XIS	X-Ray Imaging Spectrometer
XMM	X-ray Multi-Mirror Mission
XPoSat	X-ray Polarimeter Satellite
XRB	X-ray Binary
XRT	X-Ray Telescope
XRP	X-ray Pulsar

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To my parents...

“It’s a magical world, Hobbes, ol’ buddy... let’s go exploring!”

— Bill Watterson, Calvin and Hobbes

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Synopsis

The discovery of accreting X-Ray Pulsars (XRPs) happened with the detection of pulsations in X-ray flux from Cen X-3 and Her X-1 (Giacconi et al. 1972, Tananbaum et al. 1972). Anisotropic emission, along with the misaligned magnetic axis with respect to the rotational axis, gives rise to pulsations in Neutron Stars (NSs). Binary XRPs are powered by the accretion of matter from a companion star. Accretion can either occur via direct capture of stellar wind in the strong gravitational well of the NS or via Roche Lobe overflow (Pringle & Rees 1972). NSs are the most compact, stable configuration in which degeneracy pressure can still balance gravity; further compression leads to the collapse and formation of a black hole (BH).

NSs are among the most exotic objects in the Universe. Their extreme physical properties make them ideal laboratories to study the behaviour of matter under extreme conditions governed by Special and General Relativity. They can even be employed to test alternative theories of gravity (Shao & Yagi 2022). In binary XRPs, the presence of a donor companion makes these systems excellent laboratories for the study of the stellar wind environment. Binary XRPs are excellent probes of the evolutionary paths of both the binary system as a whole, as well as the individual components.

As accreted material is transferred from the companion to the NS, the gravitational potential energy of the infalling material is converted into electromagnetic radiation, predominantly emitting in the X-ray regime (Frank et al. 1992). The X-ray emission processes are broadly classified into thermal emission, non-thermal emission and atomic transitions. Approximately half of those systems are transients and these systems have mainly been investigated during their outbursts (Paul 2017). The main area of my research involves the study of spectral and timing properties from HMXB pulsars. My research interests can be divided into two categories (i) the study of reprocessing emission in High Mass X-ray Binaries (HMXBs) and (ii) the variations in the cyclotron line forming region in NS.

Reprocessing environment in HMXBs

High-mass X-ray binaries (HMXB) are binary systems with a massive main sequence (MS) star ($M > 10M_{\odot}$) and a compact object, usually an NS or a BH. Matter accreted by the compact object is predominantly from the direct capture of the stellar wind from the MS companion, sometimes leading to the formation of a temporary accretion disc. The presence of structured stellar wind is known from observations of massive stars across different energy bands (Sundqvist et al. 2012).

The observed variability in spectral and timing properties of wind-fed HMXBs was first explained using the presence of clumpy wind by Sako et al. (Sako et al. 2003). Subsequent studies have confirmed the presence of clumpy wind in a number of bright HMXBs like Vela X-1 (Fürst et al. 2011), GX 301-2 (Mukherjee & Paul 2004) and OAO 1657–415 (Pradhan et al. 2014).

GX 301-2 is known for its distinct distribution of matter around the binary orbit, which gives rise to a unique variation of source flux, with a strong flare observed near pre-periastron passage (Islam & Paul 2014, Manikantan et al. 2023b). The source is also known to exhibit clumpy stellar winds (Mukherjee & Paul 2004, Islam & Paul 2014). We observed that during a pre-periastron observation of GX 301-2, coherent pulsations were detected with a secondary period along with the spin period of the NS. The secondary period was shorter than the NS spin period and was most prominent in the iron fluorescence energy band. At the spin period of the NS, the pulsation of the iron line was found to have a low amplitude and a profile significantly different from the continuum. While at the secondary period, both the iron line and the continuum had nearly identical pulse fraction and pulse profile indicating a common origin. The additional periodicity can be attributed to the beat frequency between the spin of the neutron star and the Keplerian frequency of a stellar wind clump in retrograde motion around the neutron star. Reprocessed X-ray emissions originating from the clump can produce the observed secondary pulsations both in the continuum and the iron fluorescence line. The clump rotating around the NS is estimated to be approximately five light seconds away from the NS (Roy et al. 2024a).

Cyclotron features in XRBs

In highly magnetized ($B \geq 10^{12}$ G) NSs, the accreted matter gets channelled along the magnetic field lines to the magnetic poles of the NS. A hot spot is produced on the accretion mound near the magnetic poles of the NS, giving rise to X-ray emissions (Becker & Wolff 2007). The presence of strong magnetic fields at the polar regions leads to the quantization of electron energy levels (E_n in keV) in accordance with the Landau levels (Meszaros 1992). In accreting XRBs, the aforementioned effect manifests as an absorption feature on the continuum X-ray spectrum, commonly known as the Cyclotron Resonant Scattering Feature (CRSF). CRSF line energy facilitates the direct measurement of the magnetic field strength of the NS. While some NS spectra do not contain any CRSFs, in the sources that do contain CRSFs, the exact region responsible for the production of CRSFs is still under debate (Staubert et al. 2019). Out of the more than two hundred and fifty accreting binary XRBs, around fifty sources exhibit CRSF*.

The presence of a cyclotron line was discovered in Her X-1 (Truemper et al. 1978). The measurements of line energy of CRSF over the last fifty years have shown that CRSF varies with pulse phase (Voges et al. 1982, Soong et al. 1990, Vasco et al. 2013), time (Staubert et al. 2017) and source luminosity (Makishima et al. 1990, Mihara 1995). Becker et al. (2012) showed from physical modelling of the accretion column that variability in CRSF with luminosity can be broadly grouped into two types. At lower luminosity, in the sub-critical accretion regime, it is expected that a positive relation will be present between CRSF energy and luminosity. While at a super-critical regime, the correlation becomes negative. The change from positive to negative occurs at a ‘critical’ luminosity (Becker et al.

*http://orma.iasfbo.inaf.it:7007/~mauro/pulsar_list.html

2012).

Discovery of CRSF in new X-ray pulsars

IGR J0607.4+2205 is a transient Be X-ray binary, which was discovered two decades ago (Chenevez et al. 2004). The source underwent an outburst in 2023, during which it was observed twice with *NuSTAR*. It was the first broadband observation of the source since its discovery in 2004. The broadband spectrum of the source was modelled using a power-law continuum with a high-energy cutoff. The source showed significant variation in accretion geometry during the course of the outburst, which was evident from the evolution of the pulse profile across the two observations. The observed changes in the pulse profile with luminosity could also be associated with changes in the beaming pattern during the course of the outburst. A cyclotron absorption line at ~ 51 keV was discovered in the source at the peak of the outburst with an optical depth of ~ 1.3 . However, no cyclotron line feature was detected in the second observation when the source was an order of magnitude fainter. Additionally, a soft excess was detected in the decay phase, which most likely originates from a hot spot close to the neutron star. We estimated the magnetic field strength of the NS to be $\sim 4 \times 10^{12}$ G from the centroid energy of the cyclotron line.

Two Fundamental CRSF in 4U 0115+63 and their luminosity variations

The HMXB 4U 0115+63 is known to exhibit a fundamental CRSF along with its three harmonics (Santangelo et al. 1999). The fundamental CRSF in the source exhibited significant non-trivial variation with luminosity (Nakajima et al. 2006); however, subsequent studies have called into question the reliability of the results (Müller et al. 2013b). A paradigm shift came into the understanding of the

CRSF when the continuum model of the pulsar was updated to include two fundamental CRSFs in the source, invalidating the older studies of CRSF energy with luminosity (Iyer et al. 2015).

We analyzed the recent *NuSTAR* observations during a giant outburst in 2023 with X-ray luminosity of the source reaching $10^{38} \text{ erg s}^{-1}$ and combined the results with other recent observations of the source to get an updated view on luminosity dependence of CRSFs. The CRSF line centre showed no anti-correlation with luminosity, unlike previously reported. Instead, a weak positive correlation was found in four out of the five detected cyclotron lines of 4U 0115+63. The luminosity variation of the two fundamental CRSFs could be well explained with the prediction from the collisionless shock model (Becker et al. 2012). A tentative negative correlation was observed in the fundamental CRSF at 16 keV and its harmonics beyond a ‘critical luminosity’ of $10^{38} \text{ erg s}^{-1}$. This behaviour was not present for the 12 keV fundamental CRSF, and its harmonic at 24 keV.

Detection of CRSF in Cep X-4 at a low luminosity level

A CRSF was first detected in Cep X-4 at $\sim 30 \text{ keV}$ with *GINGA* data (Mihara et al. 1991). Subsequent observations have shown the presence of the CRSF across multiple outbursts. A positive correlation was observed between CRSF energy and X-ray luminosity with *NuSTAR* from pulse-amplitude resolved analysis (Vybornov et al. 2017). However, combining data across multiple outbursts, the CRSF line energy showed no variation with X-ray luminosity or evolution with time (Mukerjee & Antia 2021). Using *NuSTAR* data from the most recent outburst, we showed that there is indeed a positive relation between CRSF energy and luminosity. Detection of the CRSF at a low luminosity considerably widened the luminosity range over which CRSF is measured in this source and it enabled the detection of a certain

positive correlation between CRSF energy and X-ray luminosity of the source. The observed variation of CRSF energy with luminosity is in agreement with the prediction from the collisionless shock model (Becker et al. 2012). Therefore, observations of Be X-ray binary sources are required across wide ranges in luminosities to establish the actual variation of CRSF with X-ray luminosity.

”Most of the fundamental ideas of science are essentially simple, and may, as a rule, be expressed in a language comprehensible to everyone.”

Albert Einstein

1

Introduction

1.1 X-ray binaries

The brightest X-ray sources in the sky are mostly X-ray Binary (XRB) systems. While some of these systems are persistent, whose flux varies between a few to a few hundred mCrab ($1 \text{ Crab} \sim 10^{-9} \text{ erg s}^{-1} \text{ keV}^{-1} \text{ cm}^{-2}$), other sources are transient with flux ranging from below detection threshold to reaching as high as a few Crab at the peak of their outburst. XRBs are usually systems with a Main Sequence (MS) star and a compact object like a Black Hole (BH), a Neutron Star (NS) or a White Dwarf (WD). The compact object is often called the ‘primary’ star in the system,

while the MS star is identified as the ‘secondary’ companion. The compact object captures matter from the MS star through a process called accretion. The loss of gravitational potential energy of the accreted matter is emitted as electromagnetic (EM) radiation, which is predominantly X-rays. The high-energy radiations originate from close to the compact object, which allows the probing of extreme conditions close to the compact object.

X-rays cannot penetrate the atmosphere of earth, therefore, we must cross the atmosphere to experience the X-ray universe. In the initial days of X-ray astronomy, rocket-borne instruments discovered the first extraterrestrial X-ray source, Sco X-1, which was later identified as an accreting neutron star binary system. However, it was satellite-based X-ray instruments which allowed prolonged observation with excellent pointing accuracy. The first X-ray satellite was *Uhuru* which discovered the first known accretion-powered X-ray Pulsars (XRPs), where the compact object is a NS, Cen X-3 (Giacconi et al. 1972) and Her X-1 (Tananbaum et al. 1972). After the success of *Uhuru* a large number of X-ray satellites have been flown, with more than a dozen instruments currently operational. X-rays instruments work by detecting individual photons. A clock is used to record the time of detection. X-rays entering the detector produces ionisation in the detector material, and the resulting number of ionisation pair is roughly proportional to the energy of the X-ray photon. In the case of imaging instruments, the locations in the detectors where the X-ray is detected are also known. Sometimes, scattering materials are used to probe the polarisation of the incoming photons. To summarise, X-ray instruments have the ability to study spectral and timing characteristics (Chapter 2) and may have imaging or polarisation capabilities.

1.2 Classifications of XRBs

XRBs can be characterised based on the nature of the primary star; the compact object can be a BH (BH-XRB) or a NS (XRP). They can also be categorised by the relative mass of the secondary (MS) star with respect to the primary. If the mass of the MS star is greater than $10 M_{\odot}$ the system is called a High Mass X-ray Binary (HMXB), while if the mass is less than $2 M_{\odot}$ then it is classified as a Low Mass X-ray Binary (LMXB), anything in between can be classified as an Intermediate Mass X-ray Binary (IMXB). HMXBs are sometimes also classified based on the nature of the massive MS companion. If the companion is a Be-type star, it is called a Be X-ray Binary (Be-XRB), while if the MS star is a massive O/B type star, then it is called a Super Giant X-ray Binary (SGXB). The dominant accretion mechanism in XRBs depends on the relative mass of the primary compact object with respect to the companion main-sequence star. Most SGXBs are persistent in nature, with accretion occurring via Roche-Lobe overflow or through direct capture of stellar winds of the companion. BeXRBs are mostly transient in nature, and the compact object is usually a NS with highly eccentric orbits.

The consensus about the NS is that of a compact object with a canonical radius of $R_{NS} \sim 10$ km, and a canonical mass of $M_{NS} \sim 1.4$ solar mass ($M_{\odot}$). The NS in an X-ray binary accretes matter from the companion star, either by direct capture of stellar wind or via Roche-Lobe overflow. Material infalling onto the compact object in XRBs loses their gravitational potential energy, converting it into kinetic energy and finally into electromagnetic radiation.

In case of LMXBs, the main sequence star is less massive than the compact object, making the gravitational potential well deeper for the compact object compared to the MS star. During its evolution, the main sequence star fills up its

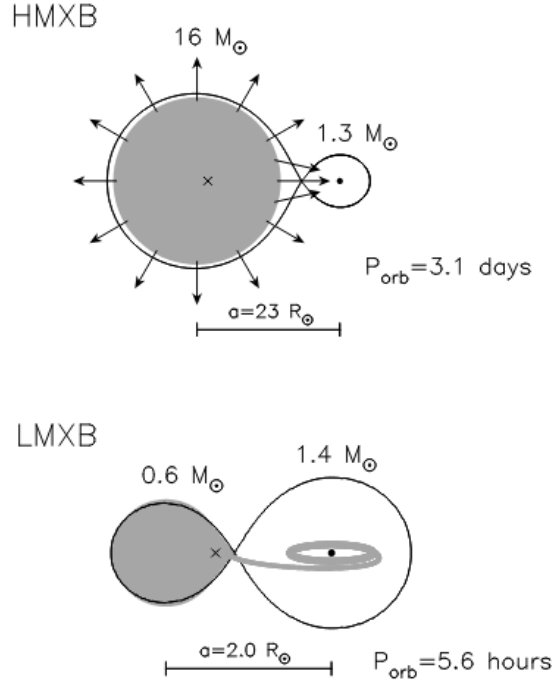


Figure 1.1: A sketch of the accretion process occurring in X-ray binaries. (Image Credit : Tauris & van den Heuvel (2006))

Roche-Lobe, resulting in matter flowing into the compact object. A sketch of the accretion process is shown in the bottom panel of Fig. 1.1. The infalling matter forms a stream as it travels towards the compact object. An accretion disc is usually formed in these systems. In HMXBs, the main sequence star is the more massive of the two stars in the binary. The accretion in that case occurs via direct capture of stellar wind as shown in the top panel of Fig. 1.1. The direct capture of stellar wind shows short-term variabilities in the time series data from these systems.

The massive O/B type main sequence stars in HMXBs have strong stellar winds with mass loss rate up to $10^{-5} M_{\odot} \text{ yr}^{-1}$. Even though direct wind capture is not as efficient as Roche-Lobe overflow, due to the large stellar mass loss rate in O/B type MS stars, significant matter is accreted onto the compact objects, making them some of the brightest known XRBs. The accreted matter, instead of directly

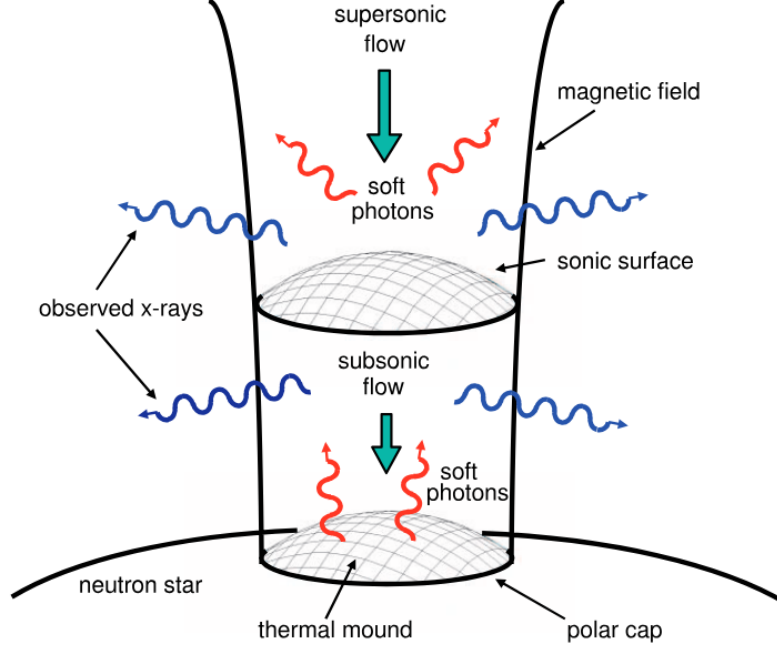


Figure 1.2: A sketch of the accretion column in X-ray binary pulsars. (Image Credit : Becker & Wolff (2007))

infalling onto the compact object, can form an accretion disc around the compact object. The accretion disc is most common in LMXBs, but can sometimes form in HMXBs as well. The accretion disc is usually modelled by a multi-temperature blackbody model. In cases of HMXB pulsars where the compact object is a NS, the presence of strong magnetic fields ($\sim 10^{12}$ G) results in matter getting attached to the magnetic field lines at the magnetospheric radius (r_M). The value of the magnetospheric radius for spherical accretion can approximately (Frank et al. 1992) be given as,

$$r_M = 5.2 \times 10^8 \mu_{30}^{4/7} m_{NS}^{-1/7} \dot{M}_{16}^{-2/7} \text{ cm} \quad (1.1)$$

where μ_{30} is the dipolar moment of the magnetic field in units of 10^{30} G cm², m_{NS} is the mass of the neutron star in units of solar mass ($M_\odot$), and $\dot{M}_{16}$ is the mass accretion rate in units of 10^{16} g s⁻¹.

1.3 Emission from XRBs

As matter falls onto the NS surface following the magnetic field lines, they are confined to smaller and smaller regions as the matter gets closer to the magnetic poles. The infalling matter finally reaches the shock forming region in the accretion column. Beyond the shock front, the matter can get thermalised and emit like a black body, or it can emit non-thermally via Bremsstrahlung emission. A sketch of the accretion column is shown in Fig. 1.2 taken from [Becker & Wolff \(2007\)](#). The blackbody or the Bremsstrahlung photons emitted from the NS surface can then be up-scattered as the EM radiation travels through the supersonic infalling material. The Compton up-scattered photons give a power-law-like spectrum. The power-law component is sometimes accompanied by a high-energy cutoff, which corresponds to the temperature of the up-scattering plasma. Anisotropic emission from the magnetic poles due to beaming effects and magnetic axis not being aligned with spin axis of the NS results in non-uniform emission as a function of the spin rotation of the NS. The shape of X-ray pulse profiles can give us information about the emission geometry in NSs. The generally regarded axially symmetric fan beam and pencil beam emission mechanisms in X-ray pulsars (Fig. 1.3) show distinct pulse profiles. Another important X-ray emission mechanism, synchrotron emission, is found in micro-quasars that have relativistic jets. In the accreting X-ray pulsars, the electrons are non-relativistic and therefore synchrotron emission is not observed in these sources.

1.4 Reprocessed emission from the binary environment

The X-ray photons originating from close to the NS shine on the wider binary environment, producing secondary X-ray photons. The most prominent emission

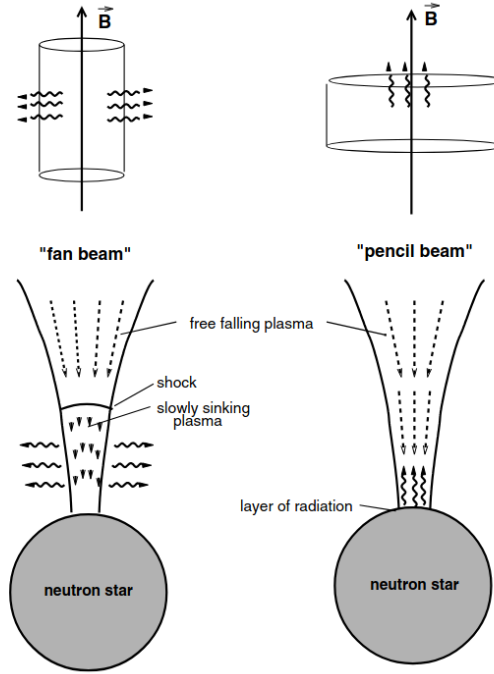


Figure 1.3: An illustration of the different X-ray beaming patterns. (Image Credit: [Schönherr et al. \(2007\)](#)).

feature for the reprocessed radiation is the fluorescence iron $K\alpha$ line. The neutral iron emission line appears at ~ 6.4 keV, and is usually the strongest line in X-ray pulsars. There can also be fluorescent emission from highly ionised species of iron at ~ 6.7 and 6.9 keV for helium-like (Fe XXV) and hydrogen-like (Fe XXVI) species of iron. The strong fluorescent emission line from near-neutral line can be accompanied by an additional somewhat broad emission line near 6.24 keV from Compton down-scattering of the strong fluorescent photons especially in a dense medium. There can also be a $K\beta$ emission line from iron at ~ 7.1 keV as well as L shell transitions of iron near ~ 1 keV. There are often emission lines from Carbon, Oxygen, Neon, Sulphur, Argon, Calcium, Chromium and Nickel.

The emission lines from near-neutral and ionised species of different elements probe different locations in the binary environment. The same emission line can originate from multiple locations in the binary system. A schematic diagram of the possible reprocessing regions in the wider binary environment is shown in Fig. 1.4.

These locations include fluorescent emission from materials close to the NS, like the accretion column of the NS or the accretion stream bringing materials from the accretion disc to the NS. The accretion disc can also produce the fluorescent emission if X-rays from near the NS shine on the disc. The wider binary environment populated by the stellar wind from the main-sequence companion or accretion disc wind can be the possible origin of the fluorescence emission. The surface of the main-sequence star can also produce fluorescence emission if enough X-ray photons are incident on its photosphere.

The fluorescent emission from XRBs can also have multiple temporal signatures. In cases where the reprocessed emission comes from homogeneous and isotropic material far from the NS, there are usually no temporal signatures. Timing signatures may originate from inhomogeneity of the reprocessing medium or the anisotropy of the material distribution. The lines can be even red-shifted if they are influenced by the strong gravity of the compact object, like a black hole. The Doppler shift in the centre of the iron emission or absorption lines can also probe any relative motion of the line-forming region and can be used to put bounds on the exact region where the fluorescent emissions originate. The advent of new generation X-ray detectors (Sato et al. 2023) with very good spectral resolution can measure the Doppler motion of the order of a few hundred km s^{-1} , enabling us to put better constraints on the possible origin scenarios of the reprocessed emission.

In NS systems, the spin of the compact object about its axis and the beamed emission from the accretion column shine on different regions of the binary environment at different pulse phases. This gives a unique set of tools to probe the binary environment using reprocessed emission lines. In the case of slow rotating pulsars ($P_{\text{spin}} \gtrsim 100$ s) like GX 301–2 or Vela X–1 the light travel distance corresponding to the spin period of the NS is larger than the binary orbit, therefore any

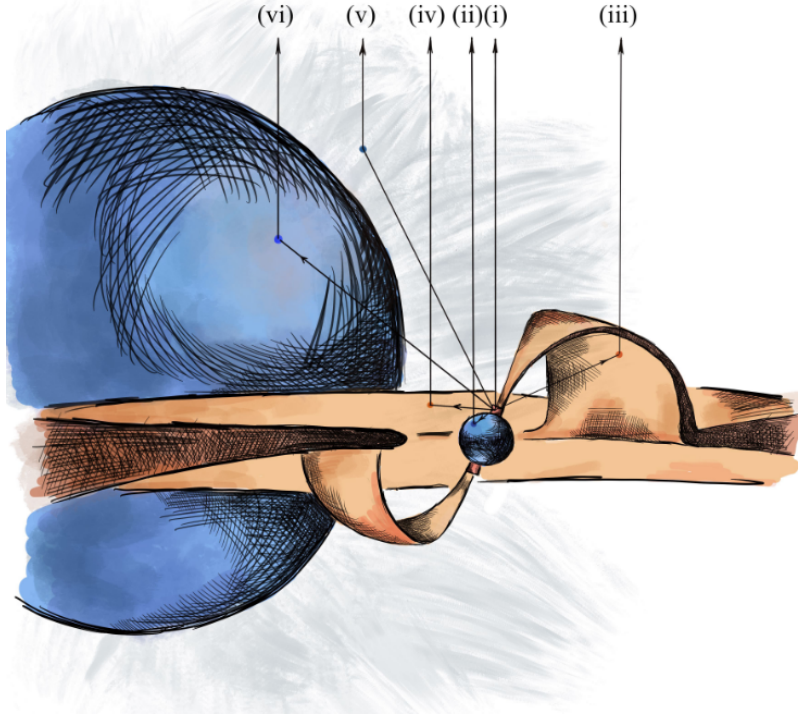


Figure 1.4: A schematic view of X-ray pulsar reprocessing region. (Image Credit: Tsygankov et al. (2022)). The Roman numerals correspond to (i) the direct emission from the hotspot, (ii) reflection from the NS surface, (iii) reflection from the accretion curtain, (iv) reflection from the accretion disk, (v) fluoresce from the stellar wind, (vi) reflection by the optical companion.

anisotropies in the wider reprocessing environment can give rise to spin-phase dependency of the iron emission lines. For fast spinning pulsars ($P_{spin} \lesssim 10$ s) like Her X–1, 4U 1626–67 and Cen X–3 the spin variation of fluorescent lines can only be produced close to the NS. Spin-phase dependent modulation in the iron $K\alpha$ emission line was first discovered in Cen X–3 with *GINGA* data (Day et al. 1993) and later confirmed with *NuSTAR* data (Tamba et al. 2023). Even though iron fluorescence emission is ubiquitous in X-ray binaries (Giménez-García et al. 2015), pulsations in the iron line have only been observed in a few sources like Her X–1 (Choi et al. 1994, Vasco et al. 2013), V0332+53 (Bykov et al. 2021), and GX 301–2 (Roy et al. 2024a). Iron line variations with spin rotation of the NS can be produced if there is an anisotropic distribution of matter in the line-producing region and if the light travel time across the region is smaller than the spin period of the NS.

In HMXBs, the radiation from the compact object illuminates the dense binary environment populated by the strong stellar wind from the MS companion. The presence of structured stellar wind is known from observations of massive stars across different energy bands (Sundqvist et al. 2012). The variability in the reprocessed emission can be used as a probe of the stellar wind properties of the companion star. The stellar wind in dense environments naturally forms clumps. Observed variability in spectral and timing properties of wind-fed HMXBs could be explained using the presence of clumpy winds (Sako et al. 2003). Subsequent studies have confirmed the presence of clumpy wind in a number of bright HMXBs like Vela X-1 (Fürst et al. 2011), GX 301-2 (Mukherjee & Paul 2004) and OAO 1657–415 (Pradhan et al. 2014).

1.5 Reprocessed emission as cyclotron lines

The radiation coming from XRBs can be influenced by the strong magnetic field in the accretion column. In a highly magnetised NS, the accreted matter gets channelled along the magnetic field lines to the magnetic poles of the NS. A hot spot is produced on the accretion mound near the magnetic poles of the NS, giving rise to X-ray emissions (Becker & Wolff 2007). The presence of strong magnetic fields at the polar regions leads to the quantisation of electron energy levels (E_n in keV) in accordance with the Landau levels (Meszaros 1992) as:

$$E_n = \frac{n}{(1+z)} \frac{eB\hbar}{m_e c} \sim \frac{11.6 \times n \times B_{12}}{1+z} \text{ keV}, \quad (1.2)$$

where m_e is the mass of an electron, B_{12} is the magnetic field strength in units of 10^{12} G, $n=1,2,3,4,\dots$ denotes the different levels, and z is the gravitational redshift due to the NS mass. In accreting XRPs, the aforementioned effect manifests

as an absorption feature on the continuum X-ray spectrum, commonly known as the Cyclotron Resonant Scattering Feature (CRSF). CRSF line energy facilitates the direct measurement of the magnetic field strength of the NS.

While some NS spectra do not contain any CRSFs, in the sources that do contain CRSFs, the exact region responsible for the production of CRSFs is still under debate (Staubert et al. 2019). Out of the more than two hundred and fifty accreting binary XRPs, around fifty sources exhibit CRSF*.

The presence of a cyclotron line was discovered in Her X-1 (Truemper et al. 1978). The measurements of line energy of CRSF across the last fifty years have shown that CRSF varies with pulse phase (Voges et al. 1982, Soong et al. 1990, Vasco et al. 2013), time (Staubert et al. 2017) and source luminosity (Makishima et al. 1990, Mihara 1995).

1.5.1 Cyclotron line variation with luminosity

The current theory of the cyclotron line central energy variation with luminosity is based on changes in the height of the shock-forming region in the accretion column of the NS with mass accretion rate and, in turn, with the X-ray luminosity (Becker et al. 2012). The magnetic fields in these systems are assumed to be dipolar. At the lowest mass accretion rate, the shock forming region is produced at a certain height above the NS surface, and there is not much change in the shock height with increasing mass accretion rate. In this regime, the cyclotron line energy does not significantly vary with luminosity. However, as the mass accretion rate keeps on increasing, the shock-forming region is pushed downwards, closer to the NS, probing stronger magnetic fields. Therefore in this ‘sub-critical regime’ the cyclotron line energy increases with luminosity. However, the shock forming

*http://orma.iasfbo.inaf.it:7007/~mauro/pulsar_list.html

height can not be pushed down indefinitely and beyond a certain mass accretion rate, radiation pressure starts dominating and the shock forming height keeps going higher with increasing mass accretion rates, probing weaker magnetic fields. Therefore, in this ‘super-critical regime’, the CRSF line energy is negatively correlated with luminosity. This change of positive to negative correlation between the CRSF line energy and luminosity occurs at the ‘critical luminosity’.

1.5.2 Collisionless Shock Model

A positive correlation is observed in cyclotron line energy with the luminosity in the collisionless shock regime (Becker et al. 2012), and beyond a critical luminosity, the relation changes to a negative correlation (Staubert et al. 2019). The variation in the line centre with flux is entirely due to the magnetic field strength at the height above the NS surface responsible for the production of the CRSFs. The scaling of the magnetic field strength with flux could well explain the luminosity dependence in Her X-1 (Staubert et al. 2007). In sources displaying a positive correlation, there is an increase in the height of the region in the accretion mound near the poles of the NS, where the CRSF is produced with a decrease in luminosity. While at a higher height in the accretion mound, the magnetic field is smaller, leading to a lesser value for the CRSF centroid energy.

The centroid energy of the CRSF is directly proportional to the magnetic field strength at the line-forming region (eq. 1.2). Assuming a dipolar magnetic field, the magnetic field strength (B) is inversely proportional to the cube of distance (r) from the centre of the NS. Therefore, the energy of the cyclotron line as a function of the height from the NS surface can be written as

$$E_{\text{cyc}}(H_S) = E_0 \left(\frac{R_{\text{NS}}}{H_S + R_{\text{NS}}} \right)^3 \times \frac{1 + z(R_{\text{NS}})}{1 + z(H_S)}, \quad (1.3)$$

where R_{NS} is the radius of the NS, E_0 is the value of the CRSF energy on the NS surface, $z(R_{NS})$ is the gravitational redshift on the NS surface, and $z(H_S)$ is the gravitational redshift at a height H_S from the NS surface. The value of gravitational redshift $z(H_S)$ at a distance H_S from the surface of the NS of radius R_{NS} is written as

$$1 + z(H_S) = \left(1 - \frac{2GM}{(R_{NS} + H_S)c^2} \right)^{-1/2}, \quad (1.4)$$

where G is the gravitational constant and c is the speed of light in vacuum. The height of the shock-forming region can be written as a function of the X-ray luminosity (L_X) as (Vybornov et al. 2017)

$$\frac{H_S(L_X)}{R_{NS}} = KL_X^{-\alpha}, \quad (1.5)$$

where α is the power law index and K is the proportionality constant. For quasi-spherical settling accretion, $\alpha = 9/11$ and $\alpha = 5/7$ for quasi-spherical Bondi accretion or disk accretion (Vybornov et al. 2017). Combining eq. 1.3, eq 1.4 and eq. 1.5, the variation in the cyclotron line energy with X-ray luminosity for the collisionless shock model can be written as

$$E_{cyc}(L_X) = \frac{E_0}{(1 + KL_X^{-\alpha})^3} \times \frac{\left(1 - \frac{2GM}{R_{NS}c^2} \right)^{-1/2}}{\left(1 - \frac{2GM}{R_{NS}(1 + KL_X^{-\alpha})c^2} \right)^{-1/2}}, \quad (1.6)$$

where G is the gravitational constant, c is the speed of light in vacuum, K and E_0 are the free parameters, and α is taken as $5/7$ corresponding to disk or Bondi quasi-spherical accretion. The collisionless shock model has been successful in describing the luminosity variation in the cyclotron line for sources such as GX 304–1 (Rothschild et al. 2017) and Cep X–4 (Vybornov et al. 2017).

The study of cyclotron line variation with luminosity can be performed well in transient XRP as they go through a large range in luminosity. Most persistent X-ray pulsars only show variability by a factor of few, so it is hard to probe a large range of luminosities in these systems. Transient XRP with a Be-type main sequence companion (BeXRP) are most useful for studying accretion onto highly magnetised NSs across a large range in luminosity since they undergo multiple outbursts. The BeXRP exhibit a wide range of luminosity, ranging from 10^{37-38} erg s⁻¹ during the peak of the outburst to 10^{32-34} erg s⁻¹ during the quiescence phase (Tsygankov et al. 2017).

In this thesis, we investigate the binary environment in HMXB pulsar using fluorescent emission lines. The strong iron K α line in GX 301-2 is as a tracer of the re-processing environment. We use archival *XMM-Newton* data to look for temporal signatures in the iron fluorescence emission lines which can come from the inhomogeneous and anisotropic matter distribution near the NS. We have also worked on the reprocessed emission from the shock forming region in the accretion column in X-ray binary pulsars, where the cyclotron lines are theorised to originate. Be-XRBs are known to exhibit a wide range in luminosity providing an ideal system to study the luminosity dependence of cyclotron lines. We study CRSF features in multiple Be-XRBs during their outburst phase to study how the line forming region in these systems depend on luminosity.

1.6 Thesis Structure

The thesis is structured in the following manner,

Chapter 2

This chapter contains a description of the X-ray telescopes that have been used

in the manuscripts contained in the thesis. The basics of the timing and spectral analysis utilised in the multiple projects have also been outlined in the chapter.

Chapter 3

This chapter is based on the study of the binary environment of GX 301-2 using the iron fluorescent emission. The project utilises archival *XMM-Newton* data as the telescope has the largest collecting area in the iron fluorescence energy band, along with good spectral resolution. The findings discussed in this chapter are part of a paper published in the journal MNRAS.

Chapter 4

This chapter contains the details of the discovery of a cyclotron line in the BeXRP IGR J06074+2205, and also observes the possible changes in accretion regime. We utilise data from *NuSTAR* telescope. The findings discussed in this chapter are part of a paper published in the journal A&A.

Chapter 5

This chapter contains the details of the study of the luminosity variation of the multiple CRSFs in 4U 0115+63. We also try to probe the origin of the two fundamental CRSF in the source. We primarily use data from *NuSTAR* telescope, but we also take results from archival observations with *RXTE* and *Suzaku* telescopes. The findings discussed in this chapter are part of a paper published in the journal A&A.

Chapter 6

This chapter contains the details of the detection of a CRSF at low luminosity level in *Cepheus X-4*. We also study the luminosity variation of the CRSF using all previous detections of CRSFs in Cep X-4. We primarily use data from *NuSTAR* telescope, but we also take results from observations taken with multiple telescopes. The findings discussed in this chapter are part of a paper published in the journal

New Astronomy.

Chapter 7

In this section we summarise the main findings of the thesis and mention some works in progress and future works.

*Science progresses best when observations force us
to alter our preconceptions.*

Vera Rubin

2

Instruments and Techniques

2.1 Introduction to X-ray observatories

The advent of satellite-based X-ray observatories has provided a gateway to study observational X-ray astrophysics. X-ray instruments are designed to detect individual X-ray photons. Most X-ray instruments are designed to record the energy (spectroscopy) and time (timing) of the detected photon, while imaging instruments are also able to record the spatial information (imaging) of the detected X-ray photons. There are different types of X-ray detectors based on the science goals of particular missions. For cases which require a lot of source photons to be

detected to perform detailed timing or polarimetric study, instruments with large collecting areas are preferred, like *RXTE/PCA*, *AstroSat/LAXPC* and *XPoSat/POLIX*. However, due to the large geometric area, a lot of background photons are also detected, leading to a small signal-to-noise ratio (SNR). Therefore, to obtain high SNR data, especially for spectroscopic purposes, low readout noise Solid State Charge-Coupled Devices (CCD) are preferred like *XMM-Newton/EPIC*, *Chandra/ACIS*, *Suzaku/XIS*, *NuSTAR/FPM*, etc. The small pixel size of the CCDs also allows for imaging studies in these sources, however, the advantage of these instruments are restricted by their low geometric area which leads to less number of detected photons. *HEAO-2* was the first telescope to use focussing optics for imaging purposes to reveal spacial variability in astrophysical objects. Focussing optics are primarily used to improve the sensitivity of X-ray detectors while providing positional sensitivities to the detectors. The detectors at the focal plane of the optics can be CCDs like in *XMM-Newton/EPIC*, *Chandra/ACIS*, *Suzaku/XIS*, *NuSTAR/FPM*, etc. On the other hand, there have been focussing optics, without CCDS, but with gas imaging detectors like *HEAO-2*, *ASCA/GIS*, *BeppoSAX/MECS* and *LECS* etc. Optics can also be to increase the effective photon collecting area like in *NICER*.

The astrophysical X-ray observatories can also be classified into pointed observatories and all-sky monitors based on the science goals of the instruments onboard the satellite. The pointed telescopes usually observe a small patch of the sky, collecting photons from astrophysical sources of interest for long exposure times and providing high-quality data. All sky monitors can cover a large part of the sky helping in the discovery of X-ray transient events like Gamma-Ray Bursts (GRBs), electromagnetic counter parts of high energetic events like Gravitation Wave events (GW), or X-ray counter parts of Fast-radio Burst (FRBs). The all-sky monitors are used to take either images of the sky via scanning the sky using low

exposure photos of multiple small patches of the sky simultaneously, looking for transient X-ray activity from XRBs or AGN, or monitor a large part of the sky at a time to look for GRBs or electro-magnetic counter part of GW events and X-ray counterparts of the FRBs. In this thesis, we have used data from pointed observatories of XRP from *XMM-Newton*/EPIC-PN and *NuSTAR*/FPM and long-term data from all-sky monitors like *Swift*/BAT and *MAXI*/GSC.

In the following sections, we introduce the X-ray instruments that have been utilised in the making of this thesis (Sec. 2.2) followed by the data reduction (Sec. 2.3) and analysis methods (Sec. 2.4) used on the observed data. We also introduce some basic concepts of timing (Sec. 2.4.1) and spectral (Sec. 2.4.2) analysis.

2.2 X-ray astronomy missions utilised for this thesis

2.2.1 X-ray Multi-Mirror Mission (*XMM-Newton*)

XMM-Newton (Jansen et al. (2001)) is an X-ray astronomical observatory launched by the European Space Agency (ESA) in 1999. It is one of the longest operational active X-ray telescopes. *XMM-Newton* uses three parallel axial Wolter Type I X-ray focusing optics to focus incident X-ray emissions to CCDs. Each X-ray telescope contain 58 concentric mirror cells with a 7.5 m focal length.

XMM-Newton has imaging, spectroscopic and timing capabilities. It consists of three X-ray detectors named *European Photo Imaging Camera* (EPIC) at the focal plane of three X-ray telescopes. Two EPIC cameras have MOS CCD detectors (Turner et al. 2001), while the third contains a PN CCD detector (Strüder et al. 2001). Additionally, there are two *Reflection Grating Spectrometers* (RGS) for high-resolution X-ray spectroscopy (den Herder et al. 2001) and an *Optical Monitor* (OM) for optical and UV imaging (Mason et al. 2001). While one of the optics directs all

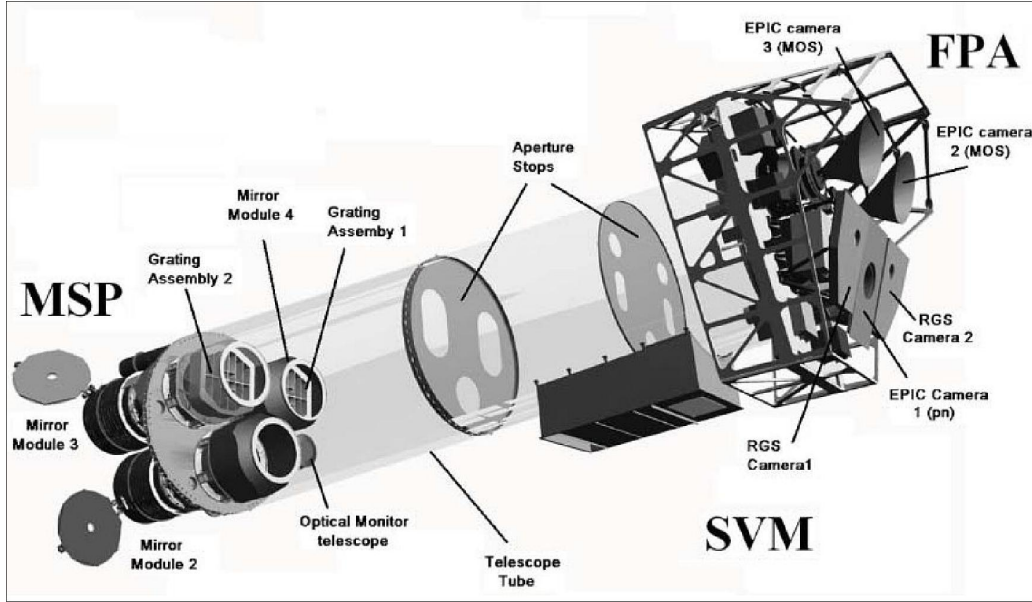


Figure 2.1: A sketch of *XMM-Newton* observatory. There are three coaxial optics for the three EPIC cameras. (Image Credit: ESA)

the incoming rays to the EPIC-PN detectors, the other two focusing telescopes split the photons equally into the EPIC-MOS CCDs and RGS CCD strips. A schematic diagram of *XMM-Newton* with different instruments is given in Fig. 2.1. The *XMM-Newton* satellite is in a highly elliptical orbit around Earth with an apogee distance of 6000 km and a perigee distance of 115,000 km. The highly eccentric orbit allows *XMM-Newton* to have continuous observation of selected patches of the sky for a long period of time.

European Photon Imaging Camera - PN (EPIC-PN)

The EPIC-PN instrument has a large effective area and collects all the photons from one of the focusing telescopes, giving it a high photon count rate. The EPIC-PN comprises of twelve monolithic Silicon CCDs arranged in two rows. Each CCD is $3\text{ cm} \times 1\text{ cm}$ in dimension, containing 64×198 pixels. The point spread function (PSF) is $13''$ wide at full-width half maxima (FWHM). As the satellite is in a highly

elliptical orbit, it spends significant time away from Earth's magnetospheric protection, suffering from soft proton flares from the Sun (Read & Ponman 2003). The EPIC-PN instrument has different science modes of operation, namely Full Frame (Full Frame / Extended Full Frame modes), Partial Window (Large Window, Small Window), TIMING and BURST modes based on the number of operational CCDs. In TIMING/BURST mode, the imaging capability is sacrificed to reduce pile-up effects of the CCD. The event timing accuracy of EPIC-PN varies from $7 \mu\text{s}$ in the BURST mode to 200 ms in the Extended full frame mode. In TIMING mode, the EPIC-PN instrument can operate till source brightness of ~ 800 cts/s without getting affected by pileup. The EPIC-PN instrument operates in the 0.5-10 keV energy range, with a spectral resolution of ~ 150 eV at 6 keV and an on-axis effective area of $\sim 900 \text{ cm}^2$ at 6 keV.

2.2.2 Nuclear Spectroscopic Telescopic Array (*NuSTAR*)

NuSTAR (Fig. 2.2) is a National Aeronautics and Space Administration (NASA) Small Explorer (SMEX) X-ray mission launched in 2012 (Harrison et al. 2013). It is a hard X-ray focusing optics telescope. The satellite is placed in a low earth orbit at a height of 600 km. The main instrument on the satellite are the two parallel Focal Plane Modules (FPMA and FPMB) at the end of two hard X-ray optics. *NuSTAR* has an angular resolution of $18''$ at FWHM.

Focal Plane Module (FPM)

The Focal Plane Modules (FPMs) of *NuSTAR* are a pair of hard X-ray detectors at the end of two Wolter Type-I focusing optics. The modules operate in the 3-79 keV energy range, with a spectral resolution of 400eV below 50 keV. The absolute resolution of the time tagging to each event is about $2 \mu\text{s}$. Hard X-rays are con-

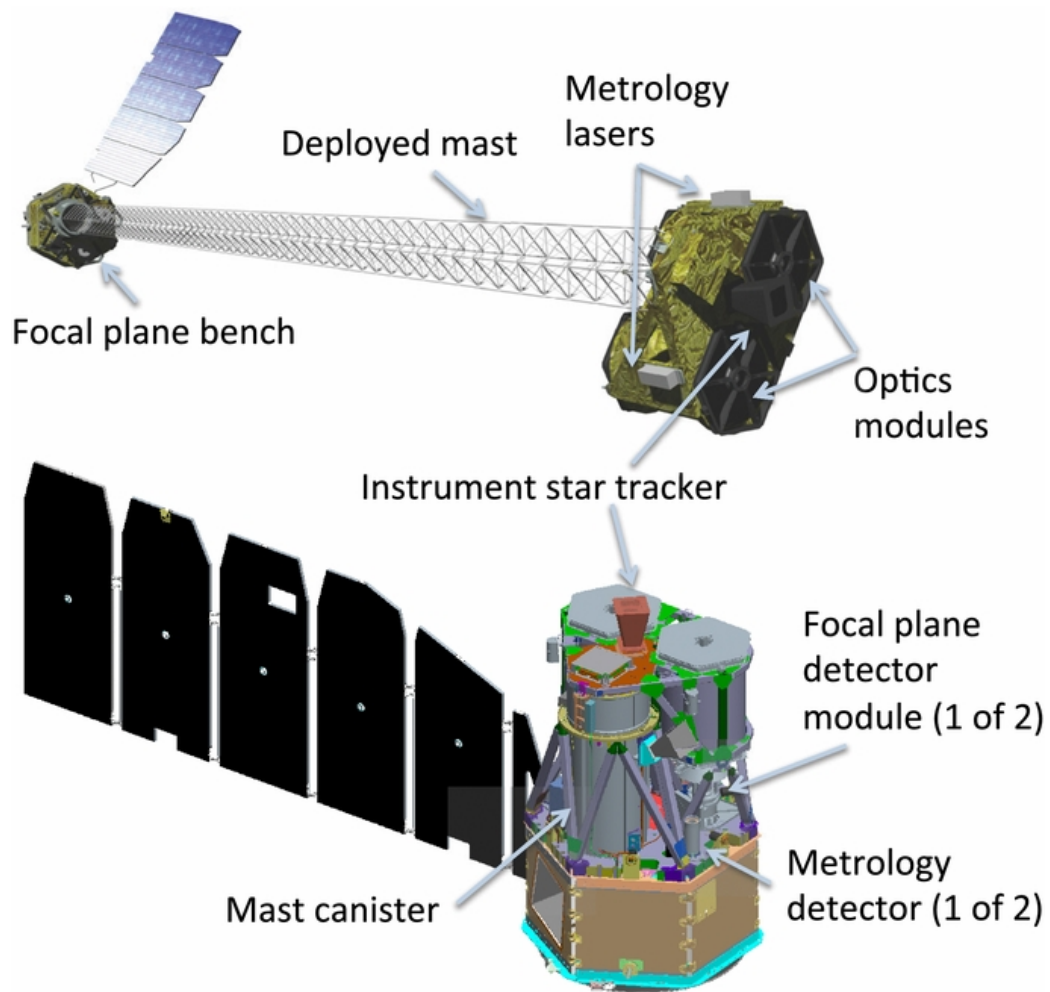


Figure 2.2: A view of *NuSTAR* in the fully deployed state (Top) and the schematic of the mast with different satellite components (Bottom). (Image credit: Harrison et al. (2013))

centrated by grazing incidence on to graded multilayer optics. The focusing optics contain 133 multi layer mirrors made of high Z materials and has a focal length of $\sim 10\text{m}$. The two identical detector arrays are called FPM A (FPMA) and FPM B (FPMB) and are made of a couple of identical Cadmium Zinc Telluride (CdZnTe) pixel detectors. At the end of each of the focusing optics lies 2×2 array of CdZnTe detectors. Each of the detector element has a size of $20\text{ mm} \times 20\text{ mm} \times 2\text{ mm}$ divided into 32×32 pixels. Each pixel in the CdZnTe detectors has a separate read-out, with each readout corresponding to a processing time of 2.5 ms. Therefore the FPM modules can operate up to a count rate of 400 cts/s in each detector without pile-up or data loss effects.

2.2.3 Monitor of All-Sky X-ray Image (*MAXI*)

MAXI is an X-ray instrument operating from the Japanese Experimental Module (Kibbo-EF) onboard the International Space Station (ISS). (Matsuoka et al. 2009). *MAXI* consists of two main science payloads, the Solid-state Slit Camera (SSC) (Tomida et al. 2011) and the Gas Slit Camera (GSC) (Mihara et al. 2011). Both X-ray detectors are X-ray slit cameras designed to observe almost the entire sky during each orbit of the ISS. While GSC instrument consists of multiple gas proportional counter operating in the 2.0 – 20.0 keV range, the SSC consists of CCD detectors operating in the 0.5 – 12.0 keV range. The ISS is operating from a low earth orbit at an altitude of $\sim 400\text{ km}$ and a ~ 50 degree inclination. The orbital period of ISS is about 92 mins. Lightcurves from *MAXI/GSC* of multiple sources are available in the 2 – 4 keV, 4 – 10 keV, and 10 – 20 keV energy band, binned to one day or one orbit of ISS via an online repository *. We have taken the lightcurves from this repository for our analysis.

*<http://maxi.riken.jp/top/lc.html>

2.2.4 Neil Gehrels Swift Observatory (*Swift*)

Swift is one of the NASA's Medium Explorer (MIDEX) missions for monitoring of GRBs. *Swift* was launched in 2004 in a low earth orbit at an altitude of 585 km. There are three scientific instruments onboard *Swift* mission operating over a wide range in energy. The three payloads are the X-Ray Telescope (XRT), Burst Alert Telescope (BAT), and the Ultraviolet-Optical Telescope (UVOT). The telescope was developed for prompt follow up observations of highly energetic GRBs.

Swift/BAT is a large field of view X-ray payload operating in the 15–150 keV range (Barthelmy et al. 2005). BAT is actively monitoring more than one thousand persistent and transient X-ray sources. The lightcurves from these sources are readily available with daily or one *Swift* orbit binned data in the 15-50 keV energy range in an online repository[†]. We have taken the lightcurves from this repository for our analysis.

[†]<https://swift.gsfc.nasa.gov/results/transients/>

2.3 X-ray data reduction

It is essential to properly extract the finished products like spectra, light curve, instrument response, ancillary response etc, from the raw instrument data before any scientific analysis can be performed. Instruments experience breaks in their operations, interrupting continuous data acquisition. All X-ray instruments are switched off when the satellite passes through regions of dense charged particles over the Atlantic Ocean, known as the South-Atlantic Anomaly (SAA), or when the satellites are affected by strongly charged particles emitted from the sun during solar storms. Data acquisition may also be interrupted when the earth eclipses the source on certain parts of the satellite orbit. Thus, we use filters for extracting data strictly taken during the Good Time Intervals (GTIs). Also, the detector characteristics, like gain parameters, may vary with time, so those are also corrected during the reduction process. Some instruments remain affected by background particle flaring or stray lights, which must be accounted for during the data reduction process.

All data from *XMM-Newton* have been extracted using the Science Analysis System (SAS). We followed all the default instructions provided by *SAS Data Analysis Threads*[‡]. The data reduction procedures relevant for *TIMING MODE* were followed from *XMM-Newton ABC Guide*[§]. We checked for pile-up in the data using the SAS tool *epatplot* and corrected for pileup if noticeable pile up was detected. We have used the latest calibration files to reduce the data.

The data from *NuSTAR* were reduced using the *HEASoft*[¶] software and the latest calibration files available via CALDB. The *nupipeline* tool was used to produce the

[‡]<https://www.cosmos.esa.int/web/xmm-newton/sas-threads>

[§]<https://heasarc.gsfc.nasa.gov/docs/xmm/abc/abc.html>

[¶]<https://heasarc.gsfc.nasa.gov/docs/software/heasoft/>

clean event files, while the `nuproduct` tool was used to extract the light curves and spectrum corresponding to the source and background regions.

The data reduction process for all sky monitors are usually carried out at the mission team end. The science products from *MAXI* were obtained from online repository^{||} in the 2–20 keV energy range. The long-term light-curves from *Swift*/BAT are downloaded from the online repository^{**} (Krimm et al. 2006).

2.4 X-ray data Analysis Techniques

Timing and spectral analysis have been performed on different data sets of XRPs to extract information on underlying physical processes for further understanding of these phenomena. The various data analysis techniques that have been utilised for the thesis are explained in this section. Almost all science data products for X-ray astrophysics are stored in Flexible Image Transport System (FITS) file format.

2.4.1 Timing Analysis

The time series ($c(t_n); n \in [0, 1, 2, \dots, N-1]$) information from an X-ray astrophysical observation is called a light curve. Wherever relevant, solar system barycentre correction was performed on data using `barycorr`^{††} tool. The light curve from XRP usually contains periodic modulations. They can either be due to the spin rotation of the NS around its rotation axis, the rotation of the NS around the secondary at the orbital period, or from modulation at even longer timescales called the super-orbital period. The `XRONOS`^{‡‡} tool `lcurve` has been used to plot the lightcurves.

Power Spectral Density

^{||}<http://maxi.riken.jp/top/lc.html>

^{**}<https://swift.gsfc.nasa.gov/results/transients/>

^{††}<https://heasarc.gsfc.nasa.gov/lheasoft/help/barycorr.html>

^{‡‡}<https://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/xronos.html>
<https://heasarc.gsfc.nasa.gov/xanadu/xronos/help/lcurve.html>

The Power Spectral Density (PSD) of a time series dataset expresses the power in different Fourier modes corresponding to different frequencies. A discrete Fourier PSD can be constructed by

$$C^2(f_k) = \frac{1}{N} \left| \sum_{n=0}^{N-1} c_n e^{-i \frac{2\pi n k}{N}} \right| ; k \in [0, 1, 2, \dots, N-1] \quad (2.1)$$

where $C^2(f_k)$ are the signal power at a given frequency (f_k). For evenly sampled time series data ($c(t_n)$) is limited by a maximum ‘Nyquist’ frequency criterion with a frequency resolution δf . The Nyquist frequency for an evenly spaced data with time separation Δt is $(2\Delta t)^{-1}$. The spectral resolution (δf) is given by $(N\Delta t)^{-1}$ where N is the total number of points in the light curve. The power-spectrum was generated using the XRONOS tool `powspec`.

Folding Period Method

An essential tool for detecting pulsations in a X-ray time-series data is the ‘Epoch folding’ method (Leahy 1987). The lightcurve is folded with different trial periods (P_j) and scaled by an appropriate number of exposures for each phase bin, giving a final folded profile (C_i with $i \in 1, 2, \dots, N$ where N is the total number of phase bins). For each constructed time series, statistic (S_j) is equal to the chi-squared value obtained from fitting a constant to the folded data C_i

$$S_j = \sum_{n=1}^N \frac{(C_i - C)^2}{\sigma_i} ; i \in 1, 2, \dots, N \quad (2.2)$$

where

$$C = \frac{1}{N} \sum_{i=1}^N C_i ; i \in 1, 2, \dots, N. \quad (2.3)$$

and σ_i is the error bar corresponding to the i^{th} phase bin.

<https://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/examples/powspec.html>

Finally, a distribution of the statistics (S_j) is calculated for each of the trial folding periods (P_j). For datasets with no periodicity, the statistic S_j would correspond to the noise amplitude, which is a χ^2 distribution with $N-1$ degrees of freedom. A deviation from this noise pattern indicates the presence of periodicity in the light curve. The XRONOS tool `efsearch` is used to extract the spin period from the lightcurve. Extreme care is taken to ensure that systematic effects in the data are isolated before calculating the different periodicity present in the data. The final folded profiles corresponding to the periodicity are extracted using the XRONOS tool `efold`.

2.4.2 Spectral Analysis

The spectrum is the distribution of source flux over a range of frequencies. The spectrum contains information about the different emission processes (Chapter 1). Spectrum of an X-ray source is measured in units of counts $\text{s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$. The photon energies are usually expressed in units of kilo-electron volts (keV). Most of the current X-ray instruments operate within the range of 0.1 to 100 keV. The X-ray telescopes measure photon energy via the voltage measured by the instrument electronics known as the pulse height amplitude (PHA). However, PHA is dependent on the instrument characteristics including the gain of the detector. Therefore the observed voltages are corrected for the gain characteristics and the PHA values are converted to an invariant quantity known as the Pulse-height Invariant (PI). The conversion of the photon energy (E) to instrument measurement (PI), calculated during the calibration of the instrument, is put into a file called the Redistribution Matrix File (RMF). The instrument efficiency is not constant across energy and the information is provided via a Ancillary Response File (ARF). The

<https://heasarc.gsfc.nasa.gov/xanadu/xronos/help/efsearch.html>

<https://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/help/efold.html>

RMF is a function of both incident photon of energy E and observed pulse-height invariant PI , while the ARF only depends on the energy of the incident photon.

The finite instrument resolution cannot always resolve sharp spectral features from astrophysical sources, therefore it is often impossible to deconvolve the observed instrument output (PI space) to physically meaningful data ($Energy$ space). Therefore it is much more advantageous to convolve the input spectral models through the instrument response to compare with the observed data. This type of using “forward” convolution of physical models via instrument response is known as ‘forward modelling’, and is ubiquitous in the field of X-ray spectral analysis.

If a source spectrum $S(E)$ is incident on a detector with a given $RMF(PI, E)$ and $ARF(E)$, the observed spectral information $O(PI)$ can be expressed as

$$O(PI) = \int RMF(PI, E) \times ARF(E) \times S(E) \times dE \quad (2.4)$$

where we integrate over all energies of incident photons (E). We fit the observed data $O(PI)$ against combinations of multiple spectral models ($S(E)$) to obtain the best fit spectral model describing the measured spectrum. For high-quality spectral data, the best fit spectral model and error on the individual parameters are calculated using least square method. The photon counting configuration of X-ray instruments result in Poissonian error in individual spectral bins, however, for very bright sources or by using spectral binning, Gaussian statistics can also be used. There are multiple packages that can perform spectral fitting of X-ray data but for this thesis we have utilised only the XSPEC package (Arnaud 1996) . XSPEC has a large collection of physical and phenomenological spectral models , however, the users can also define their own models for fitting the data. A binning

<https://heasarc.gsfc.nasa.gov/xanadu/xspec/>
<https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/Models.html>

of observed spectrum is sometimes performed to better constrain the underlying spectral parameters. However, extreme care should be taken such that sharp spectral features of the source are not lost during the binning process. Some of the spectral files were optimally binned based on algorithms developed by [Kaastra & Bleeker \(2016\)](#).

Spectral Models

In this section, we introduce some of the spectral models used in the work.

- Additive Models:
 - `bbbodyrad` - A spectral model for a blackbody emission with normalisation proportional to the surface area.
 - `compST` - A Comptonisation spectral model for the Comptonisation of cool photons by hot electrons ([Sunyaev & Titarchuk 1980](#)).
 - `compTT` - An analytic model describing Comptonisation of soft photons in a hot plasma modified to include relativistic effects ([Titarchuk 1994](#)).
 - `Gauss` - A simple gaussian line profile to model emission features in the spectrum.
 - `NPEX` - A negative-positive power law with an exponential cutoff is a phenomenological spectral model which approximates a photon number spectrum for an unsaturated thermal Comptonisation emission ([Makishima et al. 1999](#)).
 - `powerlaw` - It is a simple phenomenological photon power law spectral model.
- Multiplicative Model

- gabs - A phenomenological spectral model to describe a Gaussian absorption line.
- newhcut - A high energy cutoff model with a smooth exponential rollover (Burderi et al. 2000a).
- TBabs - The Tuebingen-Boulder ISM absorption model is used to model the absorption of the X-ray spectrum due to neutral matter present in the line of sight. The model calculates the cross section for X-ray absorption by the ISM as the sum of the cross sections for X-ray absorption due to the gas-phase ISM, the grain-phase ISM, and the molecules in the ISM (Wilms et al. 2000).

Each photon of starlight is a tiny piece of a grand puzzle, helping us to unravel the mysteries of the cosmos and our place within it.

Henrietta Swan Leavitt

3

Studying the variability of fluorescence emission and the presence of clumpy wind in HMXB GX 301–2 using *XMM-Newton*

The findings discussed in this chapter are part of a paper published in the journal MNRAS

3.1 Introduction

GX 301–2 (or 4U 1223–62) is a High Mass X-ray Binary (HMXB) pulsar discovered in 1971 during a balloon experiment (McClintock et al. 1971). It has subsequently been observed by most of the X-ray astronomy missions. The X-ray source is characterised by its variable flux with orbital phase (Rothschild & Soong 1987) and the presence of a very large absorption column density (Haberl 1991). The source has a spin period in the range of 670 - 690 s and the spin period history of the source is highly variable with random spin variations along with episodes of rapid spin-up of the neutron star (NS) (Koh et al. 1997, Manikantan et al. 2023b). From an analysis of the accretion torque it has been shown that the neutron star in this system has a retrograde motion, where the NS spins in the opposite sense to the binary rotation of the system (Mönkkönen et al. 2020).

The companion star in the binary system, WRAY 977 (Vidal 1973), is a massive early type main-sequence star with a mass of 39 to 53 $M_{\odot}$ and a radius of $\sim 62 R_{\odot}$ (Kaper et al. 2006). The orbit of the binary system is highly elliptical with an eccentricity of $e = 0.47$ (Koh et al. 1997). The orbital period was found as 41.508 days from *Tenma* data (Sato et al. 1986).

The light curve of GX 301–2 shows regular flaring ~ 1.4 days before periastron passage of the neutron star during its orbital motion (Sato et al. 1986). Isotropic and homogeneous stellar wind can't explain the presence of a pre-periastron flare. Different models have been proposed like the presence of a circumstellar disk (Pravdo & Ghosh 2001) and the presence of an accretion stream (Leahy & Kostka 2008) that can explain the presence of the very prominent pre-periastron flare and a smaller apastron flare. However, various studies (Islam & Paul 2014, Manikantan et al. 2023b) have shown that the absorption column density predicted in these models

do not match the observations.

The spectrum of GX 301–2 has a strong Fe $K\alpha$ fluorescence line at 6.4 keV (Watanabe et al. 2003, Mukherjee & Paul 2004, Suchy et al. 2012, Fürst et al. 2011, Liu et al. 2018). The fluorescence emission occurs as the companion’s stellar wind reprocesses the X-rays from the pulsar. However, the exact location and geometry of the binary environment responsible for the reprocessed X-ray emission in different orbital phases remains uncertain. Strong iron lines are ubiquitous in HMXBs (Giménez-García et al. 2015, Pradhan et al. 2018) and provide an essential tool for studying the binary environment in HMXBs. A strong Compton shoulder of the iron $K\alpha$ emission line was fully resolved at 6.24 keV using *Chandra*/HETG observation (Watanabe et al. 2003).

The presence of structured stellar wind is known from observations of massive stars across different energy bands (Sundqvist et al. 2012). The observed variability in the spectral and timing properties of wind fed HMXBs was first explained using the presence of clumpy wind by Sako et al. (2003). Subsequent studies have confirmed the presence of clumpy wind in a number of bright HMXB like Vela X-1 (Kreykenbohm et al. 2008, Fürst et al. 2010, Martínez-Núñez et al. 2014), GX 301–2 (Mukherjee & Paul 2004, Fürst et al. 2011), OAO 1657-415 (Pradhan et al. 2014, 2023) and IGR J18027-2016 (Pradhan et al. 2019). However, the precise structure and geometry of clumpy winds are of still a subject of debate (Martínez-Núñez et al. 2017).

The $K\beta$ and $K\alpha$ line flux ratio depends on the ionisation state of the fluorescing Fe atom (Palmeri et al. 2003). A previous study with an *XMM-Newton* observation of the source by Fürst et al. (2011) showed a value of this ratio as $\lesssim 0.2$ corresponding to neutral iron atoms, and showed no variation with luminosity. The study also clearly demonstrated a reduction in pulse fraction near the Fe $K\alpha$

6.4 keV energy band compared to the continuum, indicating lack of pulsation of the Fe emission line. However, a subsequent study with *Chandra* data showed the presence of strong pulsation in the Fe $K\alpha$ (6.34–6.44 keV) energy band (Liu et al. 2018) near the periastron passage of the source. But the pulsations in the Fe $K\alpha$ energy range was present only in the first 7 ks of the total 40 ks of the *Chandra* observation.

The search for the pulse modulation in the Fe $K\alpha$ line intensity due to anisotropic distribution of material in the reprocessing environment has primarily been performed by studying the timing properties of energy-resolved light curves. Any modulations in the Fe $K\alpha$ energy band can originate from either the continuum or the Fe $K\alpha$ emission line. Therefore, the continuum must be accurately modelled and subtracted from the total X-ray emission to isolate the modulations in the emission line. Spin phase-resolved spectroscopy is a useful technique to check for the variations in iron line strength as a function of the neutron star spin phase and thereby check for any anisotropy of the reprocessing medium around the neutron star.

Recently, GX 301–2 has been observed with the Imaging X-ray Polarimetry Explorer (*IXPE*) to measure polarisation of the X-ray photons originating from the source in the 2–8 keV energy range. No significant polarisation could be obtained from the overall phase averaged data (Suleimanov et al. 2023). However, the spin phase resolved analysis showed up to 10% polarisation in some pulse phase bins and large variation of polarisation angle with the pulse phase. The measured polarisation properties of GX 301–2 in the phase average and spin phase resolved data are in good agreement with the rotating vector model for the pulsar magnetosphere.

We describe the following results from analysis of data from a long *XMM-Newton*

observation of GX 301–2 in 2008: i) the spectrum of the source from the entire observation, ii) time resolved spectra with which we looked into variation of the absorption column density and the iron emission line fluxes and variation of the Fe $K\beta$ and Fe $K\alpha$ flux ratio, and iii) energy resolved pulsation, and iv) spin phase resolved spectral analysis to investigate any pulse phase dependence of the iron line flux. We also describe the presence of an additional periodicity in the X-ray light curve in the iron $K\alpha$ energy band. This periodicity was observed during the non-flaring portion of the observation.

3.2 Observation and data reduction

We present the results from analysis of the observation with *XMM-Newton* on 14th August 2008 (MJD 54692.199 - MJD 54692.882). The observation (ObsID: 0555200301) lasted ~ 65.3 ks. The observation was taken in the *TIMING MODE* using only the EPIC-PN CCD detector. The EPIC cameras operate in the energy range of 0.5–10.0 keV. Observations in *TIMING MODE* has higher threshold for pile-up ($\gtrsim 400$ counts/s), while providing better time resolution (Strüder et al. 2001).

We used the Science Analysis System (SAS) version 19.1.0 for all data extractions. We followed all the default instructions provided by *SAS Data Analysis Threads*^{*}. The data reduction procedures relevant for *TIMING MODE* were followed from *XMM-Newton ABC Guide*[†]. We checked for pile-up in the data using the SAS tool *epatplot* and found no noticeable pile-up. We have used the latest calibration files for the data reduction.

The source region was selected from the EPIC PN columns 34-41, while the background region was selected from columns 5-15. Solar system barycenter cor-

^{*}<https://www.cosmos.esa.int/web/xmm-newton/sas-threads>

[†]<https://heasarc.gsfc.nasa.gov/docs/xmm/abc/abc.html>

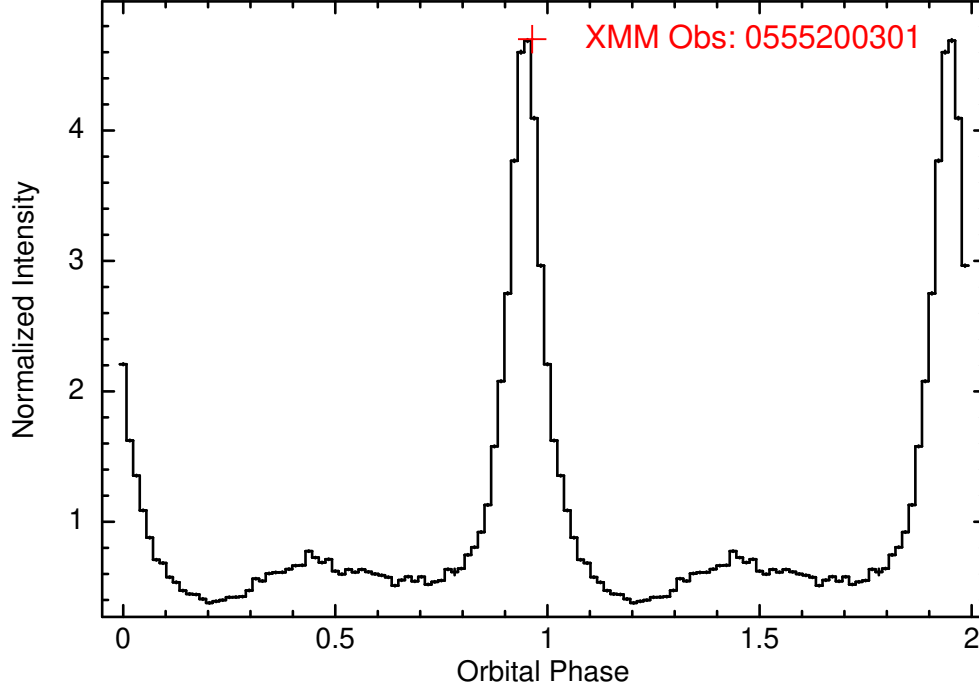


Figure 3.1: The 15-50 keV *Swift*/BAT folded orbital profile of GX 301-2 with the red marker showing the orbital phase of the *XMM-Newton* observation.

rection was performed on this data by SAS tool `barycen`. The source and background spectra were generated from the aforementioned regions. The response and ancillary files were generated using the `rmfgen` and `arfgen` tools.

The source and background light curves were also extracted from the same regions with a time resolution of 0.01 s. For both the source and background light curves, only the single and double events were taken by using the `evselect` task with $(\text{PATTERN} \leq 4)$ selection criteria. The background subtracted light curves were generated using the SAS tool `epiclccorr`.

The folded orbital profile of GX 301–2 from *SWIFT* Burst Alert Telescope (BAT) (Barthelmy et al. 2005) monitoring mission[‡] is given in Fig. 3.1. The orbital period was taken from Manikantan et al. (2023a) with the phase 0.0 taken at the periastron passage, consistent with orbital measurements from Doroshenko et al. (2010). The source was observed at an orbital phase of ~ 0.96 as shown by a red marker in Fig. 3.1.

[‡]<https://swift.gsfc.nasa.gov/results/transients/>

3.3 Data Analysis

3.3.1 Timing Analysis

Light curve

The choices of different lightcurves for GX 301-2 are based on the presence of different spectral features of the source. We use the 6.2-6.6 keV lightcurves to see the effects of the iron $K\alpha$ line. The 4.0-6.2 and 6.2-10.0 keV lightcurves are used to study the changes in the characteristics of the continuum emission of the source, on either side of the iron emission energy range. The light curve for the entire observation is plotted in Fig. 3.2 (Top panel) with a bin size of 200 s. The light curve of GX 301-2 displays instances of prominent flaring towards the beginning and the end of the observation. Similar behaviour is observed in the different energy bands of 4-6.2, 6.2-6.6 and 6.6-10 keV as shown in the middle panel of Fig. 3.2. A closer inspection of the light curve revealed that even though there are clear pulsations present throughout the observation, there are many variations in shape between individual pulses.

The main flare at the beginning of the observation lasted ~ 7 ks. The count rate of the source reached above 350 counts/s in the 0.5-10.0 keV range at the peak of the flare. There was a significant change in the hardness of the source during this part of the observation. The hardness ratio, defined as $(H-S)/(H+S)$, between the 6.6-10 keV (H) and 4-6.2 keV (S) energy range is plotted in the bottom panel of Fig. 3.2. There is a significant reduction in the hardness ratio of the source during the main flare. The smaller flare towards the end of the observation did not have any significant reduction of the hardness ratio associated with it.

To further study the emission characteristics of the source, we divided the en-

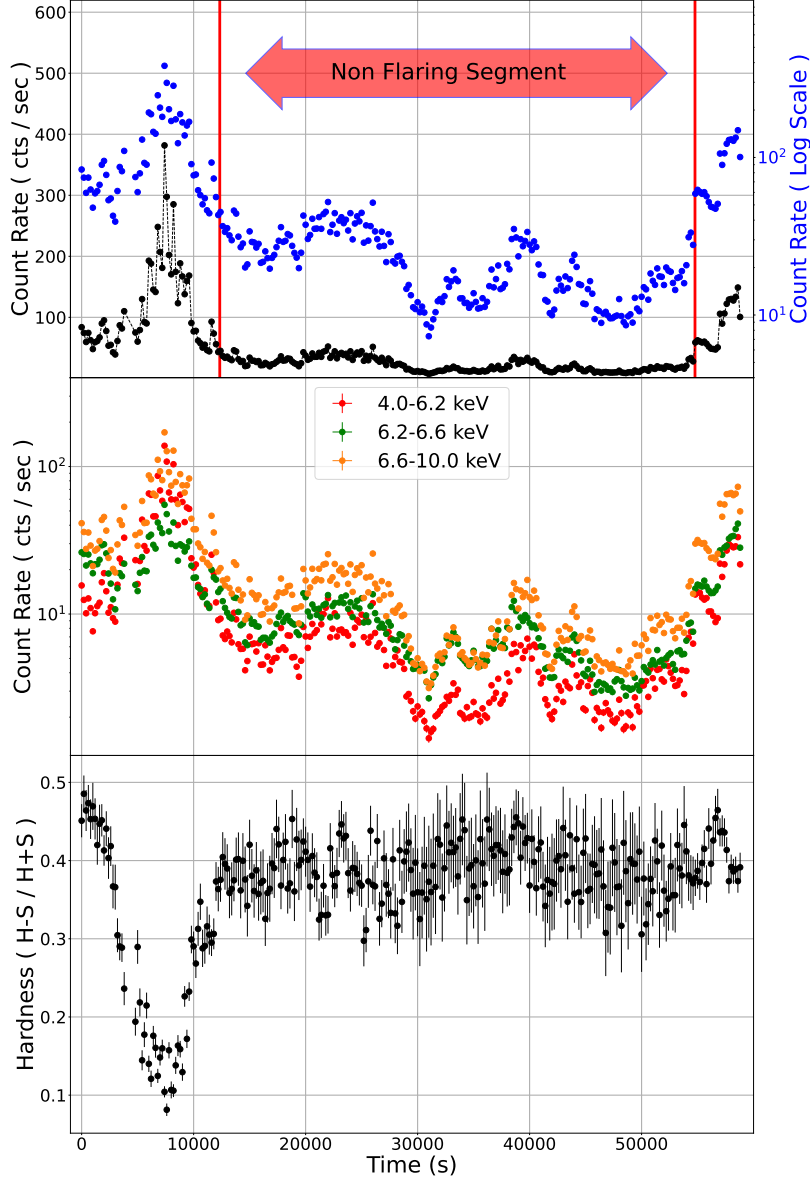


Figure 3.2: *Top:* light curve of GX 301-2 for the entire observation is plotted with a bin size of 200 s in linear (black) and logarithmic scale (blue). The label on the right side of the figure is in log scale. The region between the vertical red lines denotes the non flaring segment, characterised by lesser variability of X-ray flux. *Middle:* The energy resolved light curve in the energy range of 4–6.2, 6.2–6.6 and 6.6–10 keV are plotted with a bin size of 200 s. *Bottom:* Hardness ratio between the 4–6.2 keV and the 6.6–10 keV bands.

tire observation into the flaring and the non-flaring parts based on the X-ray count rate of the source. The non-flaring region has an average count rate of about 20 counts/s, whereas the flaring regions have an average count rate four times this value, with the maximum count rate reaching almost 20 times the average count rate of the non flaring segment. The non flaring segment is denoted in Fig. 3.2. The non flaring segment is about 41 ks long and has much less intensity variation compared to the whole observation. From the hardness ratio plot, we can see that there was no significant variations in the hardness ratio during the non flaring segment (Fig. 3.2).

Pulse Profile

The spin period of the pulsar, for the entire observation was determined to be 687.9 ± 0.1 s using the XRONOS^s epoch folding tool `efsearch`. The error on the pulse period was determined by the bootstrap method (Lutovinov et al. 2012). This value is consistent with the long-term spin-period history of the pulsar obtained from *Fermi*/Gamma-Ray Burst Monitor (GBM) mission[¶]. The pulse profile of the whole observation in the 0.5–10.0 keV energy range is shown in black in Fig. 3.3. The pulse profile of the source is complex. The time-averaged pulse profile shows an overall double-humped shape with one hump more prominent than the other. There are also many smaller features present on top of the double humped shape.

The pulse profile for the non flaring segment in the 0.5–10.0 keV energy range is shown in red in Fig. 3.3. The overall shape of the pulse profile of the non flaring segment is similar to the whole light curve. However, the pulse fraction of the non flaring segment is smaller with respect to the overall light curve. To quantify the changes in pulse profiles between the two, we have calculated the pulse fraction

^s<https://heasarc.gsfc.nasa.gov/xanadu/xronos/xronos.html>

[¶]<https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html>

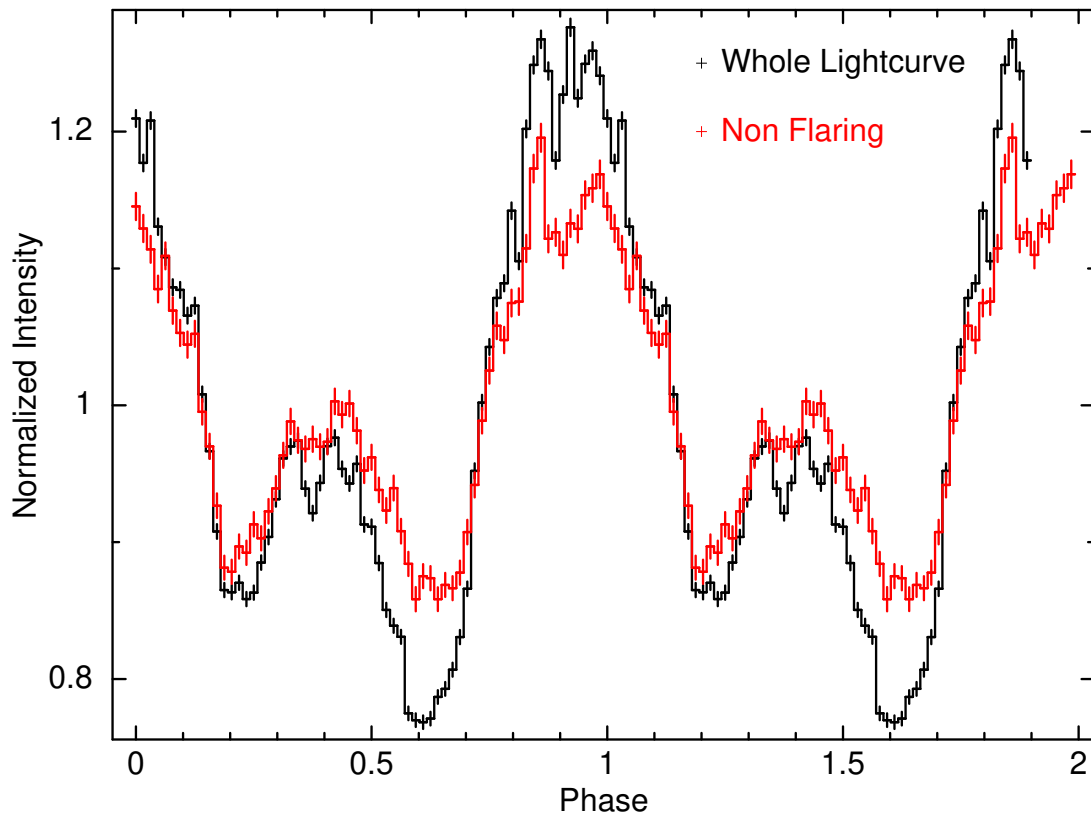


Figure 3.3: The 0.5–10.0 keV pulse profile of GX 301–2 during the entire observation (black) and the non flaring segment (red) for this observation. The folding period is 687.9 s. The non flaring segment folded profile has much less pulse modulation than the pulse profile of the whole observation.

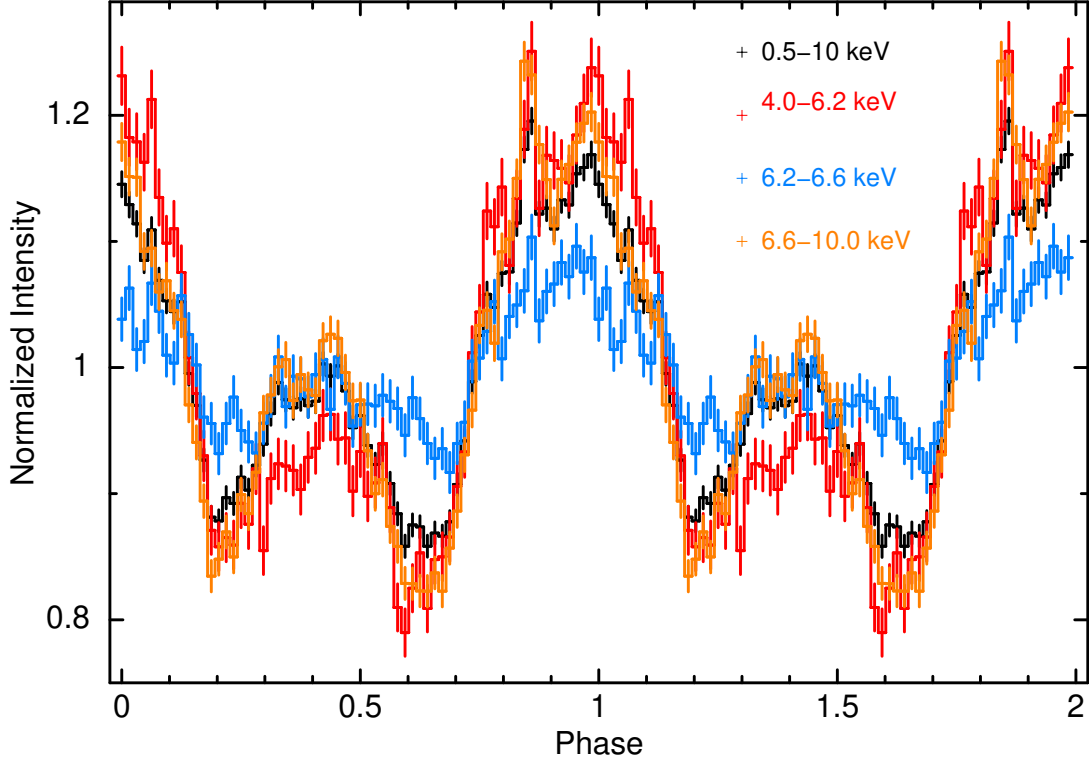


Figure 3.4: The energy dependent pulse profile of GX 301–2 for the non flaring segment. The folding period corresponds to the spin period of the NS (687.9 s).

(PF) for each pulse profiles (P). The pulse fraction PF is defined as,

$$PF = \frac{\max(P) - \min(P)}{\max(P) + \min(P)}. \quad (3.1)$$

The non flaring segment shows relatively lower pulse fraction of $16 \pm 1\%$ compared to the pulse fraction of $25 \pm 1\%$ of the total light curve. Even though overall pulse shape remains the same, the pulse fraction varies significantly with energy in the non-flaring segment. The 6.2–6.6 keV band has much less modulations than energy ranges above (6.6–10 keV) and below it (4–6.2 keV) (Fig. 3.4).

To study the dependence of pulse fraction with energy further in the non-flaring segment, we generated the light curves and folded pulse-profiles in 16 narrow energy bands in 0.5–10 keV and estimated the pulse fraction in each of them (Fig. 3.5). There is a reduction of pulse fraction near the 6.2–6.6 keV energy range.

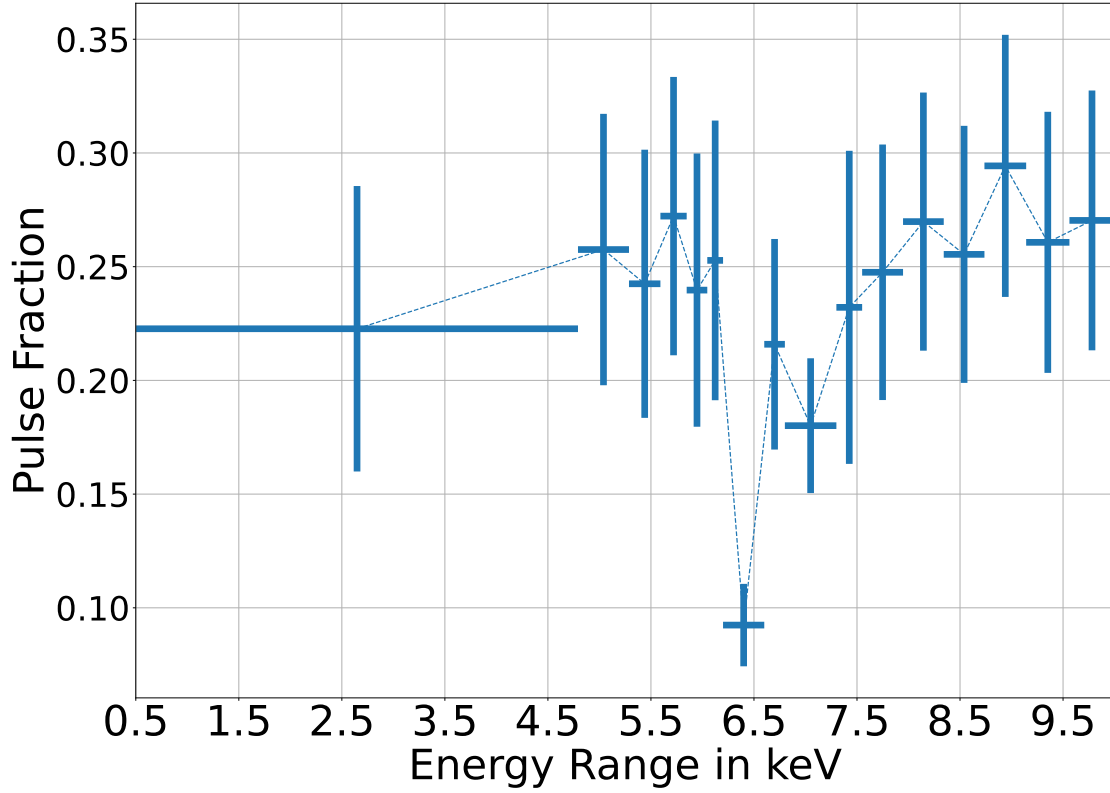


Figure 3.5: The energy dependence of pulse fraction with energy for the non flaring segment of GX 301-2 is shown in this figure.

Previous studies (Tashiro et al. 1991, Endo et al. 2002, Fürst et al. 2011) have also reported this reduction of pulse fraction in the iron energy band. This reduction in PF, has been attributed to the absence of pulsation in the fluorescence emission line. It is subsequently shown that this scenario is not entirely true. In the 6.2–6.6 keV band, the emission line contributes to about 75% of the total number of photons, while the continuum provides the rest 25% (Fig. 3.6). Hence if the iron fluorescent emission had absolutely no variation with spin phase the pulse fraction would have been much lower than observed.

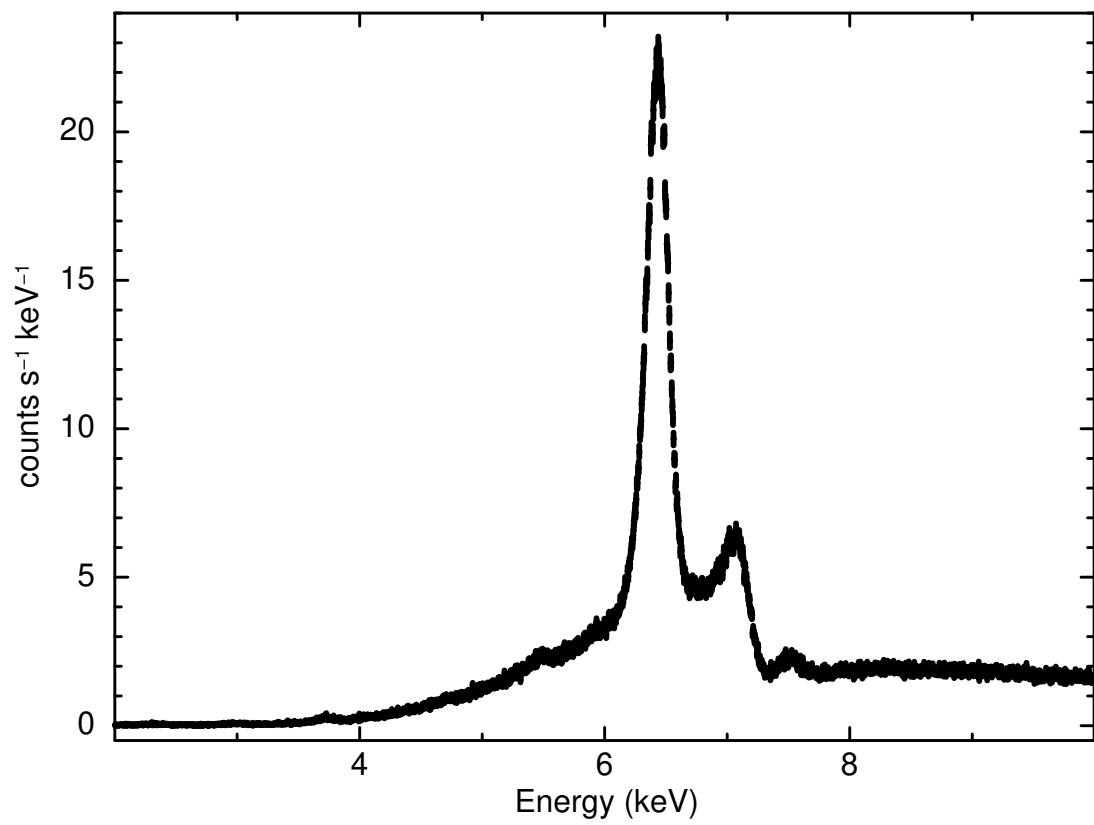


Figure 3.6: The time averaged spectrum of GX 301—2 in the non flaring segment.

Period Search in non flaring segment

During the energy-resolved timing analysis of the source in the non flaring segment of the observation, we noticed an additional pulsation feature in the 6.2-6.6 keV light curve, which is near the energy of the Fe $K\alpha$ emission line. Result of the period search program `efsearch` on the 6.2 -6.6 keV light curve is plotted in red in Fig. 3.7. In addition to the peak corresponding to the spin of the neutron star at 687.9 s we found an additional modulation with a periodicity of ~ 671.8 s. The `efsearch` result for the energy band of 0.5–5.8 keV and 8–10 keV, where the powerlaw emission component dominates is shown in blue in Fig. 3.7, in which the peak corresponding to the pulse period (687.9 s) is much stronger than the secondary peak (671.8 s).

To conduct a comprehensive search for the presence of additional period, we ran `efsearch` in light curves from different narrow energy bands, results of which are shown in Fig. 3.8. We can clearly see that the modulations corresponding to the 671.8 s period is most prominent in the iron line band of 6.2–6.6 keV and there is a hint of weak pulsation at this period in the entire energy band of 0.5-10 keV.

The folded profiles obtained with the secondary period in the Fe $K\alpha$ band energy band (6.4 ± 0.2 keV) and the continuum energy band (0.5–5.8 keV and 8–10 keV) are given in Fig. 3.9. The pulse fraction for the continuum light curve is $11 \pm 3\%$ and the Fe $K\alpha$ emission band light curve is $7 \pm 2\%$. Therefore X-ray re-processed emission with the secondary period of 671.8 s is broad band in nature, spanning the entire range of *XMM-Newton*.

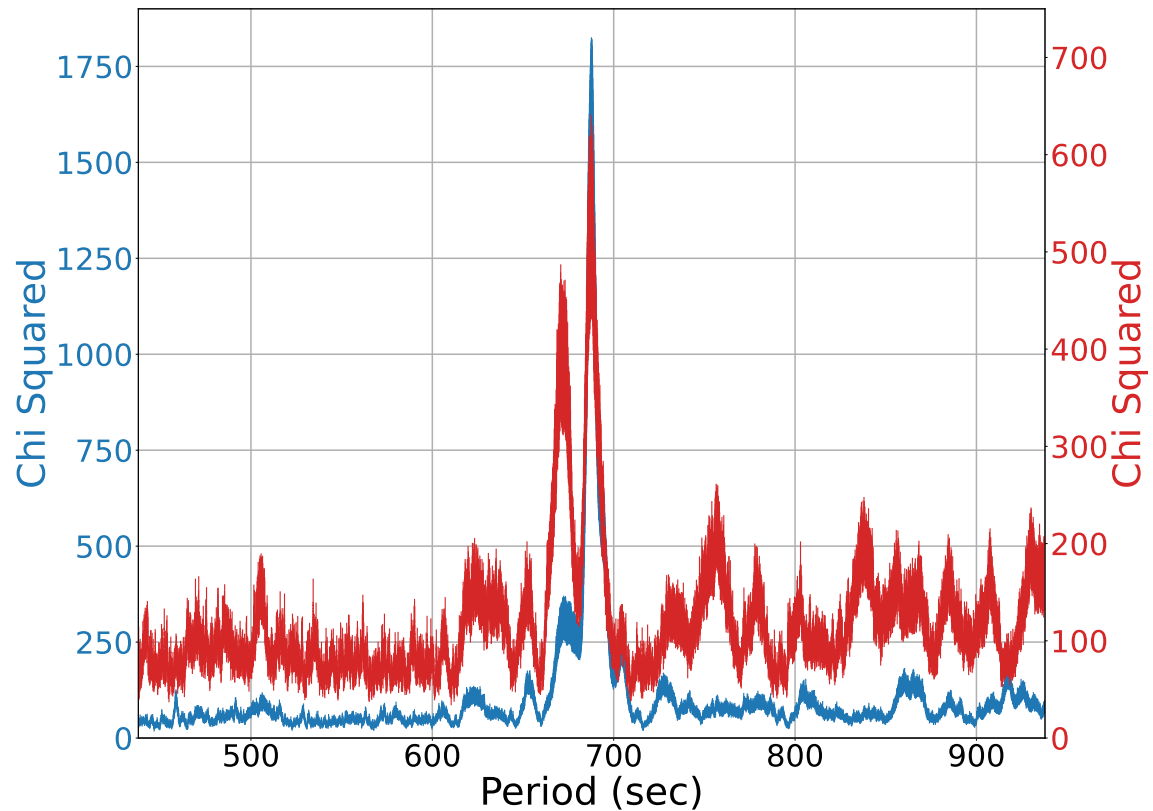


Figure 3.7: *In Blue:* The results of efsearch performed on light curves in the continuum energy range (0.5–5.8 and 8–10 keV) in the non flaring segment of GX 301–2. *In Red:* Period search in the non flaring segment of GX 301–2 in the 6.2–6.6 keV energy range where the strong Fe $K\alpha$ emission from the source is dominant. The peak on the right corresponds to the NS spin period and the relatively smaller peak on the left corresponds to the additional period of 671.8 s.

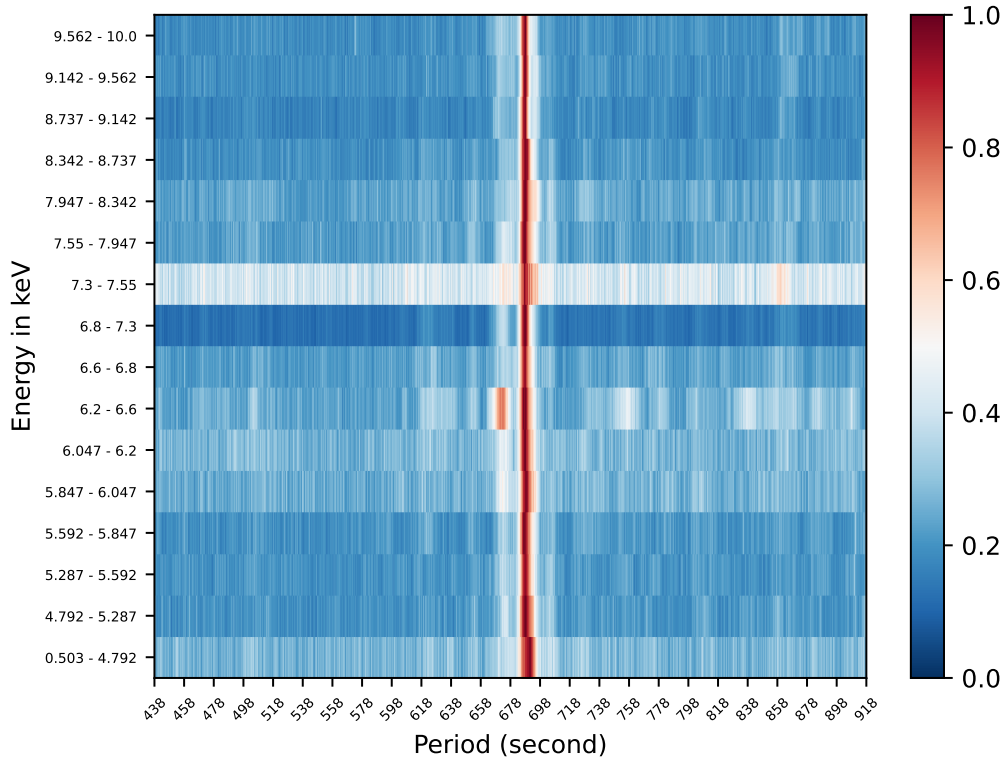


Figure 3.8: Results of efsearch on the energy-resolved light curves from the non-flaring segment of GX 301-2. The X-axis corresponds to the folding period value in intervals of 0.1 s. Along Y-axis, we have the energy interval (in keV) for which the efsearch was performed. The colour axis contains the chi-squared value, normalised to the maximum value corresponding to each energy bin. The colour axis values range from 0 to 1. The central bore in red corresponds to the spin period of the NS (687.9 s) present prominently in all energy ranges. The additional red peak present in the 6.2–6.6 keV energy range corresponds to the additional period of 671.8 s.

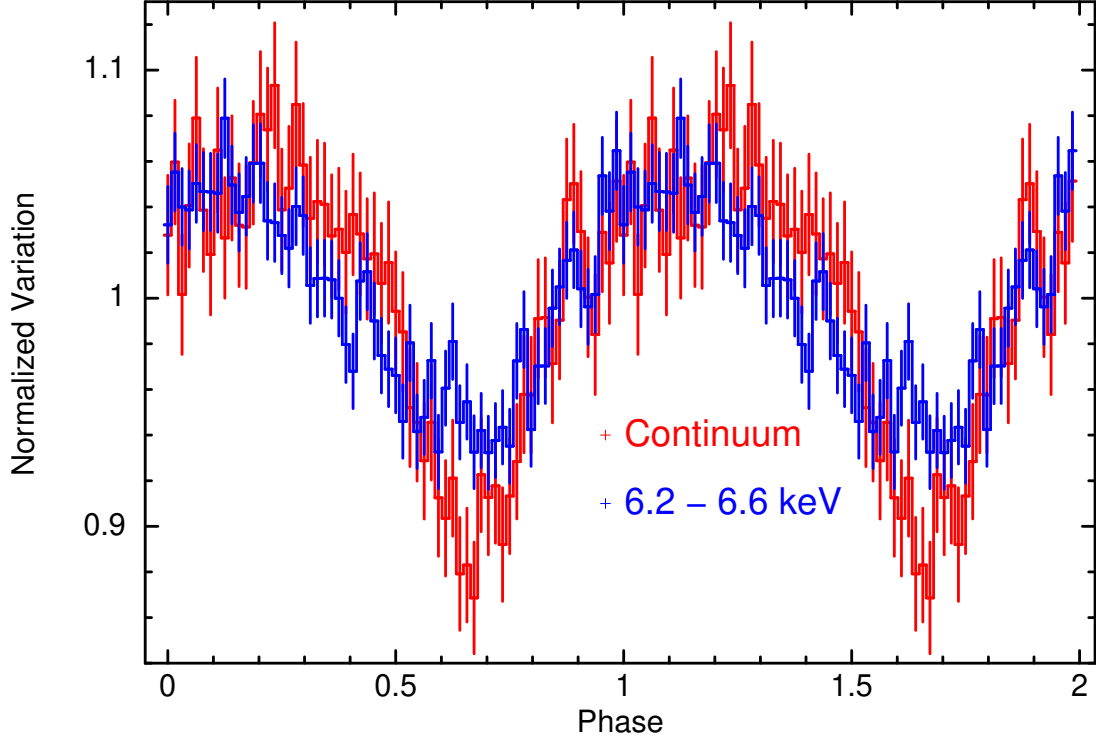


Figure 3.9: The figure shows the pulse profile corresponding to the continuum energy band (0.5–5.8 and 8–10 keV) and Fe $K\alpha$ (6.2–6.6 keV) energy band in the non flaring segment obtained with a folding period of 671.8 s for GX 301-2.

3.3.2 Spectral Analysis

Average Spectrum

The X-ray spectrum of GX 301–2 averaged over the entire observation is highly absorbed and it is dominated by many fluorescence lines, the most prominent of which is the broad neutral iron $K\alpha$ line around ~ 6.4 keV. The spectrum was fitted with a power-law with partial covering absorption and many Gaussian emission lines. The source was very bright during the course of this observation.

The spectral model used for this observation was $\text{TBabs}_1 * (\text{TBabs}_2 * \text{pcfabs} * \text{power law} + \text{Gaussian lines})$. There are three absorption components used in the spectra. The first absorption, TBabs_1 , corresponds to the Galactic component and the second absorption, TBabs_2 , and the partially covering model pcfabs are together used

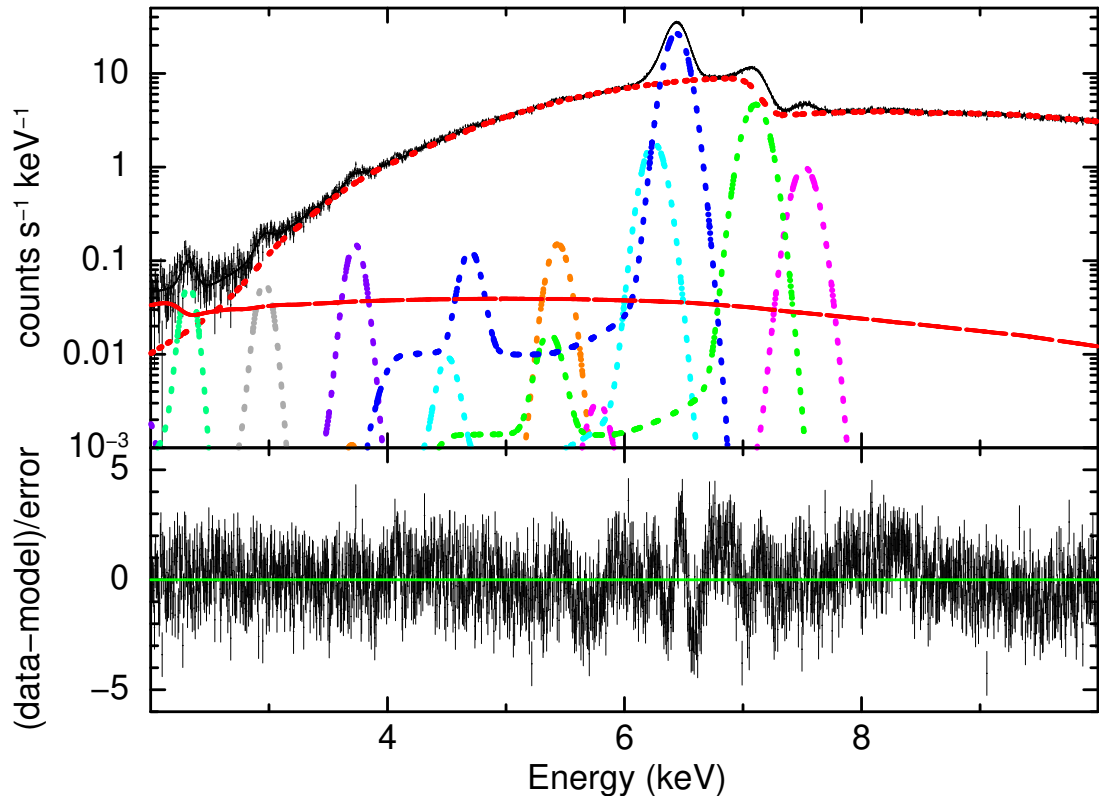


Figure 3.10: The 2.0-10 keV *XMM-Newton* EPIC PN spectrum of GX 301–2 is shown in the figure. *Top Panel* contains the data and the best-fit model components. *Bottom Panel* show the deviations between the data and the best fit model.

to model the in-homogeneous absorbing material in the local environment, as previously used by Fürst et al. (2011) and Mukherjee & Paul (2004). The Galactic absorption contribution has been fixed at 1.7×10^{22} atoms cm^{-2} (Kalberla et al. 2005). The emission lines are absorbed only by this Galactic absorption component. This particular absorption model was chosen in accordance with the analysis of another *XMM-Newton* analysis of GX 301–2 by Fürst et al. (2011), because the strength of the lower energy emission lines like that from Sulphur $K\alpha$ and Argon $K\alpha$ are not compatible with those which are coming through an absorption column density of 10^{24} atoms cm^{-2} or higher (Fürst et al. 2011, Suchy et al. 2012). The final spectral fitting with individual components are shown in Fig. 3.10.

The near neutral iron $K\alpha$ emission line centered at 6.435 ± 0.001 keV, has an equivalent width of 669^{+9}_{-5} eV. A dark blue dotted line shows the Fe $K\alpha$ fluorescence line in Fig. 3.10. There was also the presence of an Fe $K\alpha$ Compton shoulder in the spectrum, which was previously reported in GX 301–2 by Watanabe et al. (2003). The Compton shoulder is at about 0.2 keV below the iron $K\alpha$ line, which is indicated by the sky blue dotted line. The other emission lines in the spectra were identified from their centroid energy as Sulphur $K\alpha$ (Green), Argon $K\alpha$ (Light Grey), Calcium $K\alpha$ (Purple), Chromium $K\alpha$ (Orange), Iron $K\beta$ (Light Green), and Nickel $K\alpha$ (Magenta). The presence of these lines were previously reported by Fürst et al. (2011) from the other *XMM-Newton* observation of GX 301–2. The best fit spectral parameters are given in Table 3.1. The errors quoted for the spectral parameters are their 90% confidence ranges.

The spectrum above 2 keV was used for the spectral fit as all the spectral bins below this energy was background dominated. Still the spectrum in the 2–4 keV energy range could not be well fitted by the partial covering powerlaw continuum. Hence a constant DC component was added to compensate for the low continuum

emission strength in the aforementioned energy range. A similar treatment was used by Fürst et al. (2011) for the other *XMM* observation of GX 301–2. The fit significantly improved from the addition of the DC component, as the chi-squared value decreased from 3010 to 2308 for 1573 degrees of freedom. The final spectral model gave a fit to the observed 2–10 keV spectrum with a reduced χ^2 of 1.47 for 1573 degrees of freedom. The $\chi^2_{reduced}$ value of 1.47 is large compared to other fits, however, GX 301-2 is one of the brightest source, with a very high SNR, and at these high SNR any residual calibration error become very significant and results in residuals that are hard to remove. The flux in the 0.5–10.0 keV energy range for the entire observation was $7.497^{+0.017}_{-0.001} \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}$. The constant level value is given in the Table 3.1 as "DC Value". The origin of the DC component can be due to residual calibration issues from a low energy response of the large Fe K α line below it's escape peak in the response file (Fürst et al. 2011). The XIS instrument onboard *Suzaku* is known to have a similar problem (Matsumoto et al. 2006).

Time resolved Spectra

The light curves showed significant variation in the hardness ratio during the flaring segment of observation, indicating variability in either the absorption column density or the source spectrum over time. Therefore, we have carried out time-resolved spectroscopy to investigate the possible reasons for the hardness ratio variations. The spectral characteristics are expected to vary between the flaring and non flaring parts of the observation. We divided the entire observation into one hundred time segments and performed a detailed spectral analysis.

All the spectra were binned optimally according to Kaastra & Bleeker (2016) to better constrain the spectral parameters. This binning scheme led to a varying

Table 3.1: Best Fit model parameters for overall spectra of GX 301–2.

Model	Parameter	Units	Best Fit Value
Galactic Abs.	N_{galaxy}	10^{22}	1.7*
Local Abs.	N_{H1}	10^{22}	$46.43^{+0.14}_{-0.14}$
Partial Cov.	N_{H2}	10^{22}	$96.61^{+0.58}_{-0.47}$
	Covering Fraction		$0.853^{+0.001}_{-0.001}$
Powerlaw	Γ		$0.881^{+0.002}_{-0.002}$
	Norm ^a		$0.246^{+0.001}_{-0.003}$
S K α	E_{center}	keV	$2.325^{+0.010}_{-0.009}$
	Norm [§]		$1.78^{+0.23}_{-0.23} \times 10^{-5}$
Ar α	E_{center}	keV	$2.960^{+0.003}_{-0.004}$
	Norm [§]		$1.69^{+0.25}_{-0.24} \times 10^{-5}$
Ca K α	E_{center}	keV	$3.728^{+0.005}_{-0.009}$
	Norm [§]		$3.72^{+0.47}_{-0.46} \times 10^{-5}$
Cr K α	E_{center}	keV	$5.444^{+0.016}_{-0.021}$
	Norm [§]		$4.25^{+1.22}_{-1.15} \times 10^{-5}$
Fe K α	E_{center}	keV	$6.435^{+0.001}_{-0.001}$
		keV	< 0.002
	Norm [§]		$8.69^{+0.04}_{-0.03} \times 10^{-3}$
Fe K α CS	E_{center}	keV	$6.240^{+0.001}_{-0.003}$
	σ	keV	< 0.014
	Norm [§]		$5.46^{+0.27}_{-0.23} \times 10^{-4}$
Fe K β	E_{center}	keV	$7.107^{+0.001}_{-0.001}$
	σ	keV	$0.032^{+0.003}_{-0.004}$
	Norm [§]		$1.94^{+0.02}_{-0.02} \times 10^{-3}$
Ni K α	E_{center}	keV	$7.516^{+0.004}_{-0.004}$
	σ	keV	$0.004^{+0.015}_{-0.003}$
	Norm [§]		$4.58^{+0.19}_{-0.14} \times 10^{-4}$
DC	Value ^b		$3.72^{+0.23}_{-0.24} \times 10^{-5}$
Flux ^c	(0.5–10.0 keV)		$7.497^{+0.017}_{-0.001} \times 10^{-10}$
χ^2_{reduced}	(1573 d.o.f)		1.47

*The Galactic contribution of absorption density has been frozen to the line of sight value. ^a The powerlaw normalisation is in units of photons $\text{keV}^{-1} \text{cm}^{-2}$ at 1 keV. ^b The unit corresponding to the DC component is photons $\text{keV}^{-1} \text{cm}^{-2}$. ^c The units for flux is $\text{erg s}^{-1} \text{cm}^{-2}$. [§] The units of the normalisation for the Gaussian profile is in the units of photons $\text{keV}^{-1} \text{cm}^{-2}$ in the line.

number of spectral bins for each time resolved spectrum. We used the spectral model mentioned in Section 3.3.2 to fit each time-resolved spectra. The model gave us an overall good fit for each individual spectrum with reduced $\chi^2 < 2$. We set the centroid energy and width of all the emission lines except the iron $K\alpha$ line fixed to the best fit value obtained from time-averaged spectral analysis. The constant DC component was frozen to its best fit value from time average spectra. All other parameters were left to vary including the different absorption column densities, powerlaw continuum parameters as well as the line intensities. The errors in the free spectral parameters are calculated at 1σ level. The evolution of various spectral parameters with time are shown in Fig. 3.11.

The line of sight value for neutral column density is a combination of multiple absorption components. We define the effective absorption column density as

$$N_{\text{effective}} = N_{\text{galaxy}} + N_{\text{H1}} + f \times N_{\text{H2}}. \quad (3.2)$$

Here N_{galaxy} is the Galactic absorption component, N_{H1} and N_{H2} are the two components for the partial covering absorption model, and f is the partial covering fraction. $N_{\text{effective}}$ reflects the effective absorption value present due to the partially covered absorption present along the line of sight.

During the X-ray flares, a reduction in the effective absorption column density and partial covering fraction is observed. The reduction of absorption column density could result in the change in hardness ratio seen during the flaring segment of the light curve (Fig. 3.2). This reduction in effective absorption during X-ray flares can be attributed to the reduction in neutral hydrogen density along the line of sight by photo-ionisation of the absorbing medium by the source X-rays (Ferrigno et al. 2022).

The iron line strength has a similar time evolution as that of the source flux.

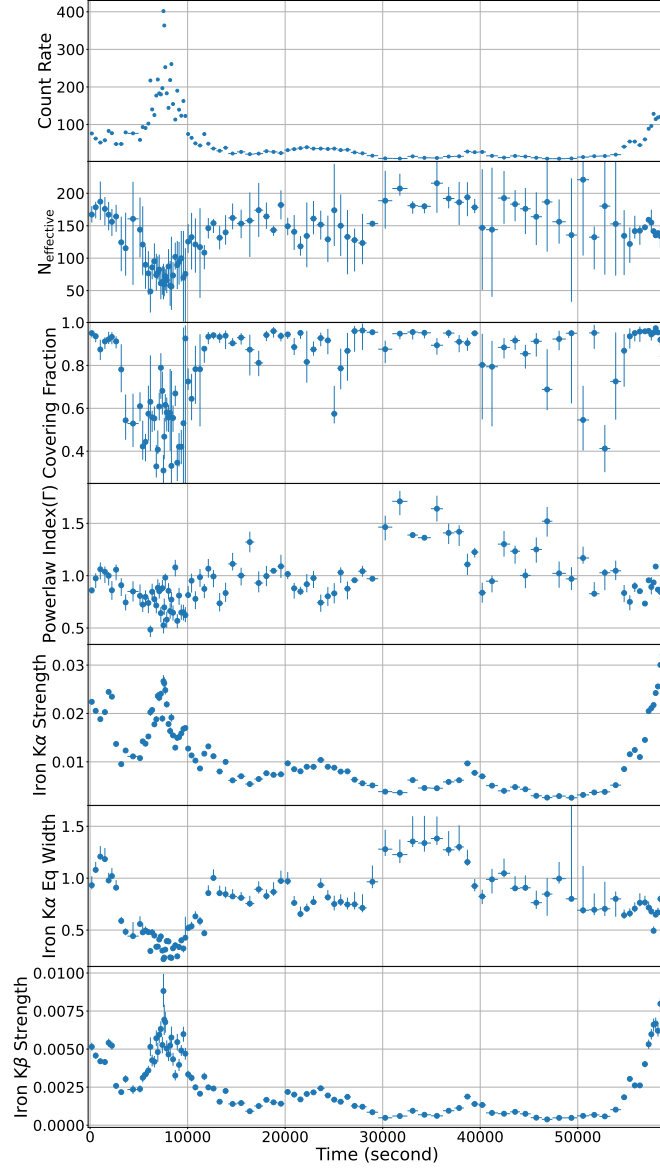


Figure 3.11: Time evolution of spectral parameters corresponding to the whole observation of GX 301-2. The panels from top to bottom are (i) EPIC PN spectral count rate in each time bin, (ii) effective absorption in units of 10^{22} atoms/cm², (iii) covering fraction, (iv) powerlaw index Γ , (v) the flux of the iron K α fluorescence line in units of photons cm⁻² s⁻¹, (vi) equivalent width of iron K α fluorescence line in keV units and (vii) flux of the iron K β fluorescence line in units of photons cm⁻² s⁻¹. The errors of the spectral parameters shown here are at the 1σ level.

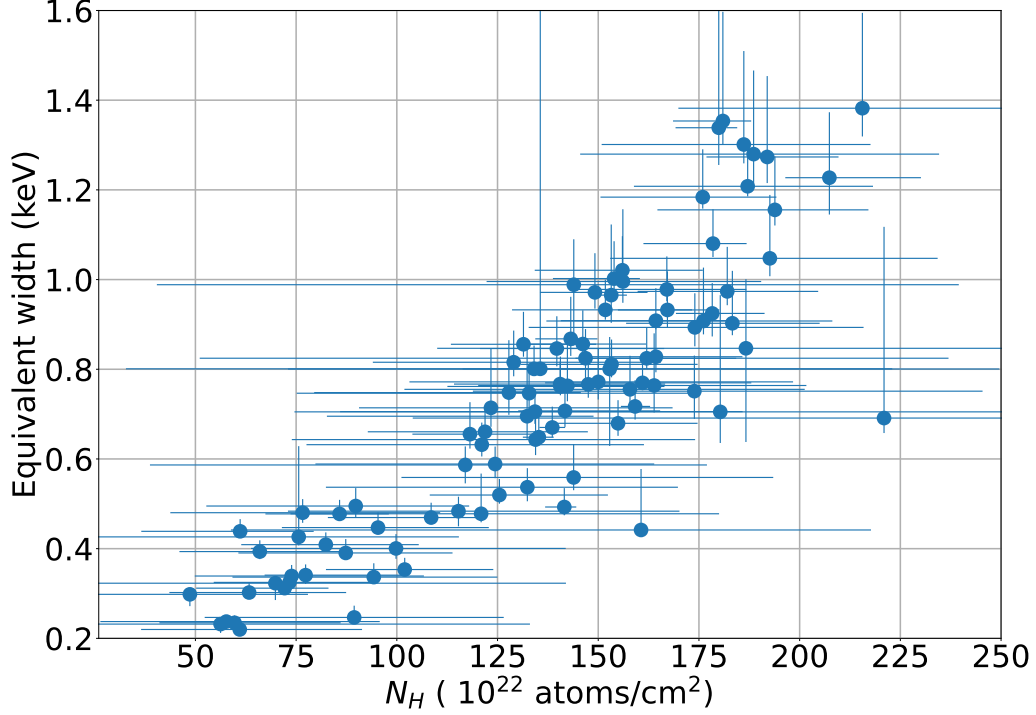


Figure 3.12: The variation of iron line equivalent width of GX 301-2 against the effective absorption column is plotted for the whole observation.

The iron line strength is more in higher luminosity of the source and lower for lower luminosity. However, the equivalent width of the iron line is low for the flaring region compared to the less luminous part of the light curve. Time evolution of equivalent width is similar to effective absorption column density. We plotted the equivalent width versus effective absorption column density in Fig. 3.12. The equivalent width vs absorption column density plot shows proportionality between the two quantities.

Next, we studied the relationship between the different iron fluorescence emission lines with luminosity. The iron $K\alpha$ (*Top Panel* Fig. 3.13) and $K\beta$ (*Middle Panel* Fig. 3.13) emission line strength were proportional to the flux of the source at lower values of source flux, but saturated at higher source brightness. There is a clear correlation between the two emission line strengths. The ratio of the $K\beta$ to $K\alpha$ line flux (*Bottom Panel* Fig. 3.13), however, was not constant with the source luminos-

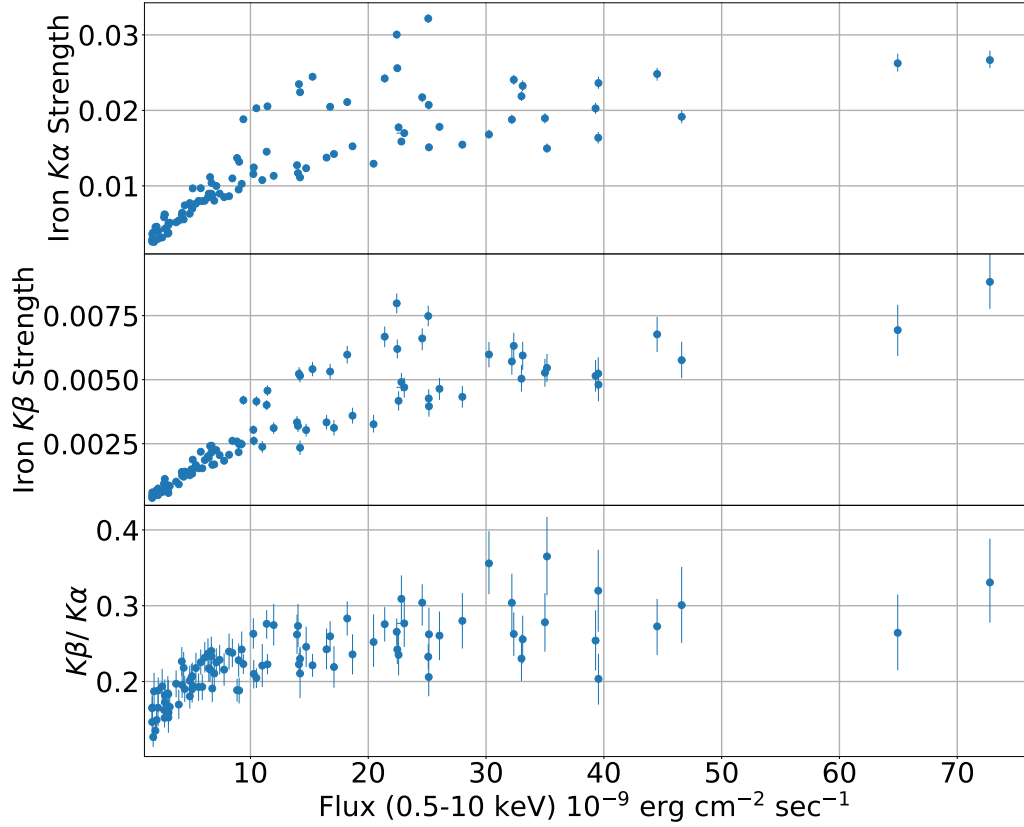


Figure 3.13: The variation of iron $K\alpha$ line strength (*Top Panel*), $K\beta$ line strength (*Middle Panel*) and the ratio of $K\beta$ to $K\alpha$ line strength (*Bottom Panel*) is plotted with the 0.5–10.0 keV flux in the figure above for GX 301-2.

ity. The relative strength of the Fe $K\beta$ fluorescence line with respect to the Fe $K\alpha$ line strength first increases and then saturates at higher source intensity. We further explore the implication of this result in further details in Section 3.4.2.

Spin Phase Resolved Spectroscopy in Non Flaring Segment

The non flaring segment of GX 301–2 was ~ 41 ks long containing about 60 spin revolutions of the neutron star about its axis. We performed spin-phase resolved spectroscopy of the non flaring segment of the observation to study the variation of the fluorescence line with the spin of the NS. The pulse profile was divided into

twenty equal phase bins and the spectrum was extracted from each phase segment. The same spectral model we fitted to the phase-averaged spectrum was used to fit the spectrum from each of these data sets. The centres and width of the emission lines were fixed to the phase averaged spectrum as the statistics wasn't enough to constrain all the parameters.

The iron line flux as a function of spin phase of the NS is shown in top panel of Fig. 3.14 along with the broad band pulse profile. It shows some variations of the iron line flux with pulse phase. The pulse fraction for the modulations of the iron line flux in the non flaring segment is ~ 0.045 , i.e. there is a 4.5% modulation about the mean value. The modulation is much less than the pulse profile modulation in the 0.5–10.0 keV energy range of $\sim 20\%$. The variation in the fluorescence emission didn't bear any resemblance to the overall pulse profile shape.

We have also performed phase-resolved spectroscopy with the periodicity of 671.8 s. This corresponds to the second peak observed in the period search of GX 301–2 during this observation (Fig. 3.7, 3.8). Similar to the last case, we divided the entire pulse profile into twenty equal phase bins and performed spectral fitting on each of them. The resulting variation of the iron $K\alpha$ emission line strength is plotted in bottom panel of Fig. 3.14. There is a 5.8% modulation present in the iron $K\alpha$ emission strength with the variation approximately sinusoidal in nature. At the secondary period of 671.8 s, both the iron line (red) and the continuum (black) have nearly identical pulse fraction and pulse profile (*Bottom Panel* Fig. 3.14).

To firmly establish the presence of modulations in the iron emission line with the two periods, we performed phase-resolved spectroscopy with fifty trial periods between 650 and 700 s. Corresponding to each period, we divided the pulse phase into twenty equal phase bins and estimated the iron line strength in each phase interval. We calculated the mean value for the iron line flux in each of the

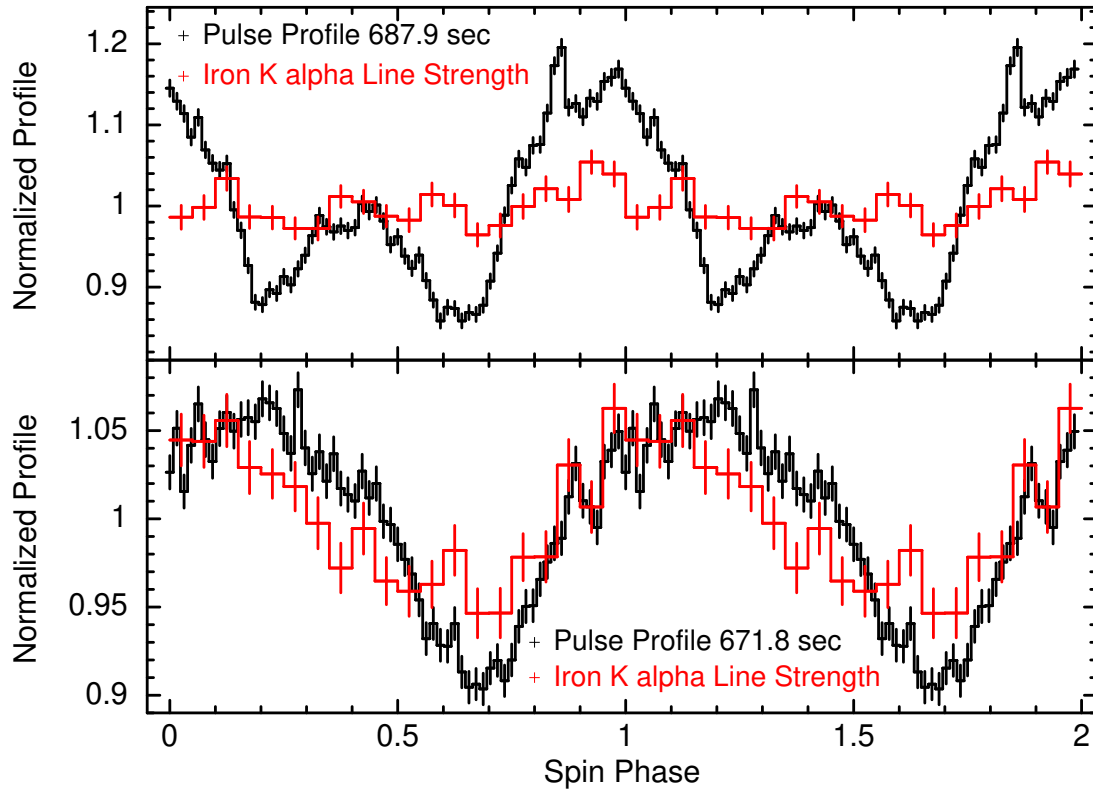


Figure 3.14: The figure shows the variation of reprocessed iron emission line (in red) with the spin phase obtained from phase-resolved spectroscopy and the folded profile of the light curve (0.5–10.0 keV) (in black) with a folding period corresponding to the NS spin period of 687.9 s (*Top Panel*) and the additional period of 671.8 s (*Bottom Panel*) in GX 301-2.

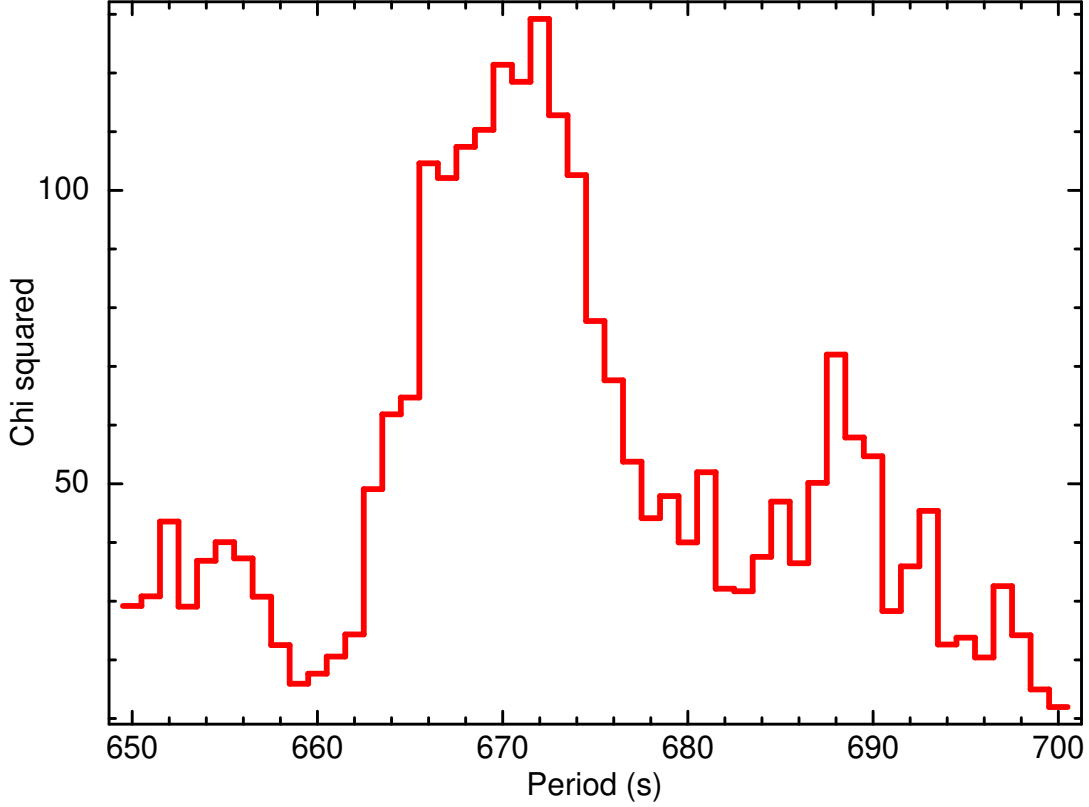


Figure 3.15: The figure shows the variation of the chi-square value of the spin modulation of iron line flux for 20 pulse phase bins with different folding periods in the non-flaring segment of GX 301–2. The plot shows the presence of a prominent peak at around ~ 672 s and a smaller peak at around ~ 688 s.

fifty sample period value. Then the total chi-square variation from the mean was calculated for each of the trial periods. The resulting graph, as seen in Fig. 3.15, clearly show two significant peaks, one around ~ 671.8 s and another near the spin period of the NS ($P_{\text{spin}} \sim 687.9$ s).

3.4 Discussion

We presented here the spectral and timing analysis of the *XMM-Newton*/EPIC-PN observation of HMXB pulsar GX 301–2 from an observation carried out in 2008. The spectra of the source was modelled using a partially covered powerlaw continuum along with multiple fluorescence emission line features corresponding to S, Ar, Ca, Cr, Fe, and Ni. The most prominent feature present in the spectrum

is the Fe $K\alpha$ emission line centred around ~ 6.4 keV (Fig. 3.6) originating from nearly neutral iron atoms. The presence of the Chromium line in the spectrum of GX 301–2 was first reported in Fürst et al. (2011) from another *XMM-Newton* observation and we confirm the presence of the Cr line centred around 5.44 keV in this observation.

3.4.1 Variability of source characteristics

GX 301–2 showed significant flux variation during the *XMM-Newton* observation. The X-ray flux in the 0.5–10.0 keV range changes by more than one order of magnitude in the flaring segment of the light curve. There were two distinct flares present in the light curve of the source. The more prominent flare was observed at the beginning of the observation. The flare was almost 7 ks long with flux in the 0.5–10.0 keV range reaching $7.3 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}$ which is almost 10 times the average value of the entire observation. There was a significant reduction in the hardness ratio between the 6.6–10 keV and 4–6.2 keV energy band during this flare. The flare was followed by a long non flaring segment which lasted for ~ 41 ks. A second flare was observed towards the end, however no corresponding changes in the hardness of the source were apparent during the second flare. The hardness ratio decreases significantly during the main flare indicating an increase in number of soft photons relative to the number of hard photons emitted by the source. From the time resolved analysis of the source spectrum, it is clearly seen that during the flare the absorption column density and covering fraction showed significant reduction without significant changes in the powerlaw index indicating that due to reduced absorption a lot of soft photons relative to hard photons were detected during the flare reducing the hardness ratio. It is very hard to comment on the reason behind the weak fluctuations of the hardness ratio during the

quiescence period in the source.

The source showed pulsations with a period of $P_{\text{spin}} = 687.9 \pm 0.1$ s. The pulse profile of the GX 301–2 showed a double-humped structure (Fig. 3.3). The pulse fraction during the periastron passage of the NS was low compared to other orbital phases (Endo et al. 2002). A reduction in pulse fraction near periastron passage has been observed in the *ASCA* observations of GX 301–2 (Endo et al. 2002) and similar effects are also present in *NuSTAR* observations of the source. During this observation, the source is inside a dense reprocessing medium which is obvious from the strong iron line. This can also cause the continuum emission to be Compton scattered multiple times resulting in reduction of the overall pulse fraction.

The reduction of pulse fraction in the iron $K\alpha$ fluorescence emission band has been previously interpreted as an effect of the fluorescent emission not varying with spin phase. For the current observation, the shape of the pulse profile in the non flaring segment was studied in different energy bands. Even though the pulse shape of the source remained unchanged, the pulsed fraction (equation 3.1) varied with energy. The pulse fraction in the iron emission band of 6.2–6.6 keV was lower than the other energy bands. As seen in Fig. 3.5, the pulse fraction of the source is relatively constant at about 25% in all energy bands except 6.2–6.6 keV, where it dips to about half the value at 10%. The lack of pulse phase variation in the emission line was explained by the homogeneous distribution of matter producing the fluorescent iron line around the X-ray producing region (Fürst et al. 2011 and references therein). However in this work, we found that the iron fluorescent line indeed varies with spin phase but with a lesser magnitude than the continuum (Top Panel of Fig. 3.14).

We performed time-resolved spectroscopy on the source to investigate the high variation of X-ray flux during the observation, and the reduction in hardness ra-

tio during the first flare. We divided the entire observation into one hundred time bins. The value of absorption column density was quite high ($\sim 10^{24}$ atoms cm^{-2}) during the entire observation and showed significant variations with time. We observed no increase in absorption column density associated with the flares present in the light curve. Similar flares, without associated increase in column density, have been observed in other HMXB Pulsars like LMC X-4 (Levine et al. 1991, Beri & Paul 2017) and SMC X-1 (Moon et al. 2003). From the results of time resolved spectroscopy, we could also observe a clear reduction in the absorption column density as well as covering fraction during the flaring segment (Fig. 3.11). Therefore the reduction in the hardness ratio may result from the reduction in absorbing materials along the line of sight from the source.

There exists a correlation between the effective absorption column density and the equivalent width of the Fe $K\alpha$ emission line (Fig. 3.12). Such a correlation can arise if the same region responsible for the emission of iron fluorescence emission is also responsible for the absorption of the X-ray spectrum. Hence, variation of absorption column density is accompanied by a respective change in equivalent width for the emission line (Inoue 1985).

The presence and time variability of the large partial covering absorption column density, is a clear indication of the presence of clumpy matter around the NS. Long term studies carried out on the source using *RXTE*/PCA data by (Mukherjee & Paul 2004) has given observational evidence for the presence of clumpy matter. The presence of clumps in the stellar wind environment of GX 301–2 has also been inferred by Fürst et al. (2011) using another *XMM-Newton* observation. Similar studies on other X-Ray binaries like Vela X-1 (Kreykenbohm et al. 2008), 4U 1700-37 (van der Meer et al. 2005), OAO 1657-415 (Pradhan et al. 2014) and Cygnus X-1 (Miškovičová et al. 2011) have also inferred the presence of structured

wind characteristics in these sources.

3.4.2 Variability of the two iron fluorescence emission lines

The time-resolved spectral analysis revealed a correlation between the flux of both the iron $K\alpha$ (top panel) and $K\beta$ (middle panel) emission lines with the luminosity of GX 301–2, as depicted in Fig. 3.13. The flux of the lines initially proportional to the flux, however, the strength of the two emission lines saturates at higher values of the source flux.

The ratio of Fe $K\beta$ to Fe $K\alpha$ emission line strength is a function of the ionisation state of the iron atoms and the ratio increases with increasing Fe ionisation state (Palmeri et al. 2003). The ratio of the two Fe emission line strengths is plotted bottom panel of in Fig. 3.13 with source flux. From the current observation we see that the $K\beta/K\alpha$ line flux ratio first increase and then saturate with increasing X-ray luminosity. The ratio of the flux of other emission lines like Ni $K\alpha$ and the iron $K\alpha$ Compton shoulder to the 6.4 keV Fe $K\alpha$ line shows no such variations.

3.4.3 Characteristics of the iron fluorescence emission in the non flaring segment

During the search for pulsation from the NS, we noticed the presence of a very prominent additional period in the 6.2–6.6 keV energy range in the non flaring segment of the light curve. The period of this additional modulation is ~ 671.8 s. Even though the second period is present in other energy bands it is the most prominent in the 6.2–6.6 keV range. The additional period is almost as strong as the NS spin period of 687.9 s in the iron fluorescent emission energy band, as seen in red in Fig. 3.7. The secondary period can originate from reprocessing of the X-ray photons from the NS by a reprocessing agent that is in relative motion

with respect to the NS. From the spectrum of GX 301–2, we can see that in this energy range, there are contributions from both the iron $K\alpha$ emission line and the continuum. Therefore to investigate the origin of this additional periodicity, phase-resolved spectroscopy was carried out for the non flaring segment of the source with both periods.

3.4.4 Phase Resolved Spectroscopy

X-rays originating from GX 301–2 are incident on the wider binary environment populated by the stellar wind of the main-sequence companion star WRAY 977, which is the source of the fluorescence iron emission (Giménez-García et al. 2015). There has been no concrete evidence for the variation of Fe $K\alpha$ emission line with the rotation of NS in a wide range of wind fed HMXBs (Fürst et al. 2011 and references therein). The lack of modulation in iron fluorescence emission was explained as an effect of smearing of the pulsed X-ray emission by the isotropic line emitting region. Deviation from this behaviour can occur if the binary environment contains anisotropic dense lumps from the companion’s stellar wind. The presence of modulations in the iron line strength with the NS spin period can indicate the possible presence of clumpy matter in the reprocessing environment of GX 301–2.

Modulation in the Iron Emission Line with the Spin Period of the NS

A recent observation of GX 301–2 with *Chandra*/HETG has shown clear pulsation in the iron $K\alpha$ energy range (Liu et al. 2018). Only the first 7 ks of the entire 40 ks observation has clear pulsation in the source. However, in the current *XMM-Newton* observation, we can clearly see from spin-phase resolved spectroscopy that modulations in the iron line are present during the entire non flaring part of the

observation with the spin period of the NS (Top Panel of Fig. 3.14).

Substantial variation of the 6.4 keV iron line intensity with the spin phase of the NS has been observed in Her X-1 across different super-orbital phase with *RXTE*/PCA (Vasco et al. 2013). Similar modulation of the O VII emission line has been observed in 4U 1626-67 with the spin period of the NS during another *XMM-Newton* observation (Beri et al. 2015). The variation of emission line strength in Her X-1 has been explained due to reprocessed emission from the accretion column with a hollow cone geometry. While in 4U 1626-67, the modulations result from the reprocessed emission originating in a warped accretion disc.

The 6.4 keV iron $K\alpha$ emission line from GX 301–2 varies with the rotation of the NS with a reduced pulse fraction compared to the X-ray continuum. The pulsation in iron $K\alpha$ line can originate from the presence of clumpy matter around the source. The presence of clumpy matter in the binary environment introduces anisotropy in the fluorescing medium resulting in variation of fluorescent emission strength originating from different directions around the NS in different spin phases.

Modulation in the Iron Emission Line with an additional period

Additionally, modulations in the iron line were also present in the source with the second period of 671.8 s (Top Panel of Fig. 3.14). The variations in the Fe $K\alpha$ line flux was significantly more intense with this period than the modulation with the NS spin period. From studying the variation in iron line strength with different periods (Fig. 3.15), we can conclude that the iron fluorescence emission from GX 301–2 is indeed varying with the rotation of the neutron star and an additional period. The second period is present in the overall *XMM-Newton*/PN energy range of 0.5–10 keV. The variation of the continuum with this additional period ($9\pm 1\%$)

is much smaller than that corresponding variations with the spin period of the NS ($16 \pm 1\%$).

Modulations in the iron emission strength with a periodicity smaller than the spin period of the NS could be produced from the beat frequency between the NS spin frequency and the frequency of the orbital period of a clump of matter in retrograde Keplerian orbit around the NS. This would create a broadband X-ray emission with particularly high emission strength in the iron fluorescence band. The observed clump detected in the non-flaring segment could originate as a stellar wind clump from the companion which is then captured in a retrograde orbit around the neutron star. As suggested by Mönkkönen et al. (2020) if the NS is indeed retrograde in nature, stellar matter captured by the NS would have a motion in the opposite sense with respect to its spin rotation. Let the time period corresponding to the orbital motion of the clump be T and P' corresponds to the additional period of 671.8 s. Therefore if the second period is produced due to the beating of the spin frequency (P_{spin}) and the orbital period T of the clump, then

$$\frac{1}{T} = \frac{1}{P'} - \frac{1}{P_{\text{spin}}}.$$

By substituting the values for P' and P_{spin} , the orbital period (T) of the clumpy wind was calculated to be ~ 8 hours. Assuming Keplerian motion for the clump of matter around the NS, we can calculate the radial distance to the clumpy matter (R), using Kepler's formula. Assuming the mass of the NS to be the canonical value of 1.4 solar mass, the distance to the clumpy wind is estimated to be approximately 5 lt-s from the NS.

3.5 Conclusion

Our inferences about the source GX 301-2 from the analysis of this *XMM-Newton* observation can be summarised as:

- There is a clear reduction of hardness ratio during the first of the two flares along with a reduction in the absorption column density and covering fraction along the line of sight to the source.
- The ratio of the $K\alpha$ and $K\beta$ emission line flux first increases and then saturates with increasing X-ray luminosity, the first detection of such behaviour from this source.
- Modulation of iron line emission estimated from spin-phase resolved spectroscopy indicates the presence of clumps in the stellar wind of WRAY 977.
- We found the presence of a secondary period, most prominent in the iron $K\alpha$ energy range (6.2–6.4 keV). The additional periodicity can be attributed to the beat frequency between the spin of the neutron star and the Keplerian frequency of a stellar wind clump in retrograde motion around the neutron star. The distance of the clumpy matter was calculated to be 5 lt-s away from the NS.

*Over and over in the history of astronomy, a new
instrument finds things we never expected to see.*

Rainer Weiss

4

Detection of a cyclotron line in the Be X-ray pulsar IGR J06074+2205

The findings discussed in this chapter are part of a paper published in the journal A&A

4.1 Introduction

Transient X-ray binary pulsars (XRPs) with a Be-type main sequence companion (BeXRPs) are useful for studying accretion onto highly magnetised neutron stars (NSs) over a wide luminosity range. The BeXRPs are known to exhibit a wide range

of luminosity, ranging from 10^{37-38} erg s $^{-1}$ during the peak of the outburst to 10^{32-34} erg s $^{-1}$ during the quiescence phase (Tsygankov et al. 2017). Many BeXRP have been detected since the launch of the first X-ray telescopes (Malacaria et al. 2020). Pioneered by the highly successful *RXTE*-ASM (Levine et al. 1996), the practice of initiating observations soon after the onset of an outburst has become standard. Recent advancements in sensitive, wide-viewing-angle X-ray instruments such as *MAXI*/GSC (Matsuoka et al. 2009), *Swift*/BAT (Krimm et al. 2006), and *Fermi*/GBM (Malacaria et al. 2020) enable the prompt identification of transients entering an outburst. Subsequent follow-up observations with sensitive broadband instruments like *NuSTAR* (Harrison et al. 2013) allow comprehensive studies of the source characteristics across a wide range of energy.

The source IGR J0607.4+2205 was discovered by the *JEM-X* instrument on board *INTEGRAL* (Chenevez et al. 2004). A follow-up *Chandra* observation of the source was performed to localise the source (Tomsick et al. 2006). Subsequent observations of the source using *XMM-Newton* (Reig & Zezas 2018) revealed pulsations with a period of 347.2 s, establishing the compact object as a NS. The companion of IGR J0607.4+2205 was found to be a B0.5Ve star establishing the source as a BeXRP, and the distance to the source was estimated to be 4.5 kpc (Reig et al. 2010). The source IGR J0607.4+2205 underwent an outburst in the beginning of October 2023 with coherent pulsation detected at 2.6700(2) mHz from *Fermi*/GBM (Malacaria et al. 2023). The source underwent three outbursts during 2022-2023 as observed with *MAXI*/GSC, and based on the assumption that the outbursts were type-I outbursts, the orbital period was calculated to be either 80 days or an integral division of the same; that is, 80/n days, where n=2,3... (Mihara et al. 2023). However, further observations are required to find the exact orbital period of IGR J0607.4+2205.

NuSTAR subsequently made two Target of Opportunity (ToO) observations of

the source after the detection of the outburst in 2023. The results obtained from the spectral and timing analysis of the two ToO observations of IGR J0607.4+2205 are explained in this chapter. The primary focus of this work is on the broadband spectral characteristics of IGR J0607.4+2205 and search for the presence of any CRSFs.

4.2 Observations and data reduction

The light curve for the October 2023 outburst was obtained from the *MAXI*^{*} website and also from the *Swift*/BAT transient monitoring mission[†]. The light curves from *MAXI*/GSC and *Swift*/BAT are plotted in Fig. 4.1 with a bin size of 1 day and 5 days, respectively.

The first of the two *NuSTAR* ToO observations was made on 8 October 2023 (MJD 60225; Obs ID: 90901331002; henceforth ObsID 02) with an effective exposure of ~ 42 ks, while the second observation was made on 15 October 2023 (MJD 60232; Obs ID: 90901331004; henceforth ObsID 04) with an effective exposure of ~ 40 ks. These two observations are marked in Fig. 4.1 along with the 2–20 keV *MAXI*/GSC and 15–50 keV *Swift*/BAT light curves of the source.

The *NuSTAR* data were reduced using HEASOFT version 6.30.1 along with the latest calibration files available via CALDB version 20231205. The nupipeline version 0.4.9 was used to produce the clean event files and the nuproduct command was used to extract the light curves and spectrum of the source and background regions. A circle of 150 arcsec in radius around the source position was used to extract the level 2 source products and a circle of the same radius away from the source region was used to extract the background products for ObsID 02. For ObsID

^{*}<http://maxi.riken.jp/mxondem/>

[†]<https://swift.gsfc.nasa.gov/results/transients/>

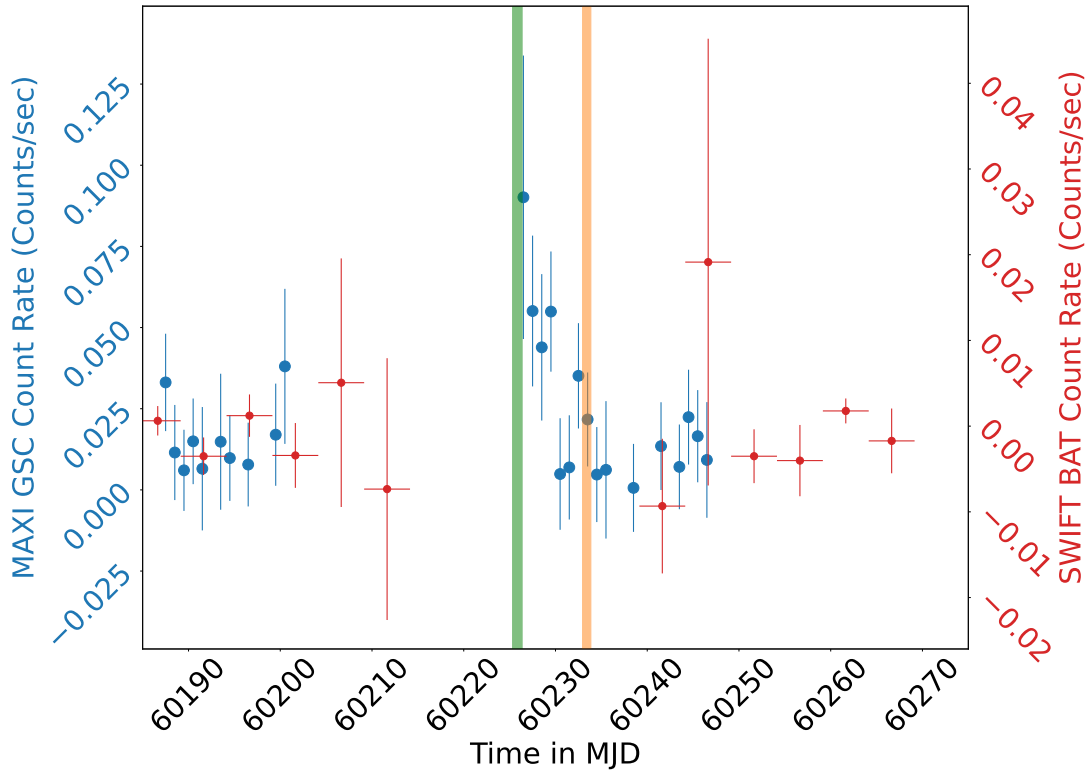


Figure 4.1: Long-term light curve of IGR J0607.4+2205 from MAXI/GSC (in blue) and *Swift*/BAT (in red) plotted with a bin size of 1 day and 5 days, respectively. The green line denotes the epoch and duration of the first ToO observation, while the second ToO observation is shown in orange.

04, the source and background region were respectively selected from a circle of 80 arcsec in radius around the source position and a circle of similar radius away from any known sources. Barycenter correction was performed using `barycorr` version 2.16. All the spectral files were optimally binned (Kaastra & Bleeker 2016). The broadband (3–78 keV) count rate of the source changed from 36 cts/s for ObsID 02 to 1.28 cts/s in the second observation.

4.3 Analysis and results

4.3.1 Timing analysis

The spin period of the source was found to be 374.60(1) s for ObsID 02 using the epoch-folding tool `efsearch`. For ObsID 04, the spin period decreased to 374.62(1) s. The broadband (3–78 keV) pulse profiles from the two observations are shown in the top panel of Fig. 4.2, where the minima of the two pulse profiles are aligned. The pulse profile for ObsID 02 was double-humped in nature, with some subpulse structures. The pulse profile changed significantly for ObsID 04 with the overall shape change of the individual peaks. We studied the energy-resolved pulse profile for both observations. We extracted pulse profiles in the energy ranges of 3–7, 7–10, 10–20, 20–40, 40–60, and 60–78 keV.

The pulse profile of ObsID 02 has a distinct main peak and a smaller peak separated by a pulse phase of ~ 0.5 . With an increase in the energy, the overall pulse shape remains the same, with the amplitude of modulation changing with energy.

The broadband 3–78 keV pulse profile for ObsID 04 exhibited notable modifications in pulse shape compared to ObsID 02. Instead of a main and secondary peak, a smaller peak emerged near the phase corresponding to the main peak in ObsID 02, coupled with a broader peak around the phase where the second peak

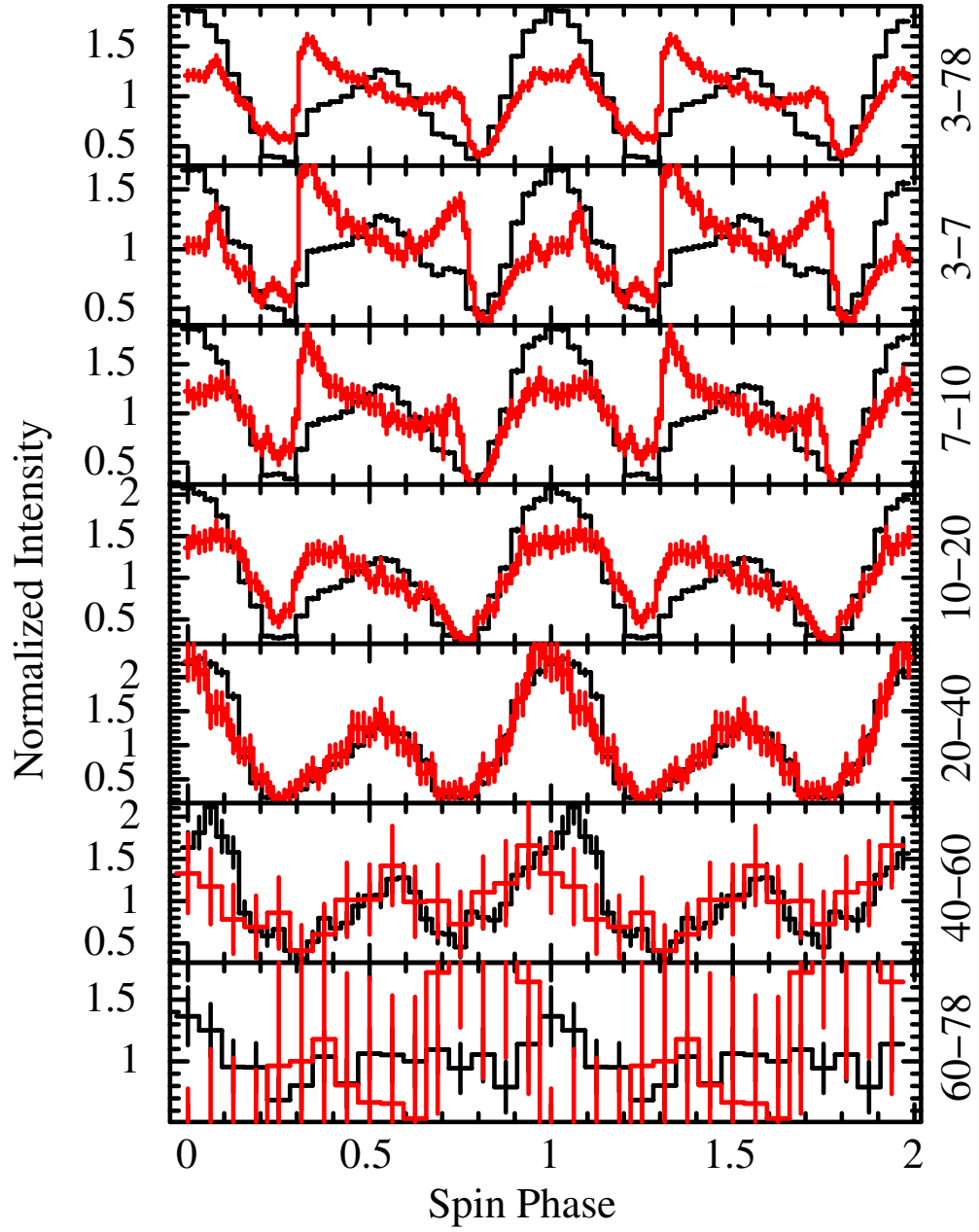


Figure 4.2: Normalised pulse profiles of combined Focal Plane Module A (FPMA) and B (FPMB) light curves from ObsID 02 (*black*) and ObsID 04 (*Red*) for IGR J0607.4+2205. The top panel consists of the pulse profile in the energy range of 3–78 keV. The remaining panels show the energy-resolved profiles in the energy ranges of 3–7, 7–10, 10–20, 20–40, 40–60, and 60–78 keV, respectively.

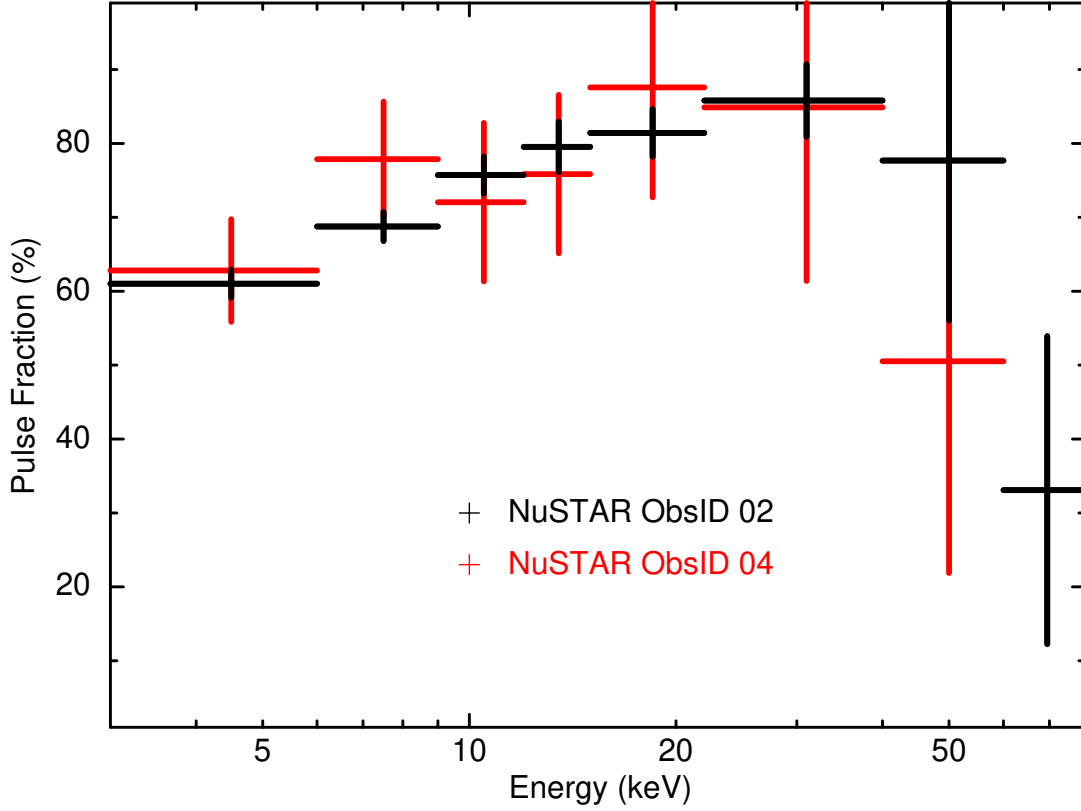


Figure 4.3: Variation of the pulsed fraction with energy for the two *NuSTAR* observations ObsID 02 (in black) and ObsID 04 (in red) for IGR J0607.4+2205.

was observed in ObsID 02. The overall pulse shape changed significantly with energy in ObsID 04. The low-energy, folded profiles show multiple peaks below ~ 20 keV. However, above 20 keV, the pulse profile becomes double humped with a primary peak and a smaller peak, similar to that in ObsID 02.

To quantify the changes in modulation in the amplitude of pulse profiles, we define the pulse fraction (PF) as $PF = (\max - \min) / (\max + \min)$, where $\max$ and $\min$ correspond to the maximum and minimum of the pulse profile. The variation of the PF with energy is plotted in Fig. 4.3 for both observations. We see an increasing trend of pulse fraction with energy until about 40 keV, beyond which there is a decrease in PF with energy, which is most prominent in ObsID 02. With the present data quality, it is not possible to comment on whether or not the decrease in the pulse fraction may be due to the presence of CRSF.

4.3.2 Spectral analysis

The phase-averaged spectra of IGR J0607.4+2205 from the two focal plane modules (FPMs) of *NuSTAR* were fitted together allowing for a relative normalisation between the two (in accordance with Madsen et al. 2015). All other parameters were tied between the two spectra. The entire spectral analysis was carried out using XSPEC version 12.12.1 (Arnaud 1996).

The *NuSTAR* broadband continuum spectrum of ObsID 02 was fitted with a power-law emission with a high-energy cutoff. The continuum model was multiplied by a `tbabs` spectral model to take into account the absorption of soft X-rays by interstellar matter with abundance taken from Wilms et al. (2000) and the photoelectric cross sections from Verner et al. (1996). Residuals left in the form of absorption were fitted with a Gaussian absorption profile, and this could be interpreted as CRSF. The CRSF line was present at 51 ± 1 keV, with a large optical depth of $1.31^{+0.14}_{-0.16}$. Addition of the CRSF improved the fit significantly and reduced the $\chi^2(\text{d.o.f.})$ from 880 (459) to 481 (456). This strong absorption feature was prominent in the raw spectrum as well. The residuals between spectral model and data are shown in Fig. 4.4, with the cyclotron line optical depth set to zero. The significance of the CRSF feature was calculated by making 100,000 simulations of the data using the XSPEC tool `simftest`. In each of the data simulations, spectral models were fitted with and without the absorption feature and the corresponding best-fit χ^2 values were calculated. The false-detection probability was then calculated to be less than 10^{-5} . The fluorescent iron $K\alpha$ line present in the spectrum was modelled using a Gaussian emission-line feature at ~ 6.3 keV with an equivalent width of 16^{+5}_{-4} eV. This emission feature was quite significant with a false detection probability of 10^{-4} calculated from 10,000 simulations in the `simftest` tool. Power-law continuum with multiple cutoff models, such as `highEcut`, `highEcut` with a smooth-

Table 4.1: The table contains the best-fit spectral parameters of the IGR J0607.4+2205 for two *NuSTAR* observations.

Spectral Parameter	ObsID 02	ObsID 04
$N_H [\times 10^{22} \text{ cm}^{-2}]$	$1.78^{+0.27}_{-0.24}$	0.43 (frozen)
Γ	$1.29^{+0.01}_{-0.01}$	$1.43^{+0.06}_{-0.07}$
$\Gamma_{\text{Norm}} [\times 10^{-2}]$	$5.33^{+0.17}_{-0.15}$	$0.41^{+0.01}_{-0.01}$
$E_{\text{cut}} \text{ (keV)}$	$15.89^{+0.65}_{-0.63}$	$30.93^{+3.03}_{-1.95}$
$E_{\text{fold}} \text{ (keV)}$	$40.14^{+7.00}_{-6.02}$	$11.81^{+6.98}_{-2.89}$
Width	$10.18^{+2.57}_{-3.24}$	5.0 (frozen)
$kT_{\text{BB}} \text{ (keV)}$	—	$1.18^{+0.03}_{-0.03}$
$\text{Radius}_{\text{BB}} \text{ (km)}$	—	$0.17^{+0.01}_{-0.01}$
$E_{\text{Fe}} \text{ (keV)}$	$6.3^{+0.1}_{-0.1}$	—
$EW_{\text{Fe}} \text{ (eV)}$	16^{+5}_{-4}	—
$E_{\text{CRSF}} \text{ (keV)}$	$50.62^{+0.97}_{-1.20}$	—
$\sigma_{\text{CRSF}} \text{ (keV)}$	$11.08^{+0.93}_{-1.18}$	—
τ_{CRSF}	$1.31^{+0.14}_{-0.16}$	—
Cross Norm	0.99 ± 0.01	0.99 ± 0.01
$\chi^2 \text{ (d.o.f.)}$	481 (456)	256 (242)
Flux $[\times 10^{-10}]^a$	$12.55^{+0.01}_{-0.01}$	$0.86^{+0.01}_{-0.11}$
Luminosity $[\times 10^{35}]^b$	$30.42^{+0.16}_{-0.34}$	$2.09^{+0.02}_{-0.26}$

The errors are quoted at 90% confidence intervals. ^a The flux is given in the energy range of 3–78 keV in units of $\text{erg cm}^{-2} \text{ s}^{-1}$. ^b The luminosity is given in the energy range of 3–78 keV in units of erg s^{-1} .

ing absorption feature, and newhcut (Burderi et al. 2000b), as well as NPEX (Makishima et al. 1999), describe the continuum well. All models show residuals in high energy around 50 keV. The newhcut model was finally chosen as it yields the lowest χ^2 in the fitting.

The final spectral model used was $\text{tbabs} \times (\text{powerlaw} \times \text{newhcut} + \text{Gaussian}) \times \text{gabs}$. The power-law component has a photon index of 1.29 ± 0.01 , which is similar to those obtained from earlier *XMM-Newton* (Reig & Zezas 2018) and *Chandra* (Tomsick et al. 2006) observations. The best-fit spectral model in $E^2 dN/dE$ (top panel) as well as the residuals for the best-fit spectrum (bottom panel) are given in Fig. 4.4. The best-fit spectral parameters are given in Table 4.1 with errors at a 90% confidence interval.

A similar continuum model as of ObsID 02 was used for ObsID 04. There was a soft excess present in the spectrum of ObsID 04, which was modelled with a black

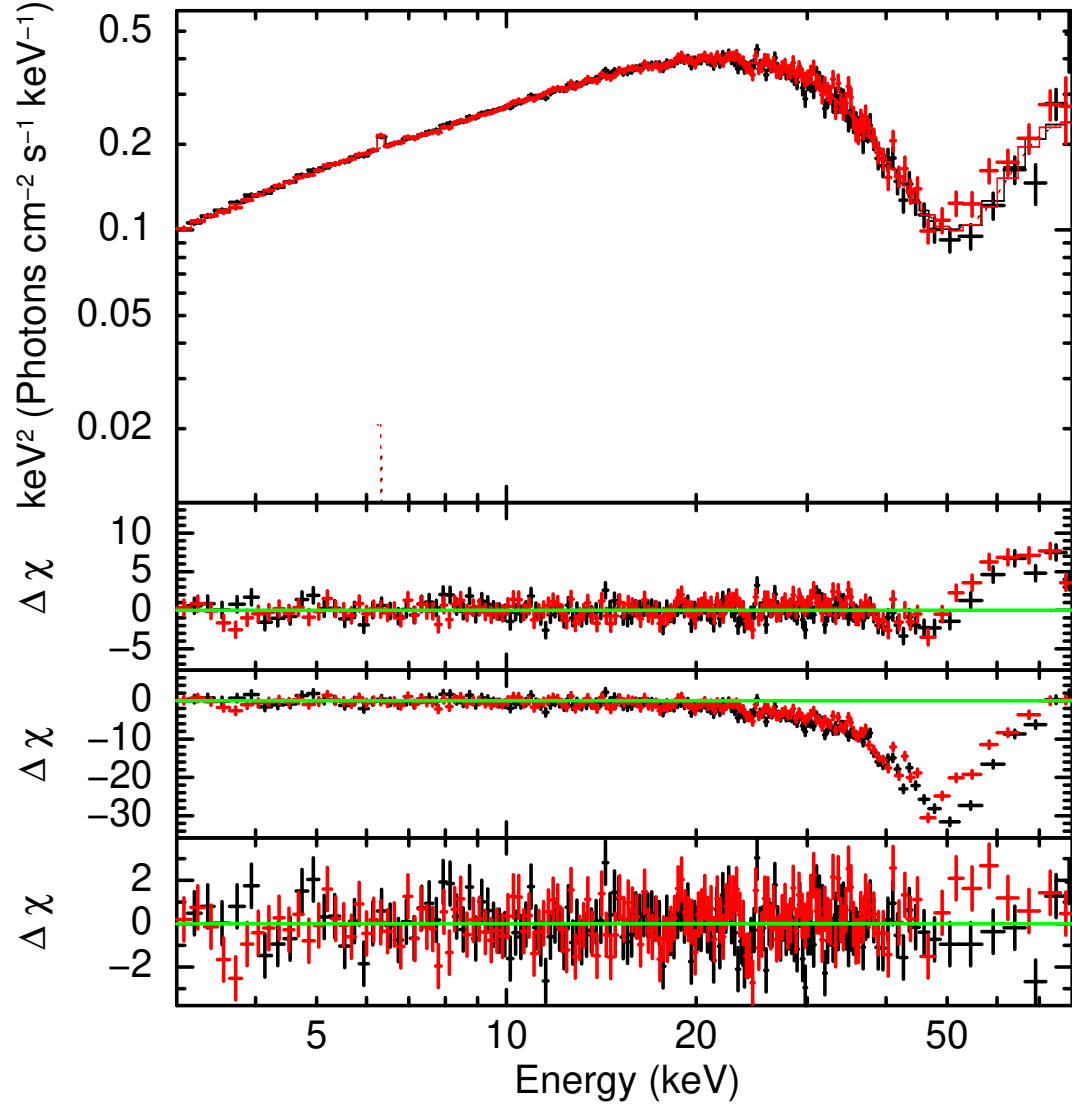


Figure 4.4: Spectrum and best-fit spectral model for ObsID 02 in IGR J0607.4+2205. The top panel consists of the best-fit model along with the different components. The second panel from the top shows the residual from the best-fit model without the addition of a cyclotron line. The third panel from the top corresponds to the residual obtained by setting the strength of the CRSF to zero. The bottom panel corresponds to the best-fit model residuals. The black points correspond to FPMA, while the red points are for FPMB.

body component. Addition of the black body component decreases the $\chi^2(\text{d.o.f.})$ from 446.58 (244) to 255.55 (242). The absorption column density cannot be constrained and was therefore fixed at a value of $0.43 \times 10^{22} \text{ atoms cm}^{-2}$, which corresponds to the Galactic absorption component along the line-of-sight (Kalberla et al. 2005, HI4PI Collaboration et al. 2016). The final spectral model of `tbabs` $\times$ (`powerlaw` $\times$ `newhcut` + `bbodyrad`) gave a χ^2 of 256 for 242 degrees of freedom (d.o.f.). The temperature of the black body component was found to be $1.18 \pm 0.03 \text{ keV}$, originating from an area of radius $0.17 \pm 0.01 \text{ km}$. The high temperature and small radius of the thermal component indicate that it probably originates from the accretion mound near the magnetic poles of the NS. The best-fit spectra and residuals are given in Fig. 4.5. In ObsID 04, the spectrum has very poor statistical significance above 40 keV, limiting the possibility for detection of a CRSF. As we are aware of the presence of a CRSF in the source for ObsID 02 at $\sim 51 \text{ keV}$, we added a Gaussian absorption component to the spectrum, with the line centre and width set to the best-fit values from ObsID 02. Nevertheless, the introduction of this extra component does not result in any enhancement in the χ^2 , yielding an upper limit on the optical depth of 0.68 at a 90% confidence level. The best-fit spectral parameters are provided in Table 4.1.

Subsequently, as we know there is a black body component from ObsID 04, we tried to add a similar black body component to ObsID 02. The temperature of the black body component cannot be constrained, and so it was frozen to the temperature from ObsID 04. The addition of the extra component leads to no significant decrease in χ^2 , yielding an upper limit on the luminosity of the black body component of $\sim 10^{34} \text{ erg s}^{-1}$ at the 90% confidence level. The luminosity of the source was calculated assuming a distance of 4.5 kpc (Reig et al. 2010).

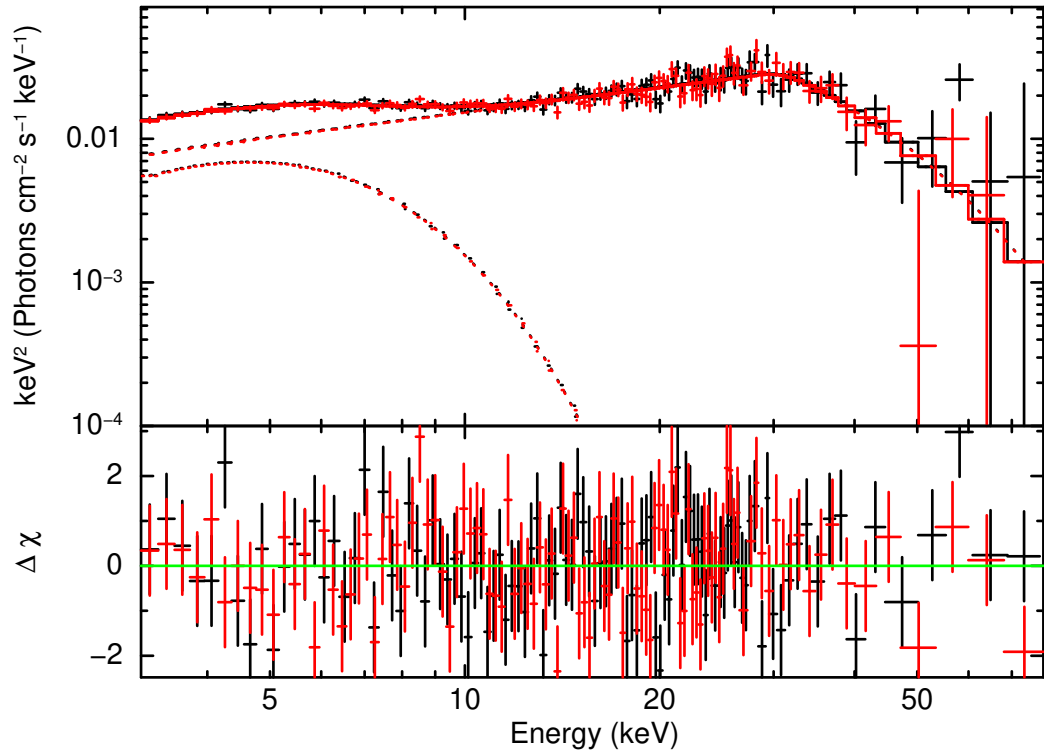


Figure 4.5: Spectrum and best-fit spectral model for ObsID 04 in IGR J0607.4+2205. The top panel consists of the best-fit models along with the different components. The bottom panel corresponds to the best-fit model residuals. The black points correspond to FPMA, while the red points are for FPMB.

4.4 Discussion

IGR J0607.4+2205 underwent an outburst in October 2023. Two ToO observations were performed with *NuSTAR*, capturing the source during an outburst for the first time. In this chapter, we explain the results from the two *NuSTAR* observations of IGR J0607.4+2205 during the 2023 outburst of the source.

Assuming a distance of 4.5 kpc (Reig et al. 2010), the source luminosity in the 3–78 keV range underwent a substantial change from 3.04×10^{36} erg/s in ObsID 02 to 2.09×10^{35} erg/s in ObsID 04. The period of pulsation obtained with *NuSTAR* is consistent with the spin frequency observed in the *XMM-Newton* observation, indicating no significant long-term slow down of the pulsar (Reig & Zezas 2018). The persistent pulsations present during ObsID 04 suggest disc accretion of matter onto the NS. The pulse profile of IGR J0607.4+2205 is double-humped in nature with a high pulse fraction ($\geq 50\%$). The source exhibits significant changes in pulse shape during the outburst. Luminosity-dependent changes in pulse profile have been observed in many X-ray pulsars (e.g. Parmar et al. 1989, Doroshenko et al. 2017, Sharma et al. 2023). The low-energy (≤ 20 keV) pulse shape of IGR J0607.4+2205 is significantly different between the two observations, while the higher energy (20–40 keV) pulse profile remains consistent. The changes in pulse profile of IGR J0607.4+2205 are most clear in the soft X-ray band. At higher energies, beyond 20 keV, the difference between the pulse profiles from the two observations may not be very clear due to larger error bars in the second observation. One possible explanation for the difference in pulse profile shapes can be the fact that there were some changes in beaming pattern. Similar behaviour has been reported for RX J0529.8–6556 (Treiber et al. 2021), where a misaligned Be disc is proposed to explain the observed changes in the pulse shape.

We modelled the broadband spectrum of the source with a cutoff power-law model as expected for HMXBs (White et al. 1983). The hard X-ray spectrum of the source is dominated by a strong non-thermal (power-law) component with a high-energy cutoff during ObsID 02. We observe a CRSF for the first time in the spectrum of IGR J0607.4+2205, as expected from a highly magnetised BeXRP. The cyclotron line was detected at a very high energy of $50.6^{+1.0}_{-1.2}$ keV. From the CRSF centroid energy, we calculated the strength of the magnetic field to be $4.4 \pm 0.1 \times 10^{12}$ G. We also obtain the first ever detection of iron $K\alpha$ fluorescent emission from IGR J0607.4+2205 with an equivalent width of 16^{+5}_{-4} eV. During ObsID 04, the source flux reduced by a factor of about 15. A significant change in the spectral properties was observed and no CRSF feature can be constrained, which is possibly due to poor statistics. An additional thermal (black-body) component at a temperature ~ 1 keV originating from a radius of ~ 170 m was present during ObsID 04. The parameters of the black-body are consistent with thermal emissions from a hot spot on the surface of the NS.

Spectral parameters have been seen to evolve significantly in BeXRBs during outbursts (e.g. Reig & Nespoli 2013, Lutovinov et al. 2021, Mandal et al. 2023). The correlation between the spectral slope and the source luminosity has been found to change at a critical luminosity, signifying an alteration in the emission mechanism and beaming pattern of the source (Becker et al. 2012). From the CRSF Becker et al. (2012), the critical luminosity of IGR J0607.4+2205 was calculated to be about 7×10^{37} erg s $^{-1}$, which is much higher than the observed luminosity during ObsID 02. This suggests that the source was well below the critical luminosity. The luminosity during ObsID 04 dropped to $\sim 2 \times 10^{35}$ erg s $^{-1}$, where accretion onto the NS surface is near free fall and radiation is dominated by the hot spot or mounds near the NS polar caps (Mushtukov et al. 2021).

The discovery of a CRSF in a new source is crucial for determining the magnetic field strength near the NS surface and advancing our understanding of accretion processes near the surface of the NS. The accretion torque acting on an NS due to mass accretion depends on its mass-accretion rate, spin period, and magnetic field. Knowledge of the magnetic field strength is therefore crucial in order to corroborate the accretion torque models. Of the hundreds of X-ray binary pulsars, around 50 or so sources exhibit a CRSF (Staubert et al. 2019, Devaraj & Paul 2022). The centroid energy of the CRSF detected in IGR J0607.4+2205 is relatively high among sources in which a CRSF has been detected. Additional broadband observations of IGR J0607.4+2205 are needed to study the luminosity dependence of the pulse profile and the CRSF.

I stand upon my desk to remind myself that we must constantly look at things in a different way. You see, the world looks very different from up here. You don't believe me? Come see for yourself. Come on. Come on! Just when you think you know something, you have to look at it in another way. Even though it may seem silly or wrong, you must try!

John Keating

5

Luminosity dependence of the multiple cyclotron lines in 4U 0115+63

The findings discussed in this chapter are part of a paper published in the journal A&A

5.1 Introduction

4U 0115+63 is a transient high mass X-ray binary (HMXB) pulsar that was discovered during the sky survey conducted with the *Uhuru* mission (Giacconi et al. 1972). The source was subsequently discovered to be a Be X-ray binary system with the

main sequence star identified as a B0.2Ve spectral-type star (Johns et al. 1978). The orbital period of 4U 0115+63 is ~ 24.3 days (Rappaport et al. 1978). The neutron star (NS) at the heart of the Be X-ray binary system has a spin period of ~ 3.6 s (Cominsky et al. 1978). The distance to the binary system has been estimated to be ~ 7 kpc (Negueruela & Okazaki 2001). 4U 0115+63 has gone through many episodes of type II outbursts, most recently in 2011 (Iyer et al. 2015), 2015 (Liu et al. 2020) and 2023 (Nakajima et al. 2023a). The latest outburst occurred during March 2023 with the X-ray luminosity reaching 10^{38} erg s $^{-1}$ (Nakajima et al. 2023a).

The cyclotron resonant scattering feature (CRSF) is the absorption feature in the spectra of pulsars due to interactions between photons and electrons in quantised energy levels present in the line-forming region of the NS. This spectral feature facilitates the direct measurement of the magnetic field strength of the NS. While some NS spectra do not contain any CRSFs, the sources that do contain CRSFs – the exact region responsible for the production of CRSFs – are still under debate (Staubert et al. 2019). Also, we do not have a complete picture when it comes to the variation of the cyclotron line with X-ray luminosity. Cyclotron line energy has been shown to be correlated with luminosity (Staubert et al. 2019). One such model used to describe the variation in the cyclotron line energy with luminosity is the shock height model (Becker et al. 2012) where the height of the CRSF formation region varies with luminosity. The cyclotron line energy and source luminosity have a positive correlation when the NS is in Coulombic shock regime. However, beyond a certain 'critical' luminosity, the parameters show negative correlation as the NS enters the radiative shock regime. Such a transition from a positive to negative correlation beyond a critical luminosity has been observed in A 0535+26 (Kong et al. 2021) and V 0332+53 (Lutovinov et al. 2015, Doroshenko

et al. 2017). A transition over critical luminosity is sometimes associated with a change in the pulse profile (Lutovinov et al. 2015, Wilson-Hodge et al. 2018). A different behaviour between the CRSF energy and luminosity has been observed in GX 304–1 (Rothschild et al. 2017) and Cep X–4 (Vybornov et al. 2017) where the CRSF energy plateaus at higher values of luminosity.

Multiple cyclotron lines have been observed in 4U 0115+63 near 11, 23, 33, 41, and 53 keV (Wheaton et al. 1979, White et al. 1983, Heindl et al. 1999, Santangelo et al. 1999, Ferrigno et al. 2009). The harmonics of a fundamental CRSF line has been seen in multiple X-ray pulsars such as Vela X-1 (Kendziorra et al. 1992, Kretschmar et al. 1996, Kreykenbohm et al. 2002, Maitra & Paul 2013), Centaurus X-3 (Nagase et al. 1992, Santangelo et al. 1998, Yang et al. 2023), Cep X-4 (Mihara et al. 1991, McBride et al. 2007, Vybornov et al. 2017), and 4U 1907+09 (Cusumano et al. 1998, Makishima et al. 1999, Tobrej et al. 2023). From the analysis of GINGA spectra of 4U 0115+63 at different luminosities during the 1991 outburst, it was reported that the CRSF line energy increased from 12 keV to 17 keV with a decrease in X-ray luminosity (Mihara et al. 1998). An anticorrelation between centroid energy of the ~ 11 keV CRSF line with luminosity was reported with RXTE data during the 1999 outburst (Nakajima et al. 2006). However, a subsequent analysis of data from the 2008 outburst of 4U 0115+63 has put the validity of this claim into question (Müller et al. 2013b, Boldin et al. 2013). A paradigm shift occurred regarding the understanding of CRSFs in 4U 0115+63 when the continuum model was modified by Iyer et al. (2015) such that two lines near 12 and 15 keV were detected simultaneously along with their higher harmonics from RXTE and *Suzaku* data. Subsequent observations of 4U 0115+63 using *NuSTAR* during the 2015 outburst (Liu et al. 2020) firmly established the presence of two fundamental CRSFs near 12 and 16 keV.

NuSTAR made four Target of Opportunity (ToO) observations of the source during the latest type II outburst in 2023. One observation was made at the peak of the outburst, another during the decay phase of the outburst, while two other observations were made when the source went back to quiescence. We describe the results from the first two observations taken at the peak and decay phase of the outburst. We also describe the evolution of CRSFs with luminosity of the pulsar, using the updated spectral model of the source with a simultaneous fitting of the 12 and 16 keV CRSF.

5.2 Observation and data reduction

The first observation by *NuSTAR* for the 2023 outburst of 4U 0115+63 occurred on 9 April 2023 (MJD 60043) (Obs ID: 90902316002) and the second one on 26 April 2023 (MJD 60060) (Obs ID: 90902316004). Hereafter Obs ID: 90902316002 and 90902316004 are abbreviated as ObsID 02 and ObsID 04. The times of the two ToO observations are given in Fig. 5.1 along with the 2–20 keV MAXI/GSC light curve of the source. The first observation was taken at the peak, while the second observation was performed during the decay phase.

The *NuSTAR* data were reduced using HEASOFT version 6.30.1 along with the latest calibration files available via CALDB. The nupipeline version 0.4.9 was used to produce the clean event files, while the nuproduct command was used to extract the light curves and spectrum corresponding to the source and background regions. A circle with a 150 arcsec radius around the source position was used for extracting the source level 2 data; similarly, a circle with the same radius away from the source region was used to extract the background data. Solar system barycenter correction was performed using barycorr version 2.16. All the spectral files were optimally binned based on [Kaastra & Bleeker \(2016\)](#). The light curve for the 2023

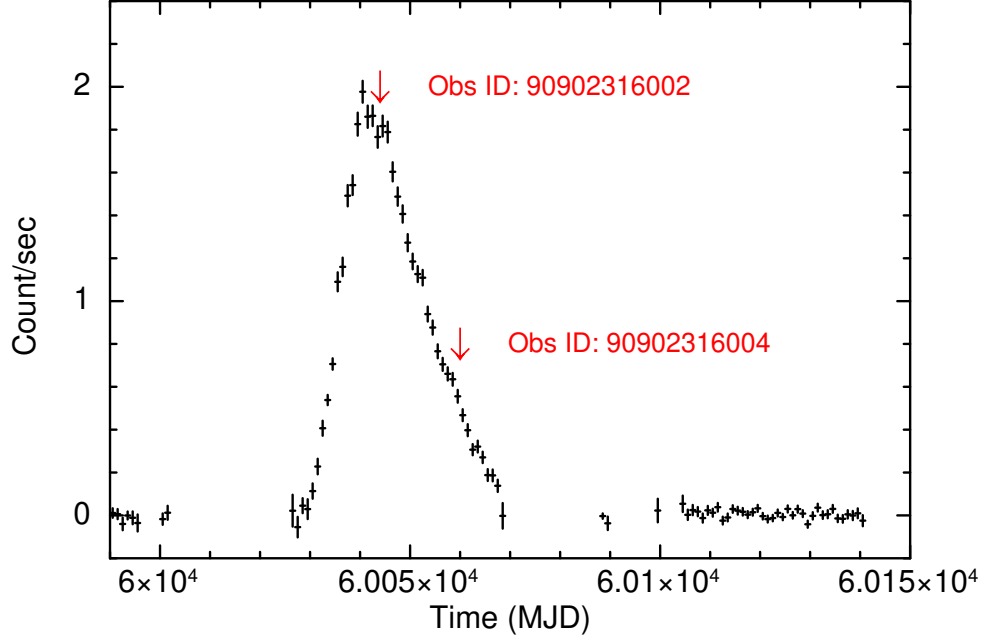


Figure 5.1: Light curve of the 2023 outburst of 4U 0115+63 as seen by MAXI/GSC. In black is the 2-20 keV MAXI/GSC count rate of the source binned to one day intervals. The two red arrows point to the two *NuSTAR* observations of the source analysed in this work.

outburst was obtained from MAXI * (Matsuoka et al. 2009) in the 2-20 keV energy range binned to intervals of one day.

5.3 Spectral and timing analysis

5.3.1 Timing analysis

The broadband (3–79 keV) FPMA and FPMB averaged count rate of the source changed from 444 cts/s for ObsID 02 to 114 cts/s in the second observation, which is a decrease by a factor of ~ 4 . The spin period of the source was found to be 3.61456(1) s for the first observation ObsID 02 using the epoch-folding tool *efsearch*. While for the second observation, ObsID 04, the spin period was reduced to 3.61309(1) s. The 3–79 keV pulse profiles of the two observations are shown in the top panel of Fig. 5.2 folded with arbitrary epochs to align the peaks. The pulse profiles were

*<http://maxi.riken.jp/mxondem/>

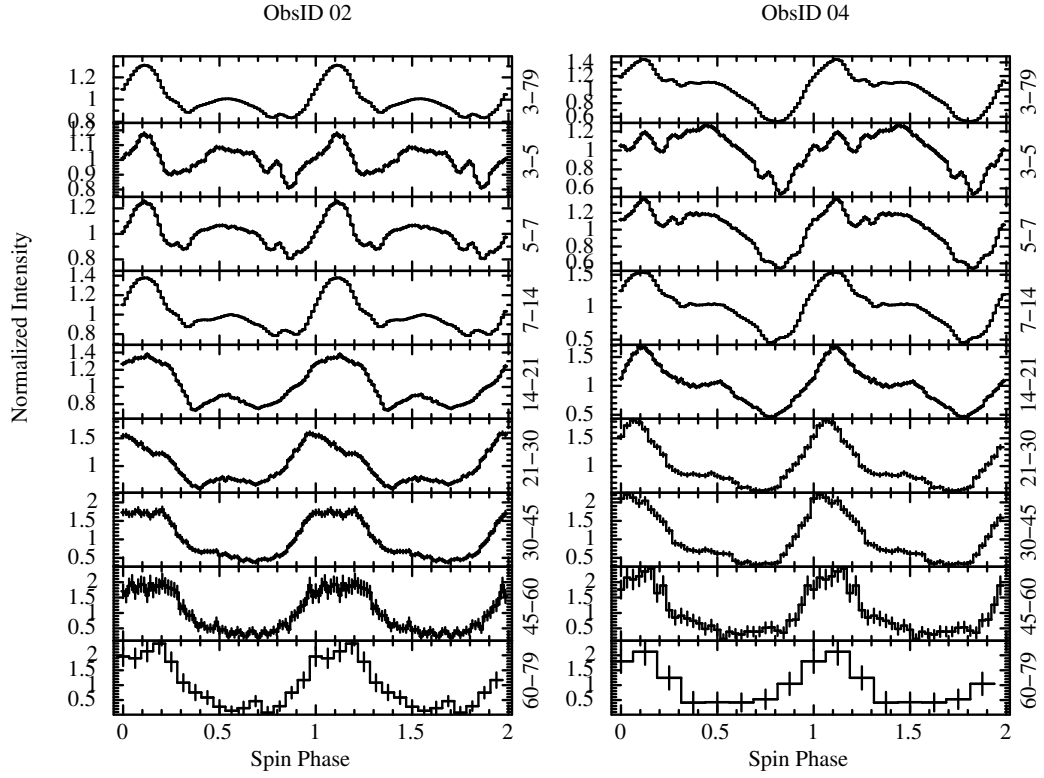


Figure 5.2: Folded profile of 4U 0115+63 from the two observations during the 2023 outburst normalised by dividing each profile by the average count rate. From the top down, we plot the overall (3–79 keV) and energy resolved (3–5, 5–7, 7–14, 14–21, 21–30, 30–45, 45–60, and 60–79 keV) pulse profiles for ObsID 02 (Left Panel) and ObsID 04 (Right Panel).

found to be broadly double peaked for both the observations with the first peak near phase ~ 0.1 and the second peak near phase ~ 0.55 . The dip between the two peaks is more prominent in ObsID 02 and there is also a hint of a smaller third peak in the same observation near the pulse phase ~ 0.8 .

We extracted the source light curve of 4U 0115+63 for multiple energy ranges to study the variation in the pulse profile with energy. The folded profiles in the energy ranges of 3–5, 5–7, 7–14, 14–21, 21–30, 30–45, 45–60, and 60–79 keV for ObsID 02 (Left Panel) and ObsID 04 (right panel) are given in Fig. 5.2. The pulse profile of 4U 0115+63 shows significant evolution with energy, as well as luminosity. The profiles show a significant change between the two observations with the pulse shape evolving from multiple peaks at lower energies to a single peak at higher energies. The pulse fraction shows an increasing trend with energy for both observations.

5.3.2 Spectral analysis

The spectra from FPMA and FPMB for 4U 0115+63 were fitted together allowing for a relative normalisation (Madsen et al. 2015), while all other parameters were tied between the two spectra. All of the spectral analyses were carried out using XSPEC version 12.12.1 (Arnaud 1996) with the absorption by the interstellar medium modelled using the Tuebingen-Boulder absorption model TBabs and elemental abundances being taken from Wilms et al. (2000) and the photoelectric cross sections from Verner et al. (1996).

The *NuSTAR* broadband continuum spectrum of ObsID 02 was fitted with the compTT spectral model describing the Comptonisation of soft photons in a hot plasma (Titarchuk 1994). A soft excess was present at lower energies which was modelled by a blackbody component (bbbodyrad) with a temperature of ~ 0.6 keV. The fluores-

cent iron $K\alpha$ line present in the spectrum was modelled using a Gaussian emission line at ~ 6.4 keV. The continuum model was multiplied by a `tbabs` spectral model to take into account the absorption of soft X-rays by interstellar matter. However, there were prominent absorption features still present in the residuals of the best fit model. We used the common absorption model `gabs` to model the different absorption features present in the spectrum. The final spectral model used was `tbabs` $\times$ (`compTT` + `bbodyrad` + `Gaussian`) $\times$ multiple `gabs`.

The spectrum of ObsID 02 (Fig. 5.3) showed two broad features around 15 and 25 keV and two narrower features around 34 and 47 keV. The broad feature around 15 keV could not be fitted with one single broad absorption feature. Therefore, we fitted two Gaussian absorption lines around this energy range, which reduced the χ^2 from 775 for 424 degrees of freedom to 542 for 421 degrees of freedom. The five distinct absorption features (modelled as `gabs`)^{† ‡} could be identified as five CRSF lines around ~ 12 , 16, 24, 34, and 47 keV.

The two CRSFs present at ~ 12 keV and ~ 16 keV cannot be harmonics from the same fundamental line. Therefore, the two CRSFs at around 12 and 16 keV must both be fundamental lines. The CRSF at ~ 24 keV is the first harmonic of the ~ 12 keV line and the line at ~ 34 keV is the combination of the second harmonic to the 12 keV fundamental and the first harmonic to the 16 keV fundamental, while the ~ 47 keV line is the combination of the third harmonic to the 12 keV fundamental and the second harmonic to the 16 keV fundamental. The best fit model gave a reduced χ^2 of 1.29 for 421 degrees of freedom. The luminosity of the source was calculated to be $12.08^{+0.02}_{-0.06} \times 10^{37}$ erg s⁻¹ in the 3–50 keV energy range, assuming a distance of 7 kpc (Negueruela & Okazaki 2001).

For the second observation ObsID 04 (Fig. 5.4), a similar spectral model was

[†]<https://heasarc.gsfc.nasa.gov/>

[‡]<https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html>

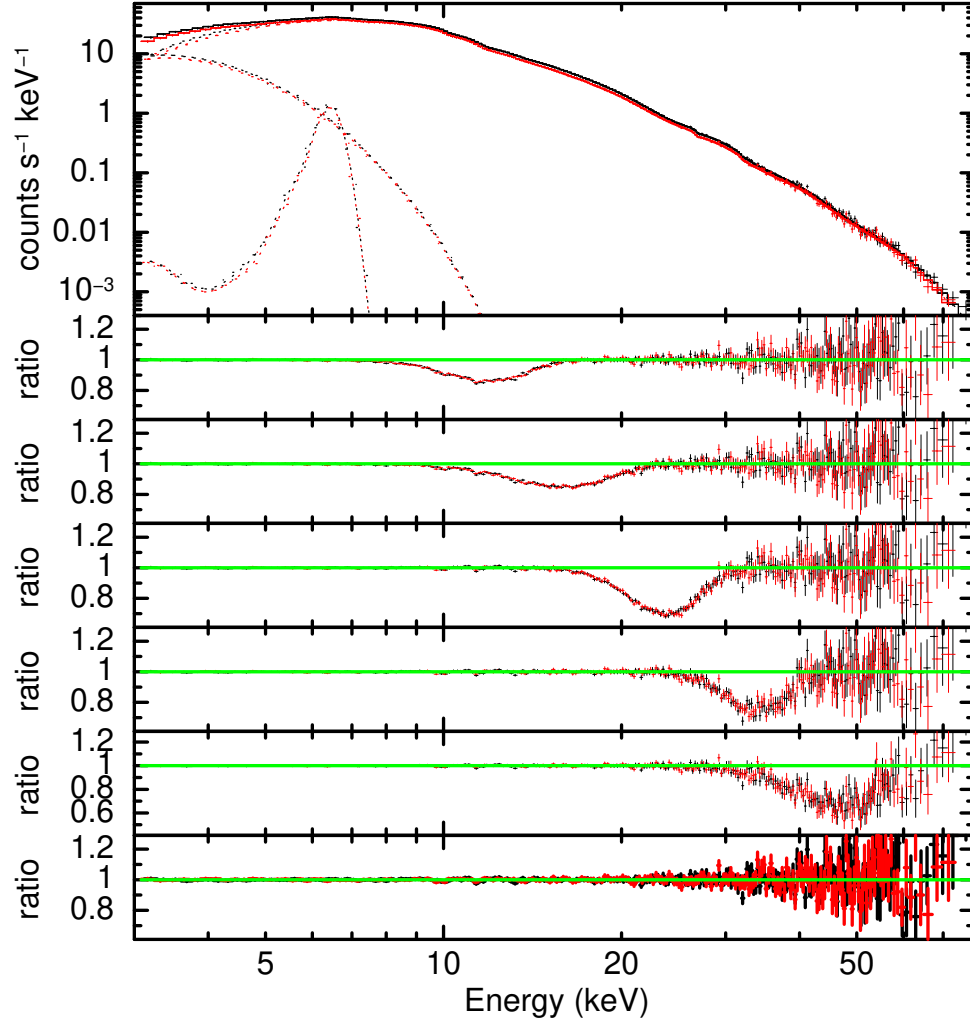


Figure 5.3: Spectrum and best fit spectral model of 4U 0115+63 for ObsID 02. The top panel consists of the best fit models along with the different components. Below this, the next five panels correspond to the residue from each of the five CRSFs at ~ 12 keV, ~ 16 keV, ~ 24 keV, ~ 34 keV, and ~ 47 keV that were removed individually from the best fit model by setting the corresponding depth to zero. The bottom panel corresponds to the best fit model residue. The black points correspond to FPMA, while red points are for FPMB.

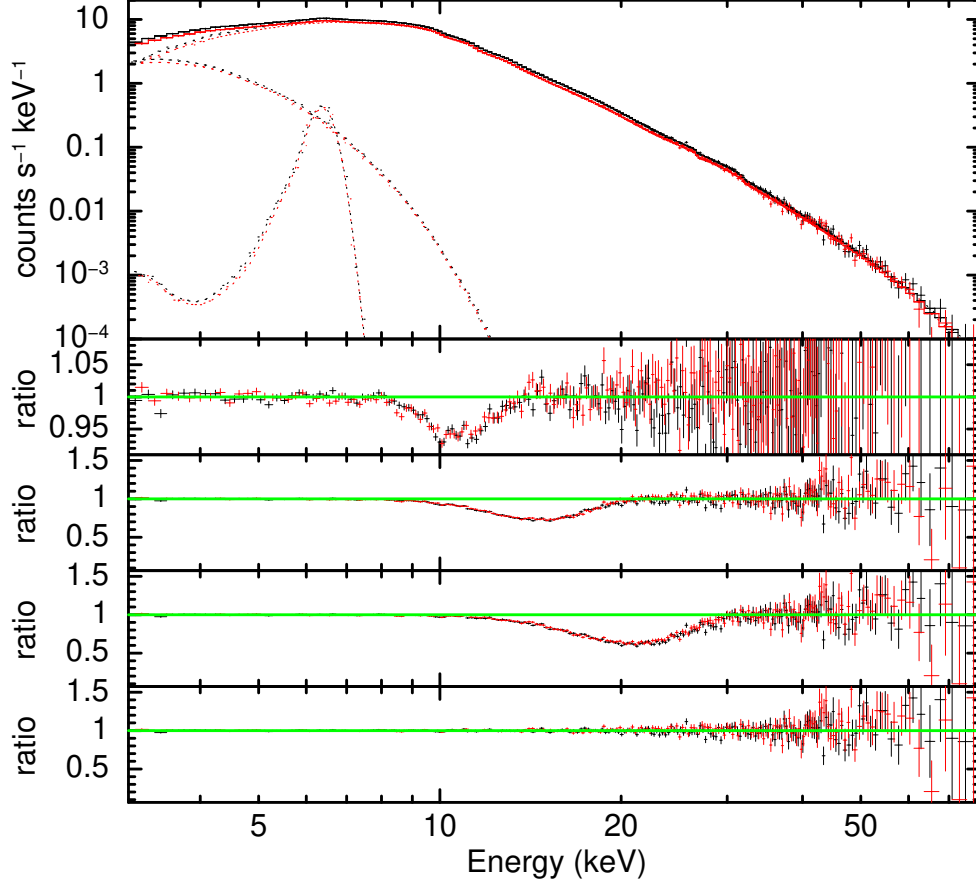


Figure 5.4: Spectrum and best fit spectral model of 4U 0115+63 for ObsID 04. The top panel consists of the best fit models along with the different components. Below this, the next three panels correspond to the residue from each of the three CRSFs at ~ 12 keV, ~ 16 keV, and ~ 24 keV that were removed individually from the best fit model by setting the corresponding depth to zero. The bottom panel corresponds to the best fit model residue. The black points correspond to FPMA, while red points are for FPMB.

used. The broadband spectrum was modelled as $\text{tbabs} \times (\text{compTT} + \text{bbbodyrad} + \text{Gaussian}) \times \text{multiple gabs}$. The spectral absorption lines at ~ 11 keV and the first harmonic at ~ 21 keV along with the line at ~ 15 keV were present. The best fit spectral model gave a reduced χ^2 of 1.28 for 369 degrees of freedom. The 3–50 keV luminosity of the source was calculated to be $2.83 \pm 0.01 \times 10^{37} \text{ erg s}^{-1}$. The best fit spectral parameters for both the observations are given in Table 5.1 with errors quoted at 90% confidence levels.

Table 5.1: Best fit parameters of the 4U 0115+63 spectral fitting from the two *NuSTAR* observations.

Spectral Model	Spectral Parameter	Units	Obs ID 2	Obs ID 4
TBabs	N_H	10^{22}	$4.11^{+0.80}_{-0.92}$	$1.77^{+1.32}_{-1.57}$
compTT	T_0	keV	$2.14^{+0.12}_{-0.08}$	$2.56^{+0.05}_{-0.04}$
	kT	keV	$7.87^{+1.75}_{-0.28}$	$61.26^{+36.15}_{-37.17}$
	τ		$2.59^{+0.62}_{-0.68}$	$0.01^{+0.16}_{-0.01}$
	Norm		$0.28^{+0.09}_{-0.04}$	$6.96^{+0.08}_{-0.08} \times 10^{-3}$
bbodyrad	kT	keV	$0.61^{+0.02}_{-0.02}$	$0.66^{+0.04}_{-0.03}$
	Radius	km	$35.51^{+4.12}_{-4.50}$	$13.41^{+2.73}_{-2.79}$
Gaussian	E_{center}	keV	$6.44^{+0.03}_{-0.03}$	$6.39^{+0.03}_{-0.03}$
	σ	keV	$0.18^{+0.05}_{-0.05}$	$0.19^{+0.06}_{-0.07}$
	Norm ^a		$3.24^{+0.78}_{-0.62} \times 10^{-3}$	$1.13^{+0.32}_{-0.26} \times 10^{-3}$
CRSF ₁	E_{center}	keV	$11.95^{+0.11}_{-0.12}$	$10.78^{+0.22}_{-0.17}$
	σ	keV	$1.80^{+0.16}_{-0.16}$	$1.21^{+0.13}_{-0.20}$
	Depth	keV	$0.70^{+0.30}_{-0.22}$	$0.20^{+0.09}_{-0.07}$
CRSF ₂	E_{center}	keV	$16.00^{+0.58}_{-0.94}$	$14.73^{+0.26}_{-0.21}$
	σ	keV	$3.02^{+1.06}_{-0.76}$	$2.59^{+0.26}_{-0.26}$
	Depth	keV	$1.25^{+1.23}_{-0.60}$	$2.09^{+0.59}_{-0.54}$
CRSF ₃	E_{center}	keV	$23.83^{+0.24}_{-0.22}$	$21.06^{+0.49}_{-0.39}$
	σ	keV	$3.07^{+0.38}_{-0.46}$	$4.19^{+0.47}_{-0.43}$
	Depth	keV	$2.82^{+0.79}_{-1.32}$	$5.01^{+0.99}_{-0.81}$
CRSF ₄	E_{center}	keV	$34.02^{+1.27}_{-0.44}$	—
	σ	keV	$3.83^{+1.17}_{-0.69}$	—
	Depth	keV	$2.86^{+1.96}_{-1.60}$	—
CRSF ₅	E_{center}	keV	$47.36^{+1.27}_{-0.71}$	—
	σ	keV	$7.59^{+0.41}_{-2.82}$	—
	Depth	keV	$8.00^{+2.00}_{-4.67}$	—
Cross Norm			$0.994^{+0.001}_{-0.001}$	$1.001^{+0.001}_{-0.001}$
χ^2_{red} (d.o.f)			1.29 (421)	1.28 (369)
Flux	(3–50 keV)	erg cm ⁻² s ⁻¹	$2.06^{+0.01}_{-0.01} \times 10^{-8}$	$4.83^{+0.01}_{-0.01} \times 10^{-9}$
Luminosity	(3–50 keV)	erg s ⁻¹	$12.08^{+0.02}_{-0.06} \times 10^{37}$	$2.83^{+0.01}_{-0.01} \times 10^{37}$

The errors are at a 90% confidence interval. ^aThe normalisation factor is in units of total photon cm⁻² s⁻¹ in the line.

5.4 Results

From the two *NuSTAR* observations of 4U 0115+63 during the 2023 type II outburst, the spin period was measured to be 3.61456(1) s and 3.61309(1) s, respectively. The source luminosity changed by a factor of four between the two observations. There was a significant change in the pulse profile across the two observations. The pulse profile for both the observations also showed variations with energy. The pulse profile were similar above 30 keV, while the profiles were substantially different below 30 keV. The pulse fraction for both the observations showed an increasing trend with energy, with the pulse fraction reaching 80% around 40 keV, similar to that observed during previous outbursts with the RXTE and INTEGRAL telescope (Tsygankov et al. 2007).

The spectrum of 4U 0115+63 was modelled with a Comptonised plasma model along with a soft thermal blackbody component with an iron emission line. There are five cyclotron lines present in the first observation and three in the second, the details of which are provided in Table 5.1. The two fundamental cyclotron lines were detected at 12 and 16 keV, along with their harmonics at 24, 34, and 48 keV. There was significant evolution of the CRSF line centre energy with X-ray flux; we discuss this phenomena in detail in the discussion section. All the cyclotron lines in both observations were present in all the pulse phases of the NS.

5.5 Discussion

The source 4U 0115+63 has undergone multiple type II outbursts since 1978, the most recent one being in 2023. The cyclotron line near ~ 12 keV and the first harmonic near 20 keV were discovered during the 1978 outburst with the HEAO 1 observatory (Wheaton et al. 1979, White et al. 1983) and were subsequently con-

firmed during the 1990 outburst with GINGA telescope (Mihara et al. 1998). The second, third, and forth harmonics of the 12 keV line near 34, 46, and 57 keV were detected during the 1999 outburst by both RXTE and *BeppoSAX* (Heindl et al. 1999, Santangelo et al. 1999, Ferrigno et al. 2009). Although the fundamental energy of the cyclotron line provides the magnitude of the magnetic field strength, it is through the detection and analysis of the harmonic lines that we can obtain the geometrical configuration of the magnetic field (Harding & Daugherty 1991, Araya-Góchez & Harding 2000, Schönherr et al. 2007).

Variation in the cyclotron line energy with luminosity

The exact luminosity dependence of cyclotron line features present in 4U 0115+63 has been a subject of much debate. The line centre of the CRSFs changed from ~ 11 keV at a high luminosity during the peak of the 1999 outburst to ≥ 15 keV at a lower luminosity (Nakajima et al. 2006). However, subsequent works have refuted this claim and attributed the result to inaccurate spectral modelling (Müller et al. 2013b, Boldin et al. 2013).

An updated spectral model was introduced by Iyer et al. (2015), which simultaneously modelled the two fundamental cyclotron lines near 12 and 16 keV, along with the harmonics of these lines. This gave a good fit of the RXTE, *Suzaku*, *Swift*, and INTEGRAL data from the 2011 outburst. The two CRSFs at 12 and 16 keV cannot be harmonically related so they were considered as two fundamental CRSFs. Subsequent examinations of the source with *NuSTAR* during the 2015 (Liu et al. 2020) and 2023 outbursts (present work) have affirmed the concurrent presence of the two fundamental lines and their harmonics in 4U 0115+63. The revised spectral model of 4U 0115+63 therefore requires a re-investigation of the previously reported variations in the centroid of the cyclotron line energy with the X-ray lu-

minosity.

In Fig. 5.5, we have plotted the line centre of multiple CRSFs in 4U 0115+63 as a function of the source luminosity in the 3–50 keV energy range. The circles correspond to the RXTE and *Suzaku* data from the 2011 outburst (taken from Iyer et al. 2015). The triangles correspond to the 2015 outburst and the squares represent the results from the 2023 outburst with *NuSTAR*. The CRSF energy and the 3–50 keV luminosity values of the *NuSTAR* observations during the 2015 and 2023 outbursts were recalculated for this work. For this work, we considered the observations where the 12 and 16 keV lines were simultaneously considered and studied the variation in the line centre with luminosity. As we can clearly see in Fig. 5.5, there is a simple positive correlation between the line centre of CRSFs and the source luminosity. While all the lines follow this behaviour, the correlation is specially prominent for the two fundamental cyclotron lines near 12 and 16 keV. The increase in the energy of the line centre of the two fundamental cyclotron lines with luminosity is about 10 percent. The change in CRSF with energy is found until 10^{38} erg/s for the 16 keV line and its harmonics as these CRSFs show a tentative negative correlation with luminosity beyond 10^{38} erg/s.

The positive correlation between the cyclotron line central energy (E_{cyc}) and luminosity (L_x) was discovered in the persistent HMXB Her X-1 (Staubert et al. 2007). Subsequently, an increase in E_{cyc} with L_x has been found in Vela X-1 (Fürst et al. 2014, La Parola et al. 2016), A 0535+63 (Müller et al. 2013a, Caballero et al. 2008), GX 304–1 (Malacaria et al. 2015, Rothschild et al. 2017), Cep X–4 (Vybornov et al. 2017), and Swift J1626.6–5156 (DeCesar et al. 2013). Her X-1 and Vela X-1 are the two persistent HMXB sources that show a positive correlation in E_{cyc} with L_x in the luminosity range of ~ 0.1 to 3×10^{37} erg s $^{-1}$. The positive correlation in Cep X-4 was observed in a pulse-to-pulse analysis (Vybornov et al. 2017), which was not

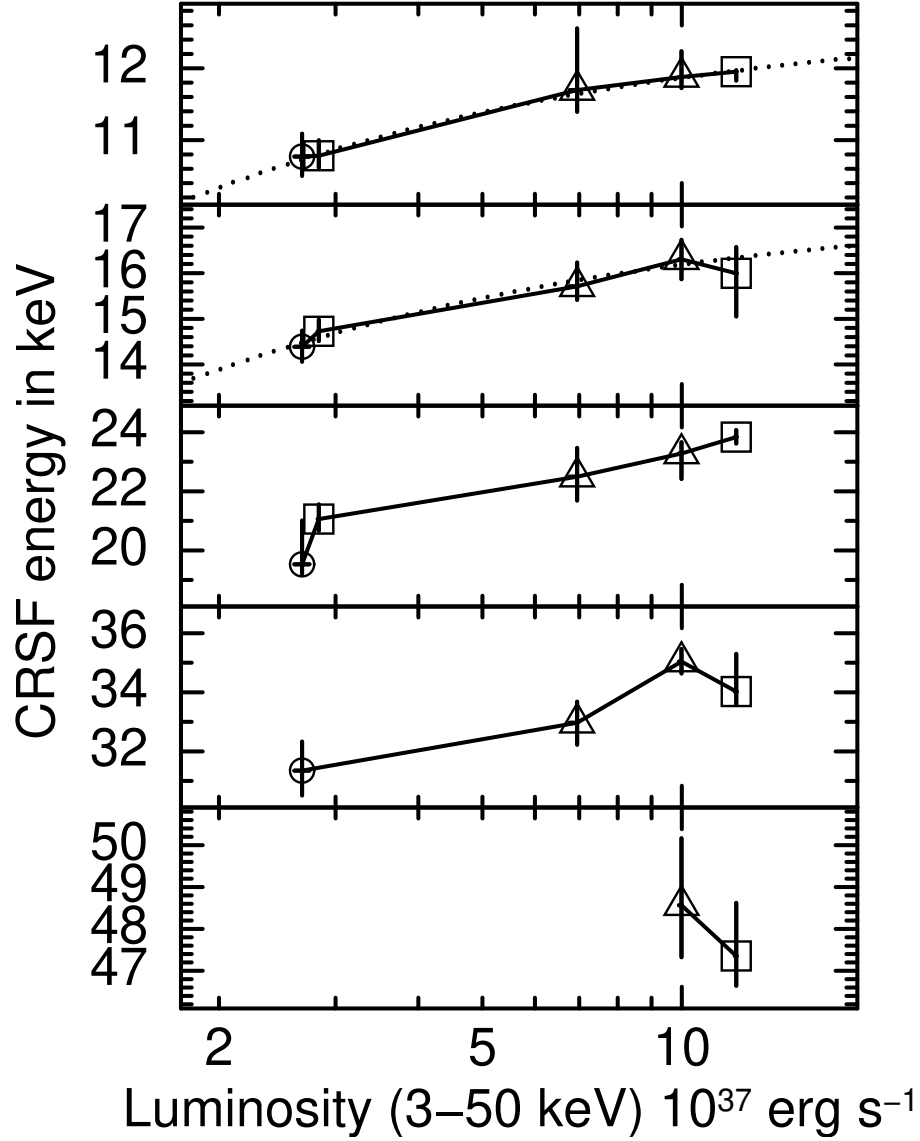


Figure 5.5: Variation in the line energies of the different cyclotron lines with the 3–50 keV luminosity of 4U 0115+63. Circles correspond to the 2011 outburst (Iyer et al. 2015), triangles correspond to the 2015 outburst, and square points represent the results from the current work. The evolution of the 12, 16, 24, 34, and 48 keV CRSFs with luminosity is shown in different panels from top to bottom. The dotted lines in the top two panels show the predicted variation in the cyclotron line (E_{cyc}) and X-ray luminosity (L_X) according to the collisionless shock model.

seen in the phase average results across the multiple outbursts of the source (Mukerjee & Antia 2021). For A 0535+63, E_{cyc} was found to be more in a flare observed before the peak of the 2005 outburst compared to the line energy during the main outburst (Caballero et al. 2008). A positive correlation was observed in the pulse-to-pulse analysis of the 2010 outburst of the source (Müller et al. 2013a); however, recent observations of the source during its 2020 outburst show a negative correlation beyond a critical luminosity (Kong et al. 2021). 4U 0115+63 is the only HMXB that shows a positive correlation between cyclotron line and luminosity over a very wide range of X-ray luminosities from ~ 2.6 to $12 \times 10^{37} \text{ erg s}^{-1}$.

A positive correlation is observed in cyclotron line energy with the luminosity in the collisionless shock regime (Becker et al. 2012), and beyond a critical luminosity the relation changes to a negative correlation (Staubert et al. 2019). The variation in the line centre with flux is entirely due to the magnetic field strength at the height above the NS surface responsible for the production of the CRSFs. The scaling of the magnetic field strength with flux could well explain the luminosity dependence in Her X-1 (Staubert et al. 2007). In sources displaying a positive correlation, there is an increase in the height of the region in the accretion mound near the poles of the NS where the CRSF is produced with a decrease in luminosity. While at a higher height in the accretion mound, the magnetic field is smaller leading to a lesser value for the CRSF centroid energy.

The evolution of the cyclotron line energy with luminosity is governed by eq. 1.6. The best fit values of the two free parameters E_0 and K were calculated to be 12.7 ± 0.1 keV and $0.130 \pm 0.004 (\text{erg/s})^\alpha$ for the 12 keV line, respectively. The magnetic field strength corresponding to the surface value of the CRSF energy was calculated from eq. 1.2 to be 1.4×10^{12} G. For the 16 keV line, the best fit value was calculated to be 17.4 ± 0.3 keV and $0.145 \pm 0.017 (\text{erg/s})^\alpha$ for α and K , respec-

tively. The fit was performed neglecting the highest luminosity data point for the 16 keV line, as there is a hint of negative correlation between E_{cyc} and L_X beyond 10^{38} erg/s. The magnetic field strength corresponding to the surface value of the 16 keV CRSF energy was calculated to be 2.0×10^{12} G. The variation in the cyclotron line (E_{cyc}) with X-ray luminosity (L_X) for the 12 and 16 keV CRSF are shown in the top two panels of Fig. 5.5. The collisionless shock model has been successful in describing the luminosity variation in the cyclotron line for sources such as GX 304–1 (Rothschild et al. 2017) and Cep X–4 (Vybornov et al. 2017).

The correlation between E_{cyc} and L_X shows a possible change from positive to negative beyond 10^{38} erg/s for the fundamental CRSFs at 16 keV. A similar behaviour can also be observed in the first (34 keV) and second (48 keV) harmonic of the same fundamental cyclotron line. However, with only one data point, this trend cannot be established beyond a reasonable doubt and more high luminosity observations of 4U 0115+63 are needed to firmly establish the negative correlation at a high luminosity. A negative correlation between E_{cyc} and L_X is observed in the radiative shock regime (Becker et al. 2012) and the transition from positive correlation occurs beyond a critical luminosity. The value of critical luminosity for 4U 0115+63 is $\sim 10^{38}$ erg/s. The change from a positive to negative correlation beyond a ‘critical’ luminosity is not seen in the 12 keV fundamental CRSFs as well as its first harmonic at 24 keV. A possible transition from a positive to negative correlation of E_{cyc} and L_X has been observed in XTE J1946+274 for one of the magnetic poles (Devaraj et al. 2024). A similar change in correlation was observed in A 0535+262 (Kong et al. 2021) during its 2020 outburst and also in V 0332+53 (Vybornov et al. 2018) from a pulse amplitude resolved analysis. The correlation was observed in both sources only after correcting for the time variation in the CRSF line center.

Two fundamental CRSFs originate from two line-forming regions in the atmosphere of the NS. The two fundamental lines can also originate from the two line-forming regions at different heights along the same pole of the NS, as has been observed in GX 301–2 (Fürst et al. 2018). The alternative model for the origin of the two fundamental CRSFs is that they are formed in two different magnetic poles of the NS. This Two Pole Cyclotron line Model (TPCM) has been preferred from the results of the 2008 (Iyer et al. 2015) and 2015 outburst (Liu et al. 2020). The TPCM origin of the two fundamental lines can be due to the non-dipolar structure of the magnetic field, misalignment of the magnetic poles, different accretion rates at the two magnetic poles, or a different structure of the accretion column at the two magnetic poles. The increase in the CRSF energy of the two fundamental lines are consistent with the collisionless shock model, and in that scenario, the two CRSFs probably originate from aligned magnetic poles with a different accretion column geometry, accretion rate, or from misaligned magnetic poles of the NS. We also tried to study the origin of the two fundamental lines using spin-phase resolved spectroscopy. Even though the two fundamental cyclotron lines and their harmonics were detected in all the phase bins, no concrete conclusion could be drawn from the data regarding the origin of the two fundamental CRSFs.

5.6 Summary

We describe the results from an analysis of the two *NuSTAR* observations of 4U 0115+63 during the 2023 outburst of the source. Two fundamental cyclotron lines near 12 and 16 keV were simultaneously observed in the source similar to the 2011 (Iyer et al. 2015) and 2015 outburst (Liu et al. 2020). Multiple harmonics of the two fundamental lines were present near 24, 34, and 47 keV.

The CRSFs present in 4U 0115+63 show a positive correlation with luminosity.

There is a hint of a negative correlation beyond the luminosity value of 10^{38} erg/s for the 16 keV CRSF as well as its harmonics. No such behaviour was observed for the fundamental and first harmonic of the 12 keV CRSF. The collisionless shock model could well describe the luminosity variation in the cyclotron line energy. Assuming that the two fundamental CRSFs are produced at the two poles of the NS (Liu et al. 2020), the dipolar magnetic field strength of the two poles were calculated to be 1.4 and 2.0×10^{12} G. We also comment on the different scenarios as to the origin of the two fundamental CRSFs. However, future observations across a wide range of luminosities is essential to distinguish between the possible scenarios.

Nature uses only the longest threads to weave her patterns so that each small piece of her fabric reveals the organisation of the entire tapestry.

Richard Feynman

6

Detection of CRSF in Cep X-4 at a low luminosity level

The findings discussed in this chapter are part of a paper published in the journal *New Astronomy*

6.1 Introduction

Transient X-ray binary pulsars with Be-type main sequence companion (BeXRP) are uniquely suited to test accretion onto highly magnetised neutron stars (NSs). The BeXRPs are known to exhibit a wide range of luminosity, ranging from 10^{32-34}

erg s⁻¹ during the quiescence phase to 10^{37–38} erg s⁻¹ during the peak of outbursts (Tsygankov et al. 2017). Many BeXRP have been detected since the launch of the first X-ray telescope, however, development of highly-sensitive X-ray instruments like *Chandra*, *NuSTAR* and *XMM-Newton* allow us to study the BeXRP at much lower luminosities across a wide range of energy (Tsygankov et al. 2017, Raman et al. 2023).

The transient BeXRP *Cepheus X-4* (henceforth *Cep X-4*) was discovered in 1972 with *OSO-7* (Ulmer et al. 1973). Since the discovery, the source has undergone multiple outbursts in 1988 (Roche et al. 1997), 1993 (Makino & GINGA Team 1988), 2002 (McBride et al. 2007), 2012 (Furst et al. 2015), 2014 (Vybornov et al. 2017) and 2018 (Mukerjee & Antia 2021). The spin period of *Cep X-4* is ~ 66 s (Koyama et al. 1991). The distance to the source was estimated to be 7.4 ± 0.5 kpc from *GAIA* DR3 data (Bailer-Jones et al. 2021, Gaia Collaboration et al. 2023).

A CRSF was first detected in the spectrum of *Cep X-4* at 30.5 ± 0.4 keV during the 1988 outburst of the source using *GINGA* telescope (Mihara et al. 1991). The CRSF was later confirmed during the 2002 outburst with *RXTE* data (McBride et al. 2007). Detailed study of the CRSF using *NuSTAR* data during the 2014 outburst, showed a clear asymmetry in the CRSF profile with an additional CRSF at around 19 keV (Furst et al. 2015, Bhargava et al. 2019). Later, the same *NuSTAR* data was used to detect the first harmonic of the 30 keV CRSF at ~ 55 keV (Vybornov et al. 2017). A positive correlation between the CRSF line centre and X-ray luminosity from pulse amplitude resolved analysis was found (Vybornov et al. 2017). Combining all previous data along with the *Astrosat* observation of *Cep X-4* during its 2018 outburst, Mukerjee & Antia (2021) showed that the CRSF central energy remained stable at an average value of 30.2 ± 0.2 keV across a span of about thirty years.

Cep X-4 underwent a type II outburst in June 2023, which was detected with

Table 6.1: Observation details of *Cep X-4* for the two *NuSTAR* observations.

Observation ID	Date	MJD	Exposure
90901322002	7 July 2023	60132	26 ks
90901322004	8 July 2023	60133	31 ks

MAXI/GSC, *Swift*/BAT and *Fermi*/GBM (Nakajima et al. 2023b). Two observations were made with *NuSTAR* during the decay phase of the outburst. Here, we describe the detection of CRSF in *Cep X-4* at the lowest luminosity level. We also study the evolution of CRSF with the luminosity of NS using all confirmed detections of CRSF from the source.

6.2 Observation and data reduction

NuSTAR made two observations of *Cep X-4* on 7 July and 8 July 2023, details of which are given in Table 6.1.

The long-term *Swift*/BAT lightcurve in the 15–50 keV energy range from *Cep X-4* binned to 3 days interval is shown in Fig. 6.1. The *NuSTAR* observation was taken towards the end of an outburst and are marked with arrows in Fig. 6.1.

For the joint fitting with the spectra from the two modules of FPM, the normalisation factor of one of the modules (FPMA) was fixed to unity while the other (FPMB) factor was left to vary. All the spectral analysis was carried out using XSPEC version 12.12.1 (Arnaud 1996) with the absorption by interstellar medium modelled using the Tuebingen-Boulder absorption model TBabs and abundance taken from Wilms et al. (2000) and the photoelectric cross sections from Verner et al. (1996).

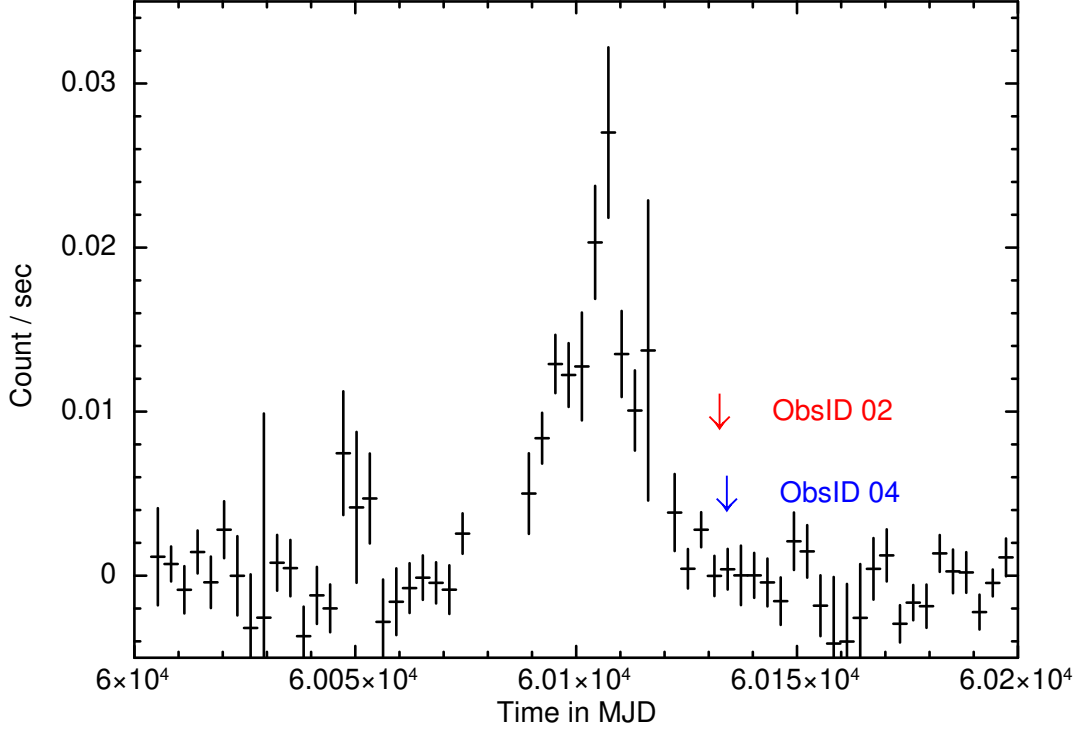


Figure 6.1: The Swift/BAT light curve of *Cep X-4* with a binning of 3 days is shown in black. The red and blue arrows correspond to the two *NuSTAR* observations of the source from 7 July 2023 and 8 July 2023, respectively.

6.3 Data Analysis

6.3.1 Timing Analysis

The light curve from *Cep X-4* shows significant variations in the count rate between the two observations. The count rate of the source changed from 0.28 counts/s for ObsID 02 to 0.074 counts/s for ObsID 04. *Cep X-4* is known to exhibit pulsations with a period of ~ 66 sec. Using the epoch folding (Leahy 1987) tool *efsearch*, we determined the spin period of the NS during the first observation to be 66.38 (1) s. The folded pulse profile for *Cep X-4* in the entire *NuSTAR* energy range of 3-79 keV is plotted in the top panel of Fig. 6.2. The pulse profile is single-peaked in nature, with complex sub-pulse features. During the second observation, the pulsations were detected with the same period of 66.38 (1)s. The overall profile,

as seen in red in Fig. 6.2, remains similar to ObsID 02.

The pulse fraction (PF) for a pulse profile (P) can be defined as

$$PF = \frac{P(max) - P(min)}{P(max) + P(min)} \quad (6.1)$$

where $P(max)$ and $P(min)$ are the maximum and minimum of the pulse profile. The pulse fraction of *Cep X-4* in the broad energy band of 3–79 keV was calculated to be 64 ± 9 % for ObsID 02 and for 49 ± 15 % ObsID 04. To study the variation of pulse profile with energy, we extracted source light curves in the energy ranges of 3–5, 5–10, 10–20, 20–35 and 35–79 keV for both observations. The energy resolved profiles are plotted in Fig. 6.2 in black for ObsID 02 and in red for ObsID 04. There was no significant detection of pulsations from the source in the 35–79 keV energy range during this period. The overall pulse profile remains very consistent across the two observations, with minor changes in the sub-pulse shape. The pulse fraction is found to be increasing with energy for both the observations.

6.3.2 Spectral Analysis

We have tried modelling the spectra with a powerlaw continuum with multiple cut-off models like highECut, FDcut (Tanaka 1986), and NewHCut (Burderi et al. 2000b) as well as physically motivated models like CompST (Sunyaev & Titarchuk 1980) and NPEX (Makishima et al. 1999). The NPEX continuum model was finally chosen as it yields the lowest χ^2 in the fitting. The *Negative and Positive power law with a common EXponential cutoff factor*, i.e. NPEX model given by Eq. 6.2 describes unsaturated Comptonised emission,

$$NPEX(E) = A(E^{-\Gamma} + f \times E^2)e^{-E/\beta} \quad (6.2)$$

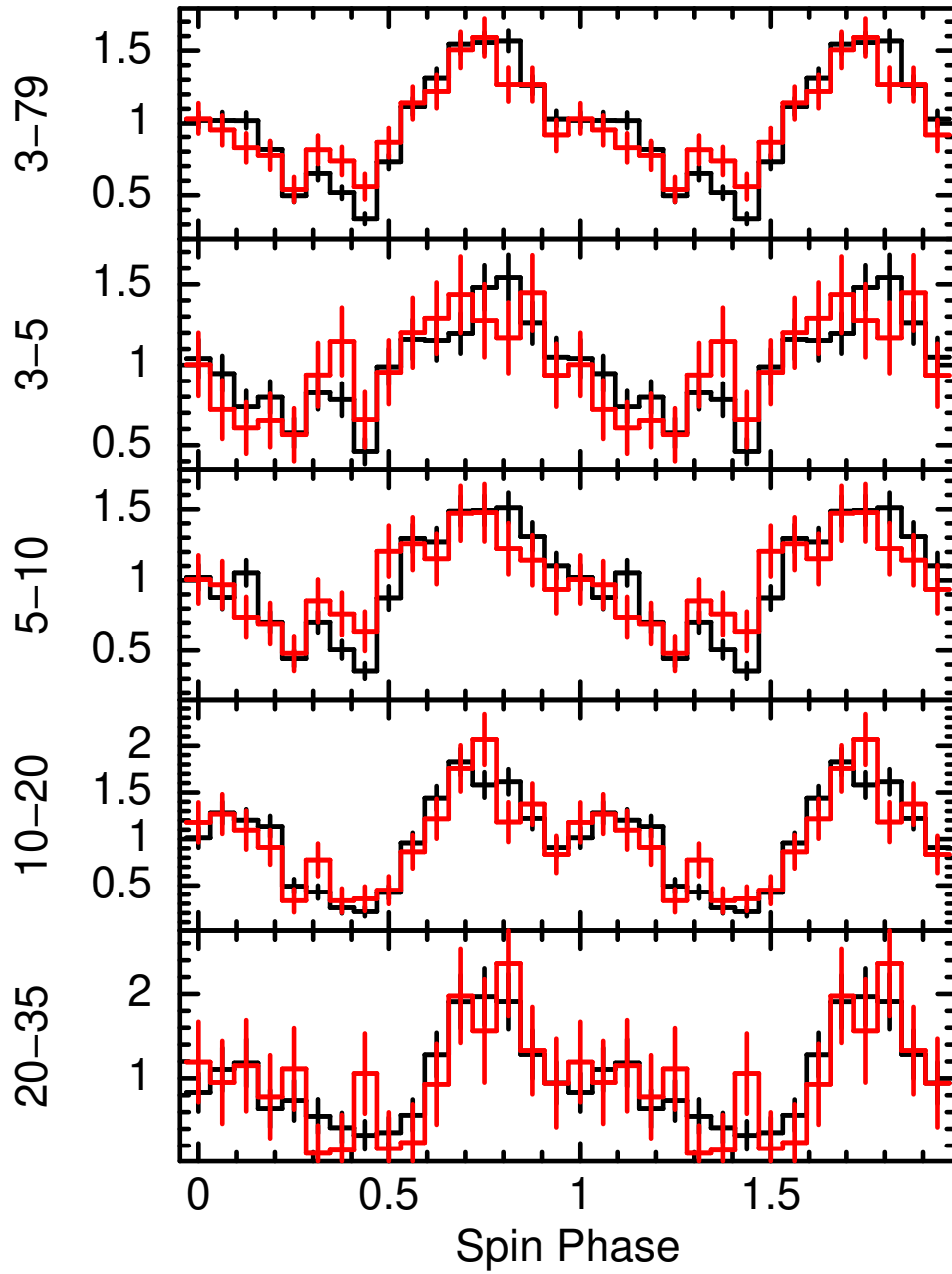


Figure 6.2: The pulse profile of *Cep X-4* for ObsID 02 (in black) and ObsID 04 (in red). The top panel consists of the pulse profile in the energy range of 3–79 keV. The remaining panels from the top show the energy-resolved profiles in the energy ranges of 3–5, 5–10, 10–20, and 20–35 keV, respectively.

where A is the powerlaw normalisation, Γ is the power law index, f is the fractional contribution of the positive powerlaw component with respect to the negative one, and the β is the high energy cutoff energy.

The best-fit parameters for the spectral modelling are given in Table 6.2 with errors provided at a 90% confidence interval. Due to the lack of low energy coverage from *NuSTAR*, the absorption column density was fixed at a value of 0.8×10^{22} atoms cm^{-2} , which corresponds to the Galactic absorption component along the line of sight (Kalberla et al. 2005, HI4PI Collaboration et al. 2016). The power law index of the *NPEX* model was $1.3^{+0.1}_{-0.1}$, which is much softer than previously observed (Bhargava et al. 2019). The exponential cutoff value of $6.4^{+0.5}_{-0.4}$ keV is consistent with older observations of the source (Makishima et al. 1999). The residual from the spectral fitting with the *NPEX* showed spectral residuals near 30 keV, where a cyclotron line is known to be present in the source (Mihara et al. 1991). Hence, an additional absorption component was used to model the cyclotron absorption feature. The addition of the cyclotron line gave a $\Delta\chi^2$ of 24 for 3 additional d.o.f. The central energy of the CRSF was found at $27.3^{+1.5}_{-1.0}$ keV with a width of $2.2^{+1.1}_{-1.0}$ keV and an optical depth of $0.83^{+0.43}_{-0.31}$. The final spectral model used to describe the continuum was $tbabs \times NPEX \times gabs$. The presence of the cyclotron line was also observed with the other spectral models with the CRSF parameters similar to the values given in Table 6.2. The best fit spectral model, along with individual components, are plotted in Fig. 6.3. Allowing the absorption column density to vary gave a higher value of N_H of about 0.8×10^{22} cm^{-2} and a softer powerlaw index. Other parameters obtained were consistent within the error.

The significance of the CRSF feature was calculated by making 100,000 simulations of the data using the *XSPEC* tool `simftest`. In each of the simulations, spectral models were fitted with and without the absorption feature and the cor-

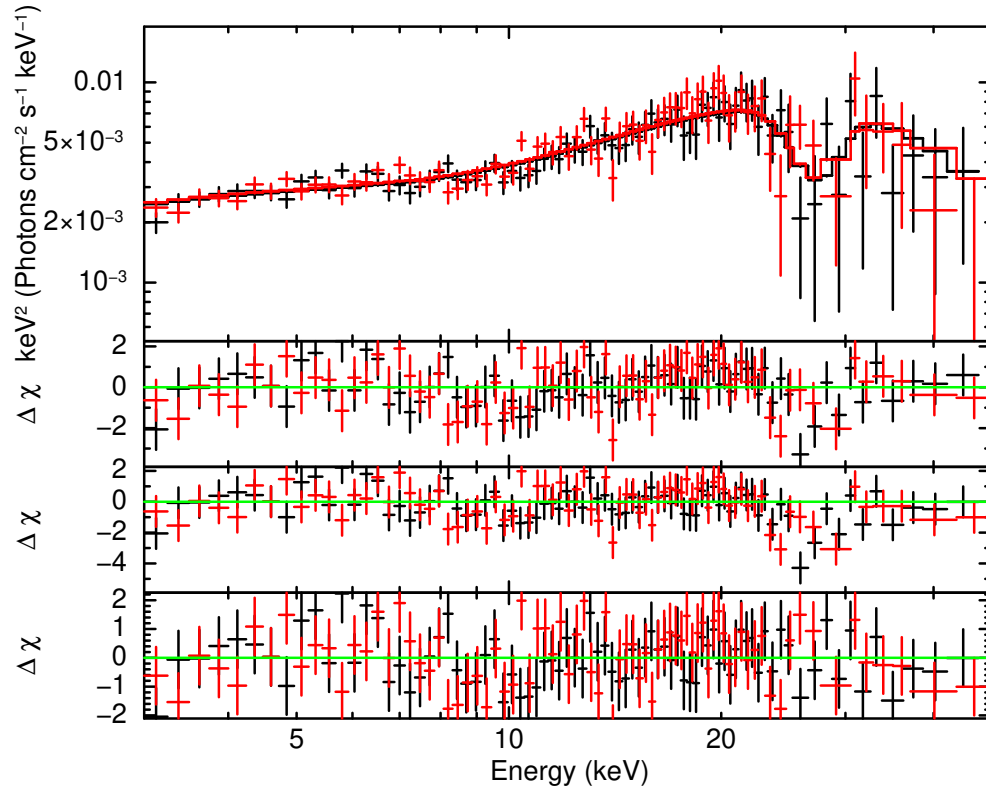


Figure 6.3: Spectrum and best-fit spectral model of *Cep X-4* for ObsID 02. The top panel correspond to the best-fit model along with the different components. The second panel from top shows the residual from the best fit model without adding the CRSF. While the third panel from top shows the residual obtained by setting the strength of the CRSF to zero. The bottom panel corresponds to the best-fit model residuals. The black points correspond to FPMA, while the red points are for FPMB.

Table 6.2: The table contains the best-fit spectral parameters of *Cep X-4* for both observations.

Spectral Parameter	ObsID 02	ObsID 04
$N_H [\times 10^{22} \text{cm}^{-2}]$	0.8 (frozen)	0.8 (frozen)
Photon Index (Γ)	$1.3^{+0.1}_{-0.1}$	$1.7^{+0.3}_{-0.3}$
$f_{NPEX} [\times 10^{-4}]$	$4.6^{+1.0}_{-0.8}$	$4.2^{+2.0}_{-1.3}$
β_{NPEX} (keV)	$6.4^{+0.5}_{-0.4}$	$5.2^{+0.7}_{-0.5}$
$\text{Norm}_{NPEX} [\times 10^{-3}]$	$1.9^{+0.3}_{-0.3}$	$1.2^{+0.5}_{-0.8}$
E_{CRSF} (keV)	$27.3^{+1.5}_{-1.0}$	—
σ_{CRSF} (keV)	$2.2^{+1.1}_{-1.0}$	—
τ_{CRSF} (keV)	$0.83^{+0.43}_{-0.31}$	—
Unabsorbed Flux ^a	$2.0^{+0.1}_{-0.1} \times 10^{-11}$	$4.4^{+0.4}_{-0.4} \times 10^{-12}$
Luminosity ^b	$1.3^{+0.1}_{-0.1} \times 10^{35}$	$3.0^{+0.2}_{-0.2} \times 10^{34}$
χ^2 (d.o.f.)	145.01 (154)	51 (37)

The errors are quoted at 90% confidence intervals. ^a The unabsorbed flux is given in the energy range of 3–79 keV in units of $\text{erg cm}^{-2} \text{s}^{-1}$. ^b The luminosity is given in the energy range of 3–79 keV in units of erg s^{-1} .

responding best-fit χ^2 values were calculated. The false-detection probability was then calculated to be about 0.06 %, making the detection significant at a confidence interval of 3.4σ . During this observation, the unabsorbed source flux was calculated to be $2.0^{+0.1}_{-0.1} \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 3–79 keV energy range. Assuming a distance of 7.4 kpc, the luminosity of the source during this observation was calculated to be $1.3^{+0.1}_{-0.1} \times 10^{35} \text{ erg s}^{-1}$.

During the second observation, ObsID 04, the source count rate was lower by a factor of ~ 5 with respect to ObsID 02. The spectra for ObsID 04 can be well described with an absorbed NPEX model $tbabs \times NPEX$. Similar to the first observation the absorption column density was frozen to the Galactic line of sight value. The best-fit power law index was 1.7 ± 0.3 , similar to the power law index for the source during ObsID 02. The best-fit spectral model for ObsID 04 is shown in Fig. 6.4. The unabsorbed flux from the source was calculated to be $4.4^{+0.4}_{-0.4} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 3–79 keV energy range. The luminosity of the source was calculated to be $3.0^{+0.2}_{-0.2} \times 10^{34} \text{ erg s}^{-1}$, assuming a distance of 7.4 kpc. The best fit spectral parameters with the errors quoted for 90% confidence interval are given in Table 6.2. With

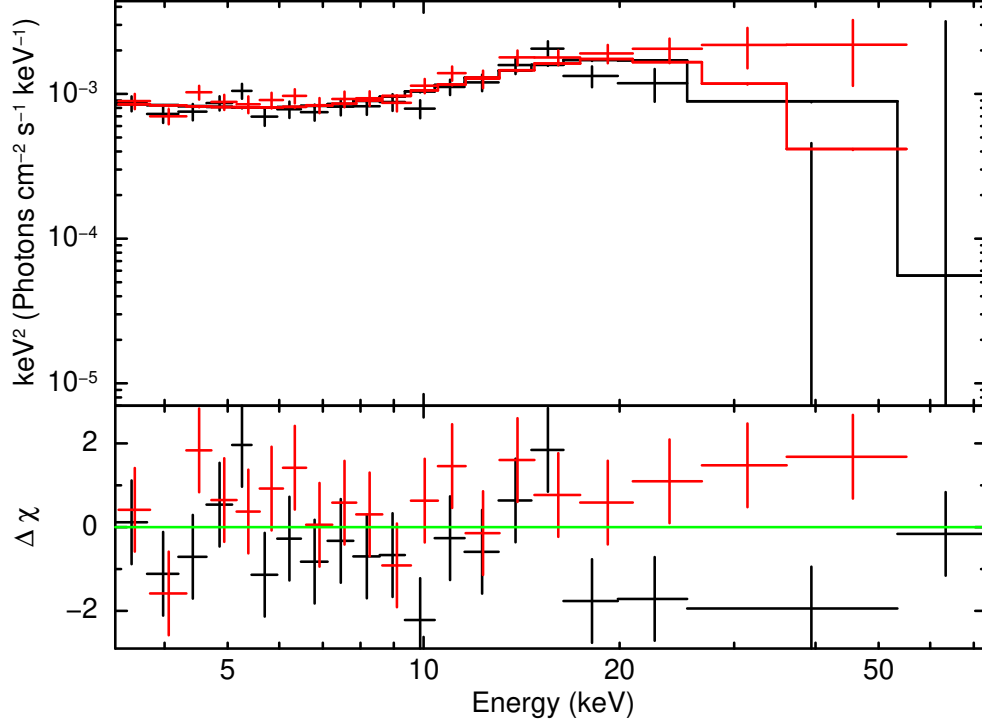


Figure 6.4: Spectrum and best-fit spectral model of *Cep X-4* for ObsID 04. The top panel correspond to the best-fit model. While the bottom panel corresponds to the best-fit model residuals. The black points correspond to FPMA, while the red points are for FPMB.

prior knowledge of the presence of CRSF in *Cep X-4*, we looked for a cyclotron line in the spectrum during ObsID 04. Since the line energy and width could not be constrained, it was frozen to the value obtained from ObsID 02. The optical depth of the line had an upper limit of 1.7, with no significant improvement of χ^2 with the addition of the new spectral component. The CRSF has a false detection probability of 28 %, making the CRSF detection in ObsID 04 not significant.

6.4 Discussion

We discuss the results from the two *NuSTAR* observations of the transient BeXRP *Cep X-4* during its 2023 outburst. The two *NuSTAR* observations were carried out during the decay phase of the outburst. The broadband continuum spectra of *Cep X-4* were modelled using an absorbed NPEX model for both observations. The spec-

trum of *Cep X-4* became softer in ObsID 04 with respect to ObsID 02, with the decay of the outburst. Sokolova-Lapa et al. (2023) analysed the combined data from two observations during the 2023 outburst. The combined data showed a CRSF at ~ 29 keV. However, combining multiple observations *with different powerlaw index*, at different flux levels can lead to spurious features in the spectrum. A significantly high black body temperature (~ 5 keV) was detected along with a broad Gaussian-like feature at ~ 20 keV, which doesn't correspond to any known prominent emission line. The large blackbody component, along with the broad emission feature at about 20 keV, are indicative of spurious spectral features from combining data across multiple flux ranges. Therefore, it is important to analyse the two observations separately so that the true spectral shape and their evolution can be properly studied.

A CRSF was detected in *Cep X-4* during ObsID 02 at around 27 keV. The detection of the cyclotron line at low luminosity needs to be considered to update the luminosity dependence of the cyclotron line. The detection of CRSF at low luminosity has been greatly facilitated by the high effective area and good spectral resolution of the *NuSTAR* telescope.

6.4.1 Luminosity variation of CRSF

We combine the results from all previous detection of CRSF in *Cep X-4* along with the data from the two 2023 *NuSTAR* observations. The CRSF central energy as a function of luminosity is plotted in Fig. 6.5. There seems to be a positive correlation between E_{cyc} and L_X with long-term data, unlike previously reported (Mukerjee & Antia 2021). The CRSF energy saturates at higher luminosity, which can be misinterpreted as a constant CRSF line energy that does not vary with luminosity. The positive correlation is in agreement with similar results reported from

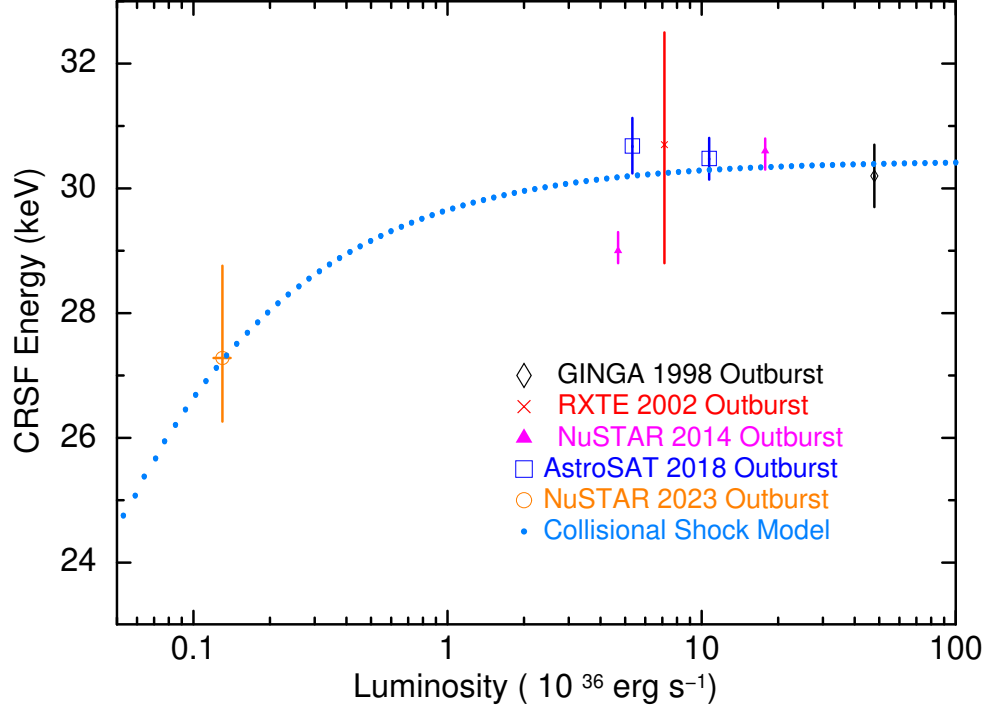


Figure 6.5: The variation of cyclotron line energy with luminosity for *Cep X-4* is plotted in the figure. The results from the collisionless shock plasma model are shown via the dotted line.

pulse-amplitude resolved analysis (Vybornov et al. 2017).

6.4.2 Collisionless Shock Model

The persistent X-ray pulsar Her X-1 was the first source where a positive correlation between E_{cyc} and L_x was observed (Staubert et al. 2007). Subsequently, similar relationships were identified in a number of persistent and transient sources like A 0535+63 (Caballero et al. 2008, Müller et al. 2013a), Swift J1626.6–5156 (DeCesar et al. 2013), Vela X-1 (Fürst et al. 2014, La Parola et al. 2016), GX 304–1 (Malacaria et al. 2015, Rothschild et al. 2017) and 2S 1553-542 (Malacaria et al. 2022). Recent reanalysis of the CRSF energy in 4U 0115+63 across multiple outbursts has also revealed a positive correlation between E_{cyc} and L_x across a wide range in luminosity (Roy et al. 2024b).

In the collisionless shock regime, a positive correlation between cyclotron line

energy and luminosity is expected (Becker et al. 2012). However, beyond a critical luminosity threshold, the CRSF energy and luminosity have a negative correlation (Staubert et al. 2019). The line centre is a direct measure of the magnetic field strength at the CRSF forming region. In systems exhibiting a positive correlation, there is a decrease in the height of the CRSF forming region from the NS surface, with an increase in luminosity, leading to an increase in E_{cyc} . The collisionless shock model was used to explain the luminosity dependency of CRSF observed in Her X–1 (Staubert et al. 2007).

The evolution of cyclotron line energy with luminosity is governed by eq. 1.6. The best-fit values of the two free parameters E_0 and K were calculated to be 30.45 ± 0.27 keV and 0.009 ± 0.002 (erg/s) $^\alpha$ respectively. The model prediction for E_{cyc} as a function of luminosity L_X is plotted in blue in Fig. 6.5. The calculated value of the magnetic field close to the NS in this work is a little lower compared to the estimates by Vybornov et al. (2017). The estimated cyclotron line energy at the surface of the NS gives a magnetic field strength of 2.6×10^{12} G.

The critical luminosity can be expressed as a function of NS parameters as

$$L_{crit} = 1.49 \times 10^{37} \left(\frac{\Lambda}{0.1} \right)^{-7/5} (\omega)^{-28/15} \left(\frac{R}{10^6 cm} \right)^{1/10} \left(\frac{M}{1.4 M_\odot} \right)^{29/30} \left(\frac{B}{10^{12} G} \right)^{16/15} \text{ erg/s} \quad (6.3)$$

where ω depends on the shape of the spectrum and Λ accounts for particular uncertainties in the magnetospheric radius effects (Becker et al. 2012). Following Becker et al. (2012) we take the value of Λ to be 0.1 and ω as 1. Assuming canonical values of NS mass to be $1.4 M_\odot$, NS radius of 10 km, and surface magnetic field strength of 2.6×10^{12} G, the critical luminosity can be calculated as 4×10^{37} erg/s.

Therefore all observations of *Cep X-4* were taken in a sub-critical regime, where shock height is determined by columbic interactions (Becker et al. 2012).

6.5 Summary

The luminosity dependence of *Cep X-4* has evolved over subsequent high-sensitivity observations. Pulse amplitude resolve analysis during the 2014 outburst showed a positive correlation between CRSF energy and X-ray luminosity (Vybornov et al. 2017). However, using data across multiple outbursts, the CRSF line energy showed no variation with X-ray luminosity nor any evolution with time (Mukerjee & Antia 2021). Using *NuSTAR* data from the most recent outburst, we showed that from long-term data also, there is a positive relation between CRSF energy and luminosity. The collisionless shock model well explains the observed variations between L_X and E_{CRSF} . This gives us a surface magnetic field strength of 2.6×10^{12} G.

The positive correlation established from the long-term data is in good agreement with similar results reported from pulse-amplitude resolved analysis (Vybornov et al. 2017). Therefore, for persistent sources that do not show significant long-term variation in flux, a pulse amplitude resolved analysis can be used to study the variation of CRSF with energy as a proxy of the actual variability with luminosity. This is particularly important for sources that have very limited observations with sensitive instruments like *NuSTAR*.

We are not at the end but at the beginning of a new physics. But whatever we find, there will always be new horizons continually awaiting us.

Michio Kaku

7

Conclusions

7.1 Summary of the works

In this thesis, we present four intertwining works, three published (Roy et al. 2024a,c,b) and one accepted for publication, regarding the study of reprocessed X-ray emissions from the binary environment of XRP.

Chapter 3 contains the details of the study of the binary environment of HMXB GX 301-2 using the strong iron fluorescence emission. The time resolved spectroscopy show strong temporal variability of absorption column density indicating the presence of structured wind from the companion star. The ratio of the iron

$K\beta$ and $K\alpha$ emission shows that the ionisation state of the emitting iron atoms evolved with source luminosity. The iron fluorescence energy range shows periodicity with the spin period of the NS and an additional periodicity. We used phase resolved spectroscopy to study the variability of the iron emission line with spin phase. The iron line shows clear periodic variability with both the spin rotation of the NS at 687.9 s and an additional period of 671.8 s. At the secondary period, both the iron line and the continuum have nearly identical pulse fraction and pulse profile, indicating that the origin might be from a small geographical region. The additional periodicity can be attributed to the beat frequency between the spin of the neutron star and the Keplerian frequency of a stellar wind clump in retrograde motion around the neutron star. Reprocessed X-ray emissions originating from the clump can produce the observed secondary pulsations both in the continuum and the iron fluorescence line. The clump rotating around the neutron star is estimated to be approximately five lt-s away from the neutron star.

In chapter 4, we study the broadband spectrum of the transient BeXRB IGR J0607.4+2205. The source was discovered serendipitously with the JEMX instrument onboard INTEGRAL during a Crab observation. During the outburst in the middle of 2023 *NuSTAR* observed the source twice, when it was observed for the first time using pointed observation outside quiescence. Pulsations were detected with a period of ~ 347.6 s in both the observations. The broadband spectrum of the source was modelled using a power-law continuum with a high-energy cutoff. In the first *NuSTAR* observation we discovered a cyclotron line in the source at ~ 51 keV with an optical depth of ~ 1.3 . In the second observation, the pulse profile of the source changed significantly indicating an associated change in the beaming pattern. No CRSF was detected in the second observation. The surface magnetic field of the NS was calculated to be about 4×10^{12} G.

The contents of chapter 5 concerns the study of luminosity variation of the cyclotron lines of 4U 0115+63. The BeXRB 4U 0116+63 was discovered using the *Uhuru* telescope in 1971. Since its discovery it has been observed multiple times with subsequent generation of X-ray telescopes. There were conflicting studies on the luminosity dependence of cyclotron line. A paradigm shift came in the understanding of the cyclotron lines when the continuum model was updated in 4U 0115+63 with higher spectral resolution data and two fundamental cyclotron lines were discovered. We combine all archival data including the recent outburst of 4U 0115+63 and fit the updated spectral model to study the cyclotron line variation with energy. The CRSF line centre shows no anti-correlation with luminosity, unlike previously reported. Instead, a weak positive correlation is found in four out of the five detected cyclotron lines of 4U 0115+63. The luminosity variation of the two fundamental CRSFs could be well explained with the prediction from the collisionless shock model. A tentative negative correlation was observed in the fundamental CRSF at 16 keV and its harmonics beyond a “critical luminosity” of 10^{38} erg/s. This behaviour was not present for the 12 keV fundamental CRSF and its harmonic at 24 keV.

Chapter 6 concerns the study of magnetic fields in Cep X-4 using the cyclotron line. The variation of CRSF show different trends of cyclotron line energy with spin-amplitude of NS, luminosity and time. Even though the cyclotron line show increasing trend with NS pulse amplitude but shows no significant variation with time or the source luminosity from individual observations. However, the study of CRSF energy with luminosity was only carried out over a shall range in luminosity. We therefore take advantage of a low luminosity observation of Cep X-4 with *NuSTAR* to extend the luminosity variability study. A CRSF feature at an energy of ~ 27 keV was observed in the source at a low luminosity level indicating

the presence of a positive correlation as previously observed with pulse amplitude resolved study. Therefore, for persistent sources that do not show significant long-term variation in flux, a pulse amplitude resolved analysis can be used to study the variation of CRSF with energy as a proxy of the actual variability with luminosity.

7.2 Future Works

The capabilities of *XMM-Newton* provide a unique opportunity to study the iron fluorescence emission from bright HMXBs. We used multiple timing and spectra analysis tools in the analysis of an *XMM-Newton* observation of the source with the brightest iron fluorescence $K\alpha$ emission, the results of which are described in Chapter 3. In future we would like to carry out a similar analysis in other bright HMXBs like Cen X-3 and Vela X-1 as well as bright LMXBs like Her X-1.

References

Araya-Góchez, R. A., & Harding, A. K. 2000, Cyclotron-Line Features from Near-critical Fields. II. On the Effect of Anisotropic Radiation Fields, *The Astrophysical Journal*, 544, 1067, doi: [10.1086/317224](https://doi.org/10.1086/317224)

Arnaud, K. A. 1996, in *Astronomical Society of the Pacific Conference Series*, Vol. 101, *Astronomical Data Analysis Software and Systems V*, ed. G. H. Jacoby & J. Barnes, 17

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., & Andrae, R. 2021, Estimating Distances from Parallaxes. V. Geometric and Photogeometric Distances to 1.47 Billion Stars in Gaia Early Data Release 3, *The Astronomical Journal*, 161, 147, doi: [10.3847/1538-3881/abd806](https://doi.org/10.3847/1538-3881/abd806)

Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005, The Burst Alert Telescope (BAT) on the SWIFT Midex Mission, *Space Science Reviews*, 120, 143, doi: [10.1007/s11214-005-5096-3](https://doi.org/10.1007/s11214-005-5096-3)

Becker, P. A., & Wolff, M. T. 2007, Thermal and Bulk Comptonization in Accretion-powered X-Ray Pulsars, *The Astrophysical Journal*, 654, 435, doi: [10.1086/509108](https://doi.org/10.1086/509108)

Becker, P. A., Klochkov, D., Schönherr, G., et al. 2012, Spectral formation in accreting X-ray pulsars: bimodal variation of the cyclotron energy with luminosity, *Astronomy & Astrophysics*, 544, A123, doi: [10.1051/0004-6361/201219065](https://doi.org/10.1051/0004-6361/201219065)

Beri, A., & Paul, B. 2017, Post-flare formation of the accretion stream and a dip in pulse profiles of LMC X-4, *Nature Astronomy*, 56, 94, doi: [10.1016/j.newast.2017.05.001](https://doi.org/10.1016/j.newast.2017.05.001)

Beri, A., Paul, B., & Dewangan, G. C. 2015, Pulse-phase dependence of emission lines in the X-ray pulsar 4U 1626-67, *Monthly Notices of the Royal Astronomical Society*, 451, 508, doi: [10.1093/mnras/stv922](https://doi.org/10.1093/mnras/stv922)

Bhargava, Y., Bhalerao, V., Ballhausen, R., et al. 2019, Explaining the asymmetric line profile in Cepheus X-4 with spectral variation across pulse phase, *Monthly Notices of the Royal Astronomical Society*, 482, 2902, doi: [10.1093/mnras/sty2823](https://doi.org/10.1093/mnras/sty2823)

- Boldin, P. A., Tsygankov, S. S., & Lutovinov, A. A. 2013, On timing and spectral characteristics of the X-ray pulsar 4U 0115+63: Evolution of the pulsation period and the cyclotron line energy, *Astronomy Letters*, 39, 375, doi: [10.1134/S1063773713060029](https://doi.org/10.1134/S1063773713060029)
- Burderi, L., Di Salvo, T., Robba, N. R., La Barbera, A., & Guainazzi, M. 2000a, The 0.1-100 KEV Spectrum of Centaurus X-3: Pulse Phase Spectroscopy of the Cyclotron Line and Magnetic Field Structure, *The Astrophysical Journal*, 530, 429, doi: [10.1086/308336](https://doi.org/10.1086/308336)
- Burderi, L., Di Salvo, T., Robba, N. R., La Barbera, A., & Guainazzi, M. 2000b, The 0.1-100 KEV Spectrum of Centaurus X-3: Pulse Phase Spectroscopy of the Cyclotron Line and Magnetic Field Structure, *The Astrophysical Journal*, 530, 429, doi: [10.1086/308336](https://doi.org/10.1086/308336)
- Bykov, S. D., Filippova, E. V., Gilfanov, M. R., et al. 2021, Pulsating iron spectral features in the emission of X-ray pulsar V 0332+53, *Monthly Notices of the Royal Astronomical Society*, 506, 2156, doi: [10.1093/mnras/stab1852](https://doi.org/10.1093/mnras/stab1852)
- Caballero, I., Santangelo, A., Kretschmar, P., et al. 2008, The pre-outburst flare of the A 0535+26 August/September 2005 outburst, *Astronomy & Astrophysics*, 480, L17, doi: [10.1051/0004-6361:20079310](https://doi.org/10.1051/0004-6361:20079310)
- Chenevez, J., Budtz-Jorgensen, C., Lund, N., et al. 2004, IGR J06074+2205 a new X-ray source discovered by INTEGRAL, *The Astronomer's Telegram*, 223, 1
- Choi, C. S., Nagase, F., Makino, F., et al. 1994, Iron Line Intensity Variations of Hercules X-1 over the Pulse Phase and the 35 Day Cycle, *The Astrophysical Journal*, 437, 449, doi: [10.1086/175008](https://doi.org/10.1086/175008)
- Cominsky, L., Clark, G. W., Li, F., Mayer, W., & Rappaport, S. 1978, Discovery of 3.6-s X-ray pulsations from 4U0115+63, *Nature*, 273, 367, doi: [10.1038/273367a0](https://doi.org/10.1038/273367a0)
- Cusumano, G., di Salvo, T., Burderi, L., et al. 1998, Detection of a cyclotron line and its second harmonic in 4U1907+09, *Astronomy & Astrophysics*, 338, L79, doi: [10.48550/arXiv.astro-ph/9809167](https://doi.org/10.48550/arXiv.astro-ph/9809167)
- Day, C. S. R., Nagase, F., Asai, K., & Takeshima, T. 1993, The Discovery of Pulsed Iron Line Emission from Centaurus X-3, *The Astrophysical Journal*, 408, 656, doi: [10.1086/172625](https://doi.org/10.1086/172625)
- DeCesar, M. E., Boyd, P. T., Pottschmidt, K., et al. 2013, The Be/X-Ray Binary Swift J1626.6-5156 as a Variable Cyclotron Line Source, *The Astrophysical Journal*, 762, 61, doi: [10.1088/0004-637x/762/1/61](https://doi.org/10.1088/0004-637x/762/1/61)
- den Herder, J. W., Brinkman, A. C., Kahn, S. M., et al. 2001, The Reflection Grating Spectrometer on board XMM-Newton, *Astronomy & Astrophysics*, 365, L7, doi: [10.1051/0004-6361:20000058](https://doi.org/10.1051/0004-6361:20000058)

Devaraj, A., & Paul, B. 2022, NuSTAR discovery of a cyclotron line in GRO J1750-27, *Monthly Notices of the Royal Astronomical Society*, 514, L46, doi: [10.1093/mnrasl/slac052](https://doi.org/10.1093/mnrasl/slac052)

Devaraj, A., Sharma, R., Nagesh, S., & Paul, B. 2024, Insights into the phase-dependent cyclotron line feature in XTE J1946+274: an AstroSat and Insight-HXMT view, *Monthly Notices of the Royal Astronomical Society*, 527, 11015, doi: [10.1093/mnras/stad3886](https://doi.org/10.1093/mnras/stad3886)

Doroshenko, V., Santangelo, A., Suleimanov, V., et al. 2010, Is there a highly magnetized neutron star in GX 301-2?, *Astronomy & Astrophysics*, 515, A10, doi: [10.1051/0004-6361/200912951](https://doi.org/10.1051/0004-6361/200912951)

Doroshenko, V., Tsygankov, S. S., Mushtukov, A. A., et al. 2017, Luminosity dependence of the cyclotron line and evidence for the accretion regime transition in V 0332+53, *Monthly Notices of the Royal Astronomical Society*, 466, 2143, doi: [10.1093/mnras/stw3236](https://doi.org/10.1093/mnras/stw3236)

Endo, T., Ishida, M., Masai, K., et al. 2002, Broadening of Nearly Neutral Iron Emission Line of GX 301-2 Observed with ASCA, *The Astrophysical Journal*, 574, 879, doi: [10.1086/341060](https://doi.org/10.1086/341060)

Ferrigno, C., Becker, P. A., Segreto, A., Mineo, T., & Santangelo, A. 2009, Study of the accreting pulsar 4U 0115+63 using a bulk and thermal Comptonization model, *Astronomy & Astrophysics*, 498, 825, doi: [10.1051/0004-6361/200809373](https://doi.org/10.1051/0004-6361/200809373)

Ferrigno, C., Bozzo, E., & Romano, P. 2022, XMM-Newton and Swift observations of supergiant high mass X-ray binaries, *Astronomy & Astrophysics*, 664, A99, doi: [10.1051/0004-6361/202243294](https://doi.org/10.1051/0004-6361/202243294)

Frank, J., King, A., & Raine, D. 1992, *Accretion power in astrophysics*, Vol. 21

Fürst, F., Kreykenbohm, I., Pottschmidt, K., et al. 2010, X-ray variation statistics and wind clumping in Vela X-1, *Astronomy & Astrophysics*, 519, A37, doi: [10.1051/0004-6361/200913981](https://doi.org/10.1051/0004-6361/200913981)

Fürst, F., Suchy, S., Kreykenbohm, I., et al. 2011, Study of the many fluorescent lines and the absorption variability in GX 301-2 with XMM-Newton, *Astronomy & Astrophysics*, 535, A9, doi: [10.1051/0004-6361/201117665](https://doi.org/10.1051/0004-6361/201117665)

Fürst, F., Pottschmidt, K., Wilms, J., et al. 2014, NuSTAR Discovery of a Luminosity Dependent Cyclotron Line Energy in Vela X-1, *The Astrophysical Journal*, 780, 133, doi: [10.1088/0004-637x/780/2/133](https://doi.org/10.1088/0004-637x/780/2/133)

Fürst, F., Pottschmidt, K., Miyasaka, H., et al. 2015, Distorted Cyclotron Line Profile in Cep X-4 as Observed by NuSTAR, *The Astrophysical Journal Letters*, 806, L24, doi: [10.1088/2041-8205/806/2/L24](https://doi.org/10.1088/2041-8205/806/2/L24)

- Fürst, F., Falkner, S., Marcu-Cheatham, D., et al. 2018, Multiple cyclotron line-forming regions in GX 301-2, *Astronomy & Astrophysics*, 620, A153, doi: [10.1051/0004-6361/201732132](https://doi.org/10.1051/0004-6361/201732132)
- Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2023, Gaia Data Release 3. Summary of the content and survey properties, *Astronomy & Astrophysics*, 674, A1, doi: [10.1051/0004-6361/202243940](https://doi.org/10.1051/0004-6361/202243940)
- Giacconi, R., Murray, S., Gursky, H., et al. 1972, The Uhuru catalog of X-ray sources., *The Astrophysical Journal*, 178, 281, doi: [10.1086/151790](https://doi.org/10.1086/151790)
- Giménez-García, A., Torrejón, J. M., Eikmann, W., et al. 2015, An XMM-Newton view of FeK α in high-mass X-ray binaries, *Astronomy & Astrophysics*, 576, A108, doi: [10.1051/0004-6361/201425004](https://doi.org/10.1051/0004-6361/201425004)
- Haberl, F. 1991, The X-Ray Properties of GX 301-2 (4U 1223-62), *The Astrophysical Journal*, 376, 245, doi: [10.1086/170273](https://doi.org/10.1086/170273)
- Harding, A. K., & Daugherty, J. K. 1991, Cyclotron Resonant Scattering and Absorption, *The Astrophysical Journal*, 374, 687, doi: [10.1086/170153](https://doi.org/10.1086/170153)
- Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, The Nuclear Spectroscopic Telescope Array (NuSTAR) High-energy X-Ray Mission, *The Astrophysical Journal*, 770, 103, doi: [10.1088/0004-637x/770/2/103](https://doi.org/10.1088/0004-637x/770/2/103)
- Heindl, W. A., Coburn, W., Gruber, D. E., et al. 1999, Discovery of a Third Harmonic Cyclotron Resonance Scattering Feature in the X-Ray Spectrum of 4U 0115+63, *The Astrophysical Journal Letters*, 521, L49, doi: [10.1086/312172](https://doi.org/10.1086/312172)
- HI4PI Collaboration, Ben Bekhti, N., Flöer, L., et al. 2016, HI4PI: A full-sky H I survey based on EBHIS and GASS, *Astronomy & Astrophysics*, 594, A116, doi: [10.1051/0004-6361/201629178](https://doi.org/10.1051/0004-6361/201629178)
- Inoue, H. 1985, TENMA Observations of Bright Binary X-Ray Sources, *Space Science Reviews*, 40, 317, doi: [10.1007/BF00212905](https://doi.org/10.1007/BF00212905)
- Islam, N., & Paul, B. 2014, Orbital phase resolved spectroscopy of GX 301-2 with MAXI, *Monthly Notices of the Royal Astronomical Society*, 441, 2539, doi: [10.1093/mnras/stu756](https://doi.org/10.1093/mnras/stu756)
- Iyer, N., Mukherjee, D., Dewangan, G. C., Bhattacharya, D., & Seetha, S. 2015, Variations in the cyclotron resonant scattering features during 2011 outburst of 4U 0115+63, *Monthly Notices of the Royal Astronomical Society*, 454, 741, doi: [10.1093/mnras/stv1942](https://doi.org/10.1093/mnras/stv1942)
- Jansen, F., Lumb, D., Altieri, B., et al. 2001, XMM-Newton observatory. I. The spacecraft and operations, *Astronomy & Astrophysics*, 365, L1, doi: [10.1051/0004-6361:20000036](https://doi.org/10.1051/0004-6361:20000036)

- Johns, M., Koski, A., Canizares, C., et al. 1978, 4U 0115+63, , 3171, 1
- Kaastra, J. S., & Bleeker, J. A. M. 2016, Optimal binning of X-ray spectra and response matrix design, *Astronomy & Astrophysics*, 587, A151, doi: [10.1051/0004-6361/201527395](https://doi.org/10.1051/0004-6361/201527395)
- Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, The Leiden/Argentine/Bonn (LAB) Survey of Galactic HI. Final data release of the combined LDS and IAR surveys with improved stray-radiation corrections, *Astronomy & Astrophysics*, 440, 775, doi: [10.1051/0004-6361:20041864](https://doi.org/10.1051/0004-6361:20041864)
- Kaper, L., van der Meer, A., & Najarro, F. 2006, VLT/UVES spectroscopy of Wray 977, the hypergiant companion to the X-ray pulsar <ASTROBJ>GX301-2</ASTROBJ>, *Astronomy & Astrophysics*, 457, 595, doi: [10.1051/0004-6361:20065393](https://doi.org/10.1051/0004-6361:20065393)
- Kendziorra, E., Mony, B., Kretschmar, P., et al. 1992, in *NASA Conference Publication*, Vol. 3137, NASA Conference Publication, 217
- Koh, D. T., Bildsten, L., Chakrabarty, D., et al. 1997, Rapid Spin-Up Episodes in the Wind-fed Accreting Pulsar GX 301-2, *The Astrophysical Journal*, 479, 933, doi: [10.1086/303929](https://doi.org/10.1086/303929)
- Kong, L. D., Zhang, S., Ji, L., et al. 2021, Luminosity Dependence of the Cyclotron Line Energy in 1A 0535+262 Observed by Insight-HXMT during the 2020 Giant Outburst, *The Astrophysical Journal Letters*, 917, L38, doi: [10.3847/2041-8213/ac1ad3](https://doi.org/10.3847/2041-8213/ac1ad3)
- Koyama, K., Kawada, M., Tawara, Y., et al. 1991, A New X-Ray Pulsar GS 2138+56 (Cepheus X-4), *The Astrophysical Journal Letters*, 366, L19, doi: [10.1086/185900](https://doi.org/10.1086/185900)
- Kretschmar, P., Pan, H. C., Kendziorra, E., et al. 1996, Absorption features in the hard X-ray spectra of PSR A 0535+26 and VELA X-1., , 120, 175
- Kreykenbohm, I., Coburn, W., Wilms, J., et al. 2002, Confirmation of two cyclotron lines in Vela X-1, *Astronomy & Astrophysics*, 395, 129, doi: [10.1051/0004-6361:20021181](https://doi.org/10.1051/0004-6361:20021181)
- Kreykenbohm, I., Wilms, J., Kretschmar, P., et al. 2008, High variability in Vela X-1: giant flares and off states, *Astronomy & Astrophysics*, 492, 511, doi: [10.1051/0004-6361:200809956](https://doi.org/10.1051/0004-6361:200809956)
- Krimm, H. A., Barthelmy, S. D., Markwardt, C. B., et al. 2006, in *AAS/High Energy Astrophysics Division*, Vol. 9, AAS/High Energy Astrophysics Division #9, 13.47
- La Parola, V., Cusumano, G., Segreto, A., & D'Ai, A. 2016, The Swift-BAT monitoring reveals a long-term decay of the cyclotron line energy in Vela X-1, *Monthly Notices of the Royal Astronomical Society*, 463, 185, doi: [10.1093/mnras/stw1915](https://doi.org/10.1093/mnras/stw1915)

Leahy, D. A. 1987, Searches for pulsed emission - Improved determination of period and amplitude from epoch folding for sinusoidal signals, *Astronomy & Astrophysics*, 180, 275

Leahy, D. A., & Kostka, M. 2008, Stellar wind accretion in GX 301-2: evidence for a high-density stream, *Monthly Notices of the Royal Astronomical Society*, 384, 747, doi: [10.1111/j.1365-2966.2007.12754.x](https://doi.org/10.1111/j.1365-2966.2007.12754.x)

Levine, A., Rappaport, S., Putney, A., Corbet, R., & Nagase, F. 1991, LMC X-4: GINGA Observations and Search for Orbital Period Changes, *The Astrophysical Journal*, 381, 101, doi: [10.1086/170632](https://doi.org/10.1086/170632)

Levine, A. M., Bradt, H., Cui, W., et al. 1996, First Results from the All-Sky Monitor on the Rossi X-Ray Timing Explorer, *The Astrophysical Journal Letters*, 469, L33, doi: [10.1086/310260](https://doi.org/10.1086/310260)

Liu, B.-S., Tao, L., Zhang, S.-N., et al. 2020, A Peculiar Cyclotron Line near 16 keV Detected in the 2015 Outburst of 4U 0115+63?, *The Astrophysical Journal*, 900, 41, doi: [10.3847/1538-4357/aba4a5](https://doi.org/10.3847/1538-4357/aba4a5)

Liu, J., Soria, R., Qiao, E., & Liu, J. 2018, Discovery of a pulsating Fe K α line in GX 301-2, *Monthly Notices of the Royal Astronomical Society*, 480, 4746, doi: [10.1093/mnras/sty2180](https://doi.org/10.1093/mnras/sty2180)

Lutovinov, A., Tsygankov, S., & Chernyakova, M. 2012, Strong outburst activity of the X-ray pulsar X Persei during 2001-2011, *Monthly Notices of the Royal Astronomical Society*, 423, 1978, doi: [10.1111/j.1365-2966.2012.21036.x](https://doi.org/10.1111/j.1365-2966.2012.21036.x)

Lutovinov, A., Tsygankov, S., Molkov, S., et al. 2021, SRG/ART-XC and NuSTAR Observations of the X-Ray pulsar GRO J1008-57 in the Lowest Luminosity State, *The Astrophysical Journal*, 912, 17, doi: [10.3847/1538-4357/abec43](https://doi.org/10.3847/1538-4357/abec43)

Lutovinov, A. A., Tsygankov, S. S., Suleimanov, V. F., et al. 2015, Transient X-ray pulsar V 0332+53: pulse-phase-resolved spectroscopy and the reflection model, *Monthly Notices of the Royal Astronomical Society*, 448, 2175, doi: [10.1093/mnras/stv125](https://doi.org/10.1093/mnras/stv125)

Madsen, K. K., Harrison, F. A., Markwardt, C. B., et al. 2015, Calibration of the NuSTAR High-energy Focusing X-ray Telescope., *The Astrophysical Journal Supplement Series*, 220, 8, doi: [10.1088/0067-0049/220/1/8](https://doi.org/10.1088/0067-0049/220/1/8)

Maitra, C., & Paul, B. 2013, Pulse-phase-resolved Spectroscopy of Vela X-1 with Suzaku, *The Astrophysical Journal*, 763, 79, doi: [10.1088/0004-637x/763/2/79](https://doi.org/10.1088/0004-637x/763/2/79)

Makino, F., & GINGA Team. 1988, X-Ray Outburst, , 4575, 1

- Makishima, K., Mihara, T., Nagase, F., & Tanaka, Y. 1999, Cyclotron Resonance Effects in Two Binary X-Ray Pulsars and the Evolution of Neutron Star Magnetic Fields, *The Astrophysical Journal*, 525, 978, doi: [10.1086/307912](https://doi.org/10.1086/307912)
- Makishima, K., Mihara, T., Ishida, M., et al. 1990, Discovery of a Prominent Cyclotron Absorption Feature from the Transient X-Ray Pulsar X0331+53, *The Astrophysical Journal Letters*, 365, L59, doi: [10.1086/185888](https://doi.org/10.1086/185888)
- Malacaria, C., Jenke, P., Roberts, O. J., et al. 2020, The Ups and Downs of Accreting X-Ray Pulsars: Decade-long Observations with the Fermi Gamma-Ray Burst Monitor, *The Astrophysical Journal*, 896, 90, doi: [10.3847/1538-4357/ab855c](https://doi.org/10.3847/1538-4357/ab855c)
- Malacaria, C., Jenke, P., & Wilson-Hodge, C. A. 2023, Fermi-GBM detection of the Be/X-ray Binary IGR J06074+2205, *The Astronomer's Telegram*, 16307, 1
- Malacaria, C., Klochkov, D., Santangelo, A., & Staubert, R. 2015, Luminosity-dependent spectral and timing properties of the accreting pulsar GX 304-1 measured with INTEGRAL, *Astronomy & Astrophysics*, 581, A121, doi: [10.1051/0004-6361/201526417](https://doi.org/10.1051/0004-6361/201526417)
- Malacaria, C., Bhargava, Y., Coley, J. B., et al. 2022, Accreting on the Edge: A Luminosity-dependent Cyclotron Line in the Be/X-Ray Binary 2S 1553-542 Accompanied by Accretion Regimes Transition, *The Astrophysical Journal*, 927, 194, doi: [10.3847/1538-4357/ac524f](https://doi.org/10.3847/1538-4357/ac524f)
- Mandal, M., Sharma, R., Pal, S., et al. 2023, Probing spectral and timing properties of the X-ray pulsar RX J0440.9 + 4431 in the giant outburst of 2022-2023, *Monthly Notices of the Royal Astronomical Society*, 526, 771, doi: [10.1093/mnras/stad2767](https://doi.org/10.1093/mnras/stad2767)
- Manikantan, H., Kumar, M., Paul, B., & Rana, V. 2023a, Investigating the orbital evolution of the eccentric HMXB GX 301-2 using long-term X-ray lightcurves, *Monthly Notices of the Royal Astronomical Society*, doi: [10.1093/mnras/stad3090](https://doi.org/10.1093/mnras/stad3090)
- Manikantan, H., Paul, B., Roy, K., & Rana, V. 2023b, Changes in the distribution of circum-binary material around the HMXB GX 301-2 during a rapid spin-up episode of the neutron star, *Monthly Notices of the Royal Astronomical Society*, 520, 1411, doi: [10.1093/mnras/stad037](https://doi.org/10.1093/mnras/stad037)
- Martínez-Núñez, S., Torrejón, J. M., Kühnel, M., et al. 2014, The accretion environment in Vela X-1 during a flaring period using XMM-Newton, *Astronomy & Astrophysics*, 563, A70, doi: [10.1051/0004-6361/201322404](https://doi.org/10.1051/0004-6361/201322404)
- Martínez-Núñez, S., Kretschmar, P., Bozzo, E., et al. 2017, Towards a Unified View of Inhomogeneous Stellar Winds in Isolated Supergiant Stars and Supergiant High Mass X-Ray Binaries, *Space Science Reviews*, 212, 59, doi: [10.1007/s11214-017-0340-1](https://doi.org/10.1007/s11214-017-0340-1)

- Mason, K. O., Breeveld, A., Much, R., et al. 2001, The XMM-Newton optical/UV monitor telescope, *Astronomy & Astrophysics*, 365, L36, doi: [10.1051/0004-6361:20000044](https://doi.org/10.1051/0004-6361:20000044)
- Matsumoto, H., Nakajima, H., Yamaguchi, H., et al. 2006, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 6266, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. M. J. L. Turner & G. Hasinger, 626641, doi: [10.1117/12.671033](https://doi.org/10.1117/12.671033)
- Matsuoka, M., Kawasaki, K., Ueno, S., et al. 2009, The MAXI Mission on the ISS: Science and Instruments for Monitoring All-Sky X-Ray Images, *Publications of the Astronomical Society of Japan*, 61, 999, doi: [10.1093/pasj/61.5.999](https://doi.org/10.1093/pasj/61.5.999)
- McBride, V. A., Wilms, J., Kreykenbohm, I., et al. 2007, On the cyclotron line in Cepheus X-4, *Astronomy & Astrophysics*, 470, 1065, doi: [10.1051/0004-6361:20077238](https://doi.org/10.1051/0004-6361:20077238)
- McClintock, J. E., Ricker, G. R., & Lewin, W. H. G. 1971, Rapid Fluctuations in the High-Energy X-Ray Flux from a Source in Crux, *The Astrophysical Journal Letters*, 166, L73, doi: [10.1086/180742](https://doi.org/10.1086/180742)
- Meszaros, P. 1992, High-energy radiation from magnetized neutron stars
- Mihara, T. 1995, PhD thesis, University of Tokyo, Japan
- Mihara, T., Makishima, K., Kamijo, S., et al. 1991, Discovery of a Cyclotron Resonance Feature at 30 keV from the Transient X-Ray Pulsar Cepheus X-4, *The Astrophysical Journal Letters*, 379, L61, doi: [10.1086/186154](https://doi.org/10.1086/186154)
- Mihara, T., Makishima, K., & Nagase, F. 1998, Cyclotron line variability, *Advances in Space Research*, 22, 987, doi: [10.1016/s0273-1177\(98\)00128-8](https://doi.org/10.1016/s0273-1177(98)00128-8)
- Mihara, T., Nakajima, M., Sugizaki, M., et al. 2011, Gas Slit Camera (GSC) onboard MAXI on ISS, *Publications of the Astronomical Society of Japan*, 63, S623, doi: [10.1093/pasj/63.sp3.s623](https://doi.org/10.1093/pasj/63.sp3.s623)
- Mihara, T., Nakajima, M., Negoro, H., et al. 2023, MAXI/GSC observations of weak X-ray outbursts from the Be/X-ray binary pulsar IGR J06074+2205 and the possible binary orbital period, *The Astronomer's Telegram*, 16351, 1
- Miškovičová, I., Hanke, M., Wilms, J., et al. 2011, Spectroscopy of the Stellar Wind in the Cygnus X-1 System, *Acta Polytechnica*, 51, 85, doi: [10.48550/arXiv.1103.2711](https://doi.org/10.48550/arXiv.1103.2711)
- Mönkkönen, J., Doroshenko, V., Tsygankov, S. S., et al. 2020, Discovery of a retrogradely rotating neutron star in the X-ray pulsar GX 301-2, *Monthly Notices of the Royal Astronomical Society*, 494, 2178, doi: [10.1093/mnras/staa906](https://doi.org/10.1093/mnras/staa906)

- Moon, D.-S., Eikenberry, S. S., & Wasserman, I. M. 2003, SMC X-1 as an Intermediate-Stage Flaring X-Ray Pulsar, *The Astrophysical Journal Letters*, 582, L91, doi: [10.1086/367782](https://doi.org/10.1086/367782)
- Mukerjee, K., & Antia, H. M. 2021, Studies of Cepheus X-4 during the 2018 Outburst Observed with AstroSat, *The Astrophysical Journal*, 920, 139, doi: [10.3847/1538-4357/ac11f1](https://doi.org/10.3847/1538-4357/ac11f1)
- Mukherjee, U., & Paul, B. 2004, Orbital phase spectroscopy of GX 301-2 with RXTE-PCA, *Astronomy & Astrophysics*, 427, 567, doi: [10.1051/0004-6361:20034407](https://doi.org/10.1051/0004-6361:20034407)
- Müller, D., Klochkov, D., Caballero, I., & Santangelo, A. 2013a, A 0535+26 in the April 2010 outburst: probing the accretion regime at work, *Astronomy & Astrophysics*, 552, A81, doi: [10.1051/0004-6361/201220347](https://doi.org/10.1051/0004-6361/201220347)
- Müller, S., Ferrigno, C., Kühnel, M., et al. 2013b, No anticorrelation between cyclotron line energy and X-ray flux in 4U 0115+634, *Astronomy & Astrophysics*, 551, A6, doi: [10.1051/0004-6361/201220359](https://doi.org/10.1051/0004-6361/201220359)
- Mushtukov, A. A., Suleimanov, V. F., Tsygankov, S. S., & Portegies Zwart, S. 2021, Spectrum formation in X-ray pulsars at very low mass accretion rate: Monte Carlo approach, *Monthly Notices of the Royal Astronomical Society*, 503, 5193, doi: [10.1093/mnras/stab811](https://doi.org/10.1093/mnras/stab811)
- Nagase, F., Corbet, R. H. D., Day, C. S. R., et al. 1992, GINGA Observations of Centaurus X-3, *The Astrophysical Journal*, 396, 147, doi: [10.1086/171705](https://doi.org/10.1086/171705)
- Nakajima, M., Mihara, T., Makishima, K., & Niko, H. 2006, A Further Study of the Luminosity-dependent Cyclotron Resonance Energies of the Binary X-Ray Pulsar 4U 0115+63 with the Rossi X-Ray Timing Explorer, *The Astrophysical Journal*, 646, 1125, doi: [10.1086/502638](https://doi.org/10.1086/502638)
- Nakajima, M., Negoro, H., Iwakiri, W., et al. 2023a, MAXI/GSC observation of brightest outburst of the Be/X-ray binary pulsar 4U 0115+63 in 27 years, *The Astronomer's Telegram*, 15975, 1
- Nakajima, M., Niida, Y., Mihara, T., et al. 2023b, MAXI/GSC detection of an X-ray outburst from the Be/X-ray binary pulsar Cep X-4 (Ginga 2138+56), *The Astronomer's Telegram*, 16088, 1
- Negueruela, I., & Okazaki, A. T. 2001, The Be/X-ray transient 4U 0115+63/V635 Cassiopeiae. I. A consistent model, *Astronomy & Astrophysics*, 369, 108, doi: [10.1051/0004-6361:20010146](https://doi.org/10.1051/0004-6361:20010146)
- Palmeri, P., Mendoza, C., Kallman, T. R., Bautista, M. A., & Meléndez, M. 2003, Modeling of iron K lines: Radiative and Auger decay data for Fe II-Fe IX, *Astronomy & Astrophysics*, 410, 359, doi: [10.1051/0004-6361:20031262](https://doi.org/10.1051/0004-6361:20031262)

- Parmar, A. N., White, N. E., & Stella, L. 1989, The Transient 42 Second X-Ray Pulsar EXO 2030+375. II. The Luminosity Dependence of the Pulse Profile, *The Astrophysical Journal*, 338, 373, doi: [10.1086/167205](https://doi.org/10.1086/167205)
- Paul, B. 2017, Neutron Stars in X-ray Binaries and their Environments, *Journal of Astrophysics and Astronomy*, 38, 39, doi: [10.1007/s12036-017-9475-4](https://doi.org/10.1007/s12036-017-9475-4)
- Pradhan, P., Bozzo, E., & Paul, B. 2018, Supergiant fast X-ray transients versus classical supergiant high mass X-ray binaries: Does the difference lie in the companion wind?, *Astronomy & Astrophysics*, 610, A50, doi: [10.1051/0004-6361/201731487](https://doi.org/10.1051/0004-6361/201731487)
- Pradhan, P., Bozzo, E., Paul, B., Manousakis, A., & Ferrigno, C. 2019, Probing Clumpy Wind Accretion in IGR J18027-2016 with XMM-Newton, *The Astrophysical Journal*, 883, 116, doi: [10.3847/1538-4357/ab3a40](https://doi.org/10.3847/1538-4357/ab3a40)
- Pradhan, P., Maitra, C., Paul, B., Islam, N., & Paul, B. C. 2014, Variations in the pulsation and spectral characteristics of OAO 1657-415, *Monthly Notices of the Royal Astronomical Society*, 442, 2691, doi: [10.1093/mnras/stu1034](https://doi.org/10.1093/mnras/stu1034)
- Pradhan, P., Ferrigno, C., Paul, B., et al. 2023, Clumpy Wind Studies and the Non-detection of a Cyclotron Line in OAO 1657-415, *The Astrophysical Journal*, 945, 51, doi: [10.3847/1538-4357/acb2cb](https://doi.org/10.3847/1538-4357/acb2cb)
- Pravdo, S. H., & Ghosh, P. 2001, An Orbital Light-Curve Model for GX 301-2, *The Astrophysical Journal*, 554, 383, doi: [10.1086/321350](https://doi.org/10.1086/321350)
- Pringle, J. E., & Rees, M. J. 1972, Accretion Disc Models for Compact X-Ray Sources, *Astronomy & Astrophysics*, 21, 1
- Raman, G., Varun, Pradhan, P., & Kennea, J. 2023, Quiet, but not silent: uncovering quiescent state properties of two transient high-mass X-ray binaries, *Monthly Notices of the Royal Astronomical Society*, 526, 3262, doi: [10.1093/mnras/stad2577](https://doi.org/10.1093/mnras/stad2577)
- Rappaport, S., Clark, G. W., Cominsky, L., Joss, P. C., & Li, F. 1978, Orbital elements of 4U 0115+63 and the nature of the hard X-ray transients., *The Astrophysical Journal Letters*, 224, L1, doi: [10.1086/182745](https://doi.org/10.1086/182745)
- Read, A. M., & Ponman, T. J. 2003, The XMM-Newton EPIC background: Production of background maps and event files, *Astronomy & Astrophysics*, 409, 395, doi: [10.1051/0004-6361:20031099](https://doi.org/10.1051/0004-6361:20031099)
- Reig, P., & Nespoli, E. 2013, Patterns of variability in Be/X-ray pulsars during giant outbursts, *Astronomy & Astrophysics*, 551, A1, doi: [10.1051/0004-6361/201219806](https://doi.org/10.1051/0004-6361/201219806)

Reig, P., & Zezas, A. 2018, Discovery of X-ray pulsations in the Be/X-ray binary IGR J06074+2205, *Astronomy & Astrophysics*, 613, A52, doi: [10.1051/0004-6361/201732533](https://doi.org/10.1051/0004-6361/201732533)

Reig, P., Zezas, A., & Gkouvelis, L. 2010, The optical counterpart to IGR J06074+2205: a Be/X-ray binary showing disc loss and V/R variability, *Astronomy & Astrophysics*, 522, A107, doi: [10.1051/0004-6361/201014788](https://doi.org/10.1051/0004-6361/201014788)

Roche, P., Green, L., & Hoenig, M. 1997, *Cepheus X-4*, , 6698, 2

Rothschild, R. E., & Soong, Y. 1987, Two Binary Cycles of GX 301-2, *The Astrophysical Journal*, 315, 154, doi: [10.1086/165121](https://doi.org/10.1086/165121)

Rothschild, R. E., Kühnel, M., Pottschmidt, K., et al. 2017, Discovery and modelling of a flattening of the positive cyclotron line/luminosity relation in GX 304-1 with RXTE, *Monthly Notices of the Royal Astronomical Society*, 466, 2752, doi: [10.1093/mnras/stw3222](https://doi.org/10.1093/mnras/stw3222)

Roy, K., Manikantan, H., & Paul, B. 2024a, Studying the variability of fluorescence emission and the presence of clumpy wind in HMXB GX 301-2 using XMM-Newton, *Monthly Notices of the Royal Astronomical Society*, 527, 2652, doi: [10.1093/mnras/stad3395](https://doi.org/10.1093/mnras/stad3395)

Roy, K., Manikantan, H., & Paul, B. 2024b, Luminosity dependence of the multiple cyclotron lines in 4U 0115+63, *Astronomy & Astrophysics*, 690, A50, doi: [10.1051/0004-6361/202450395](https://doi.org/10.1051/0004-6361/202450395)

Roy, K., Sharma, R., Manikantan, H., & Paul, B. 2024c, Detection of a cyclotron line in the Be X-ray pulsar IGR J06074+2205, *Astronomy & Astrophysics*, 686, A145, doi: [10.1051/0004-6361/202348998](https://doi.org/10.1051/0004-6361/202348998)

Sako, M., Kahn, S. M., Paerels, F., et al. 2003, Structure and Dynamics of Stellar Winds in High-mass X-ray Binaries, *arXiv e-prints*, astro, doi: [10.48550/arXiv.astro-ph/0309503](https://doi.org/10.48550/arXiv.astro-ph/0309503)

Santangelo, A., del Sordo, S., Segreto, A., et al. 1998, BeppoSAX detection of a Cyclotron Feature in the spectrum of Cen X-3, *Astronomy & Astrophysics*, 340, L55

Santangelo, A., Segreto, A., Giarrusso, S., et al. 1999, A BEPPOSAX Study of the Pulsating Transient X0115+63: The First X-Ray Spectrum with Four Cyclotron Harmonic Features, *The Astrophysical Journal Letters*, 523, L85, doi: [10.1086/312249](https://doi.org/10.1086/312249)

Sato, Uchida, & Ishikawa. 2023, Hitomi/XRISM micro-calorimeter, *arXiv e-prints*, arXiv:2303.01642, doi: [10.48550/arXiv.2303.01642](https://doi.org/10.48550/arXiv.2303.01642)

Sato, N., Nagase, F., Kawai, N., et al. 1986, Orbital Elements of the Binary X-Ray Pulsar GX 301-2, *The Astrophysical Journal*, 304, 241, doi: [10.1086/164157](https://doi.org/10.1086/164157)

Schönherr, G., Wilms, J., Kretschmar, P., et al. 2007, A model for cyclotron resonance scattering features, *Astronomy & Astrophysics*, 472, 353, doi: [10.1051/0004-6361:20077218](https://doi.org/10.1051/0004-6361:20077218)

Shao, L., & Yagi, K. 2022, Neutron stars as extreme laboratories for gravity tests, *Science Bulletin*, 67, 1946, doi: [10.1016/j.scib.2022.09.018](https://doi.org/10.1016/j.scib.2022.09.018)

Sharma, R., Jain, C., & Paul, B. 2023, 4U 1626-67 returns to spin-down: timing features toe the line, *Monthly Notices of the Royal Astronomical Society*, 526, L35, doi: [10.1093/mnrasl/slad110](https://doi.org/10.1093/mnrasl/slad110)

Sokolova-Lapa, E., Zalot, N., Stierhof, J., et al. 2023, Low-luminosity accretion in Cep X-4 during the transition to quiescence observed by NuSTAR, *The Astronomer's Telegram*, 16171, 1

Soong, Y., Gruber, D. E., Peterson, L. E., & Rothschild, R. E. 1990, Spectral Behavior of Hercules X-1: Its Long-Term Variability and Pulse Phase Spectroscopy, *The Astrophysical Journal*, 348, 641, doi: [10.1086/168272](https://doi.org/10.1086/168272)

Staubert, R., Klochkov, D., Fürst, F., et al. 2017, Inversion of the decay of the cyclotron line energy in Hercules X-1, *Astronomy & Astrophysics*, 606, L13, doi: [10.1051/0004-6361/201731927](https://doi.org/10.1051/0004-6361/201731927)

Staubert, R., Shakura, N. I., Postnov, K., et al. 2007, Discovery of a flux-related change of the cyclotron line energy in Hercules X-1, *Astronomy & Astrophysics*, 465, L25, doi: [10.1051/0004-6361:20077098](https://doi.org/10.1051/0004-6361:20077098)

Staubert, R., Trümper, J., Kendziorra, E., et al. 2019, Cyclotron lines in highly magnetized neutron stars, *Astronomy & Astrophysics*, 622, A61, doi: [10.1051/0004-6361/201834479](https://doi.org/10.1051/0004-6361/201834479)

Strüder, L., Briel, U., Dennerl, K., et al. 2001, The European Photon Imaging Camera on XMM-Newton: The pn-CCD camera, *Astronomy & Astrophysics*, 365, L18, doi: [10.1051/0004-6361:20000066](https://doi.org/10.1051/0004-6361:20000066)

Suchy, S., Fürst, F., Pottschmidt, K., et al. 2012, Broadband Spectroscopy Using Two Suzaku Observations of the HMXB GX 301-2, *The Astrophysical Journal*, 745, 124, doi: [10.1088/0004-637x/745/2/124](https://doi.org/10.1088/0004-637x/745/2/124)

Suleimanov, V. F., Forsblom, S. V., Tsygankov, S. S., et al. 2023, X-ray polarimetry of the accreting pulsar GX 301–2, *Astronomy & Astrophysics*, 678, A119, doi: [10.1051/0004-6361/202346994](https://doi.org/10.1051/0004-6361/202346994)

Sundqvist, J. O., Owocki, S. P., & Puls, J. 2012, in *Astronomical Society of the Pacific Conference Series*, Vol. 465, *Proceedings of a Scientific Meeting in Honor of Anthony F. J. Moffat*, ed. L. Drissen, C. Robert, N. St-Louis, & A. F. J. Moffat, 119, doi: [10.48550/arXiv.1110.0485](https://doi.org/10.48550/arXiv.1110.0485)

Sunyaev, R. A., & Titarchuk, L. G. 1980, *Comptonization of X-Rays in Plasma Clouds - Typical Radiation Spectra*, *Astronomy & Astrophysics*, 86, 121

Tamba, T., Odaka, H., Tanimoto, A., et al. 2023, *Orbital- and Spin-phase Variability in the X-Ray Emission from the Accreting Pulsar Centaurus X-3*, *The Astrophysical Journal*, 944, 9, doi: [10.3847/1538-4357/acadde](https://doi.org/10.3847/1538-4357/acadde)

Tanaka, Y. 1986, in *IAU Colloq. 89: Radiation Hydrodynamics in Stars and Compact Objects*, ed. D. Mihalas & K.-H. A. Winkler, Vol. 255, 198, doi: [10.1007/3-540-16764-1_12](https://doi.org/10.1007/3-540-16764-1_12)

Tananbaum, H., Gursky, H., Kellogg, E. M., et al. 1972, *Discovery of a Periodic Pulsating Binary X-Ray Source in Hercules from UHURU*, *The Astrophysical Journal Letters*, 174, L143, doi: [10.1086/180968](https://doi.org/10.1086/180968)

Tashiro, M., Makishima, K., Ohashi, T., Sakao, T., & Sansom, A. E. 1991, *Non-periodic intensity variations in the X-ray pulsar GX301-2.*, *Monthly Notices of the Royal Astronomical Society*, 252, 156, doi: [10.1093/mnras/252.1.156](https://doi.org/10.1093/mnras/252.1.156)

Tauris, T. M., & van den Heuvel, E. P. J. 2006, in *Compact stellar X-ray sources*, ed. W. H. G. Lewin & M. van der Klis, Vol. 39, 623–665, doi: [10.48550/arXiv.astro-ph/0303456](https://doi.org/10.48550/arXiv.astro-ph/0303456)

Titarchuk, L. 1994, *Generalized Comptonization Models and Application to the Recent High-Energy Observations*, *The Astrophysical Journal*, 434, 570, doi: [10.1086/174760](https://doi.org/10.1086/174760)

Tobrej, M., Rai, B., Ghising, M., Tamang, R., & Paul, B. C. 2023, *A high-mass X-ray binary pulsar 4U 1907+09 with multiple absorption-line features in the spectrum*, *Monthly Notices of the Royal Astronomical Society*, 518, 4861, doi: [10.1093/mnras/stac3203](https://doi.org/10.1093/mnras/stac3203)

Tomida, H., Tsunemi, H., Kimura, M., et al. 2011, *Solid-State Slit Camera (SSC) Aboard MAXI*, *Publications of the Astronomical Society of Japan*, 63, 397, doi: [10.1093/pasj/63.2.397](https://doi.org/10.1093/pasj/63.2.397)

Tomsick, J. A., Chaty, S., Rodriguez, J., Walter, R., & Kaaret, P. 2006, *IGR J06074+2205 is a Be X-ray Binary*, *The Astronomer's Telegram*, 959, 1

Treiber, H., Vasilopoulos, G., Bailyn, C. D., et al. 2021, *RX J0529.8-6556: a BeXRB pulsar with an evolving optical period and out of phase X-ray outbursts*, *Monthly Notices of the Royal Astronomical Society*, 503, 6187, doi: [10.1093/mnras/stab807](https://doi.org/10.1093/mnras/stab807)

- Truemper, J., Pietsch, W., Reppin, C., et al. 1978, Evidence for strong cyclotron line emission in the hard X-ray spectrum of Hercules X-1., *The Astrophysical Journal Letters*, 219, L105, doi: [10.1086/182617](https://doi.org/10.1086/182617)
- Tsygankov, S. S., Lutovinov, A. A., Churazov, E. M., & Sunyaev, R. A. 2007, 4U 0115+63 from RXTE and INTEGRAL data: Pulse profile and cyclotron line energy, *Astronomy Letters*, 33, 368, doi: [10.1134/s1063773707060023](https://doi.org/10.1134/s1063773707060023)
- Tsygankov, S. S., Wijnands, R., Lutovinov, A. A., Degenaar, N., & Poutanen, J. 2017, The X-ray properties of Be/X-ray pulsars in quiescence, *Monthly Notices of the Royal Astronomical Society*, 470, 126, doi: [10.1093/mnras/stx1255](https://doi.org/10.1093/mnras/stx1255)
- Tsygankov, S. S., Doroshenko, V., Poutanen, J., et al. 2022, The X-Ray Polarimetry View of the Accreting Pulsar Cen X-3, *The Astrophysical Journal Letters*, 941, L14, doi: [10.3847/2041-8213/aca486](https://doi.org/10.3847/2041-8213/aca486)
- Turner, M. J. L., Abbey, A., Arnaud, M., et al. 2001, The European Photon Imaging Camera on XMM-Newton: The MOS cameras, *Astronomy & Astrophysics*, 365, L27, doi: [10.1051/0004-6361:20000087](https://doi.org/10.1051/0004-6361:20000087)
- Ulmer, M. P., Baity, W. A., Wheaton, W. A., & Peterson, L. E. 1973, New Transient Source, Cepheus X-4, Observed by OSO-7, *The Astrophysical Journal Letters*, 184, L117, doi: [10.1086/181302](https://doi.org/10.1086/181302)
- van der Meer, A., Kaper, L., di Salvo, T., et al. 2005, XMM-Newton X-ray spectroscopy of the high-mass X-ray binary 4U 1700-37 at low flux, *Astronomy & Astrophysics*, 432, 999, doi: [10.1051/0004-6361:20041288](https://doi.org/10.1051/0004-6361:20041288)
- Vasco, D., Staubert, R., Klochkov, D., et al. 2013, Pulse phase and precession phase resolved spectroscopy of Hercules X-1: studying a representative Main-On with RXTE, *Astronomy & Astrophysics*, 550, A111, doi: [10.1051/0004-6361/201220181](https://doi.org/10.1051/0004-6361/201220181)
- Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, Atomic Data for Astrophysics. II. New Analytic FITS for Photoionization Cross Sections of Atoms and Ions, *The Astrophysical Journal*, 465, 487, doi: [10.1086/177435](https://doi.org/10.1086/177435)
- Vidal, N. V. 1973, The Association of a High-Luminosity B Star with 3u 1223-62, *The Astrophysical Journal Letters*, 186, L81, doi: [10.1086/181362](https://doi.org/10.1086/181362)
- Voges, W., Pietsch, W., Reppin, C., et al. 1982, Cyclotron lines in the hard X-ray spectrum of HER X-1., *The Astrophysical Journal*, 263, 803, doi: [10.1086/160550](https://doi.org/10.1086/160550)
- Vybornov, V., Doroshenko, V., Staubert, R., & Santangelo, A. 2018, Changes in the cyclotron line energy on short and long timescales in V 0332+53, *Astronomy & Astrophysics*, 610, A88, doi: [10.1051/0004-6361/201731750](https://doi.org/10.1051/0004-6361/201731750)

- Vybornov, V., Klochkov, D., Gornostaev, M., et al. 2017, Luminosity-dependent changes of the cyclotron line energy and spectral hardness in Cepheus X-4, *Astronomy & Astrophysics*, 601, A126, doi: [10.1051/0004-6361/201630275](https://doi.org/10.1051/0004-6361/201630275)
- Watanabe, S., Sako, M., Ishida, M., et al. 2003, Detection of a Fully Resolved Compton Shoulder of the Iron $K\alpha$ Line in the Chandra X-Ray Spectrum of GX 301-2, *The Astrophysical Journal Letters*, 597, L37, doi: [10.1086/379735](https://doi.org/10.1086/379735)
- Wheaton, W. A., Doty, J. P., Primini, F. A., et al. 1979, An absorption feature in the spectrum of the pulsed hard X-ray flux from 4U0115 + 63, *Nature*, 282, 240, doi: [10.1038/282240a0](https://doi.org/10.1038/282240a0)
- White, N. E., Swank, J. H., & Holt, S. S. 1983, Accretion powered X-ray pulsars., *The Astrophysical Journal*, 270, 711, doi: [10.1086/161162](https://doi.org/10.1086/161162)
- Wilms, J., Allen, A., & McCray, R. 2000, On the Absorption of X-Rays in the Interstellar Medium, *The Astrophysical Journal*, 542, 914, doi: [10.1086/317016](https://doi.org/10.1086/317016)
- Wilson-Hodge, C. A., Malacaria, C., Jenke, P. A., et al. 2018, NICER and Fermi GBM Observations of the First Galactic Ultraluminous X-Ray Pulsar Swift J0243.6+6124, *The Astrophysical Journal*, 863, 9, doi: [10.3847/1538-4357/aace60](https://doi.org/10.3847/1538-4357/aace60)
- Yang, W., Wang, W., Liu, Q., et al. 2023, Discovery of two cyclotron resonance scattering features in X-ray pulsar cen X-3 by Insight-HXMT, *Monthly Notices of the Royal Astronomical Society*, 519, 5402, doi: [10.1093/mnras/stad048](https://doi.org/10.1093/mnras/stad048)