Timing and Spectral Analysis of a Galactic Microquasar

December 18, 2009

Authors:

Jayant P. Thatte[1]

Aniruddha A. Bapat[2]

Abhishek B. Oswal[3]

Himalay Senapati[4]

Mentor:

Dr. Manojendu Choudhury

Abstract

The following report is aimed at discussing aspects of X-ray astronomy in general and X-ray binaries and microquasars in particular. First, the various physical processes which give rise to x-ray emissions are discussed. Then, X-ray binaries and microquasars have been described in some detail. Then the report moves to the specific object of study, 4U1630-47. The data obtained from *Rossi* XTE[5] was analysed over a week. The analysis of the data has been presented. Finally the inferences drawn about 4U1630-47 from the analysis have been discussed.

---

[1] Indian Institute Of Technology Madras, Chennai

[2] The Army Public School,Pune.

[3] The Army Public School,Pune.

[4] Bhadrak Jr. College,Bhadrak.

[5] NASA's Rossi X-Ray Timing Explorer

1 Introduction

X-rays are a part of the electromagnetic (EM) spectrum with energies ranging from $\sim$ 0.1 keV to $\sim$50 keV (wavelengths $\sim$ 0.1 - 120 Å). X-rays can be further divided into hard and soft X-rays. Hard X-rays range from 0.5-12 keV and soft X-rays range from$\sim$ 12-50 keV (MANOJENDU CHOUDHURY 2004) after which they are regarded as soft Gamma rays. There are many X-ray sources in the universe, making the X-ray band a rich window for astronomical observations. In particular, Black Hole Binary (BHB) systems are very interesting X-ray objects, due to the astrophysical phenomena occuring in them. In this project, one such transient BHB, 4U1630-47, was studied.

2 High Energy Processes and Phenomena

Wien's displacement law suggests that, considering a thermal origin of the X-rays, the temperature of the radiating body should be $\sim 10^6$- 10^8K to generate X-ray photons. Thus, there are only a few thermal processes which give rise to X-ray emissions. Soon, however, it was discovered that there are many non-thermal processes which also give rise to X-ray emissions, e.g. synchrotron radiation. Given below are a few physical processes and phenomena which give rise to X-ray emissions.

2.1 Comptonisation

Compton scattering is the physical process by which a high energy photon collides with an electron, thereby imparting energy to the electron and itself becoming a lower energy/frequency photon. The exact opposite of this is when a low energy photon passes through a cloud of energetic electrons and itself gets energised due to collisions with the electrons. This is known as Inverse Compton Scattering.

2.2 Bremsstrahlung

Bremsstrahlung is a German word derived from *bremsen* = to brake and *Strahlung* = radiation. Thus Bremsstrahlung means "braking radiation" or decelerating radiation. It is the radiation given out when a light charged particle, *e.g.* electron, gets deflected by a larger charged particle, *e.g.* an atomic nucleus. Bremsstrahlung is a *free-free* emission, *i.e.* the electron transits from one of its free states to another.

2.3 Synchrotron Radiation

The physical process of radiation due to acceleration of charged particles, *e.g.* electrons, under the influence of a magnetic field is known as synchrotron radiation. It occurs for relativistic speeds of electrons; for non-relativistic speeds the process is known as *Cyclotron* emission.

$$I(\nu) \propto B^{\frac{p+1}{2}} \left(\frac{1}{\nu}\right)^{\frac{p-1}{2}} \tag{1}$$

where B is the magnetic field, p is the spectral index and ν is the frequency.

2.4 Blackbody Radiation

A blackbody is defined as an ideal object that absorbs all the radiation that is incident on it. The characteristic radiation observed from such a blackbody is known as Blackbody Radiation. It is given by Planck's Law :

$$I_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \tag{2}$$

where I_ν = specific intensity, T = Kelvin temperature of source, ν = frequency of radiation and h, k and c are the Planck constant, Boltzmann constant and speed of light respectively.
A temperature of 10^6 K has maximum radiation in the X-ray band.

2.5 The Accretion Phenomenon

Accretion of matter onto compact objects is one of the most common phenomena that gives rise to X-ray emission. In this, a compact object, such as a black hole, accretes matter from a companion star. The matter being accreted forms a disc around the accretor, due to conservation of angular momentum. Due to the viscous forces within the disc, the angular momentum is transported outward (SHAKURA & SUNYAEV, 1973), and in the process, the matter slowly spirals inwards. The lost gravitational potential energy is emitted as radiation.
X-ray radiation is also emitted from some other phenomena, such as supernovae.

3 Basics of microquasars

3.1 Introduction

The most common X-ray sources in the Galaxy are *X-ray Binary (XRB) Systems* . The XRBs basically consist of a compact object, usually a black hole (BH) or a neutron star accreting matter from its companion, which usually is a main sequence star. Outside the Galaxy, the primary source of X-rays are the *Active Galactic Nuclei (AGN).* The AGN are supermassive BHs ($M \sim 10^{6-9} M_\odot$) at the centre of the galaxies, that accrete matter from their neighbourhood. It is found that XRBs simulate the AGN in a much scaled down version. Hence the XRBs are also called *Microquasars.* Thermal emission is usually received from the disc while non-thermal radiation is received from the central comptonising cloud.

3.2 Physical Model of Accretion

Consider a mass m being accreted to a body of mass M and radius R. The loss of gravitational potential energy is $\frac{GMm}{R}$ which, if converted to EM radiation will cause the system to have a luminosity of

$$L = \frac{GM\dot{m}}{R} = \frac{1}{2}\dot{m}c^2\frac{r_g}{R} = \xi\dot{m}c^2 \tag{3}$$

where $r_g = \frac{2GM}{c^2}$ is the *Schwarzschild Radius* and $\xi = \frac{1}{2}(r_g/R)$ gives the efficiency of the accretion process.

Thus, the efficiency of accretion depends only on the compactness of the accreting object. ξ ranges from 0.06 for a typical Schwarzschild BH to 0.426 for a *Kerr* BH, as against thermonuclear fusion for which $\xi = 0.007$[6]. This high value of ξ indicates that accretion is an efficient mechanism for energy production.

From the above equation, it may seem that the luminosity of an accreting object can be arbitrarily large if it accretes matter at a sufficiently large rate. However, it is limited by the fact that the radiation pressure tends to resist the accretion of matter. At a certain critical luminosity, the outward radiation pressure balances the inward gravitational force. This critical luminosity is called Eddington Luminosity (EL). Assume that matter is fully ionised into protons and electrons, therefore

$$F_{grav} = \frac{GM(m_p + m_e)}{R^2} \approx \frac{GMm_p}{R^2} \tag{4}$$

and the outward force due to radiation pressure on photons is given by

$$F_{rad} = \frac{\sigma_T L}{4\pi R^2 c} \tag{5}$$

Equations (3), (4) and (5) imply

$$L_{edd} = \frac{4\pi GMm_pc}{\sigma_T} \sim 3\cdot 10^{13}\left(\frac{M}{10^9 M_\odot}\right)L_\odot \tag{6}$$

This is the EL.[7]

3.3 The states of microquasars

The microquasars or the XRB exhibit four different types of states (REMILLARD & MCCLINTOCK 2006).

1. The *high/soft* state, described as ∼1keV thermal emission (soft X-rays), is usually observed when the source is bright (in optical range), hence prompting the name high/soft state. In this state, it is found that the contribution of the disc to the total luminosity greatly exceeds that from the comptonising cloud.

---

[6] Refer *High Energy Astrophysics Vol. 2 by* MALCOLM S. LONGAIR

[7] Refer *Introduction to High Energy Astrophysics* by *Stephan Rosswog* and *Markus Brüggen* for detailed derivation.

2. The *low/hard* state is characterised by high contribution of the non-thermal component of radiation, which falls in the region of hard X-rays. In this state, the size of the central cloud increases, whereas that of the disc reduces. The source does not emit much in optical band; hence the name low state.

3. *Steep Power Law (SPL) State,* as the name suggests, is characterised by a large value of photon index (~2.5). Also, large number of Quasi-Periodic Oscillations and high luminosity ($\gtrsim 0.1 L_{edd}$) are typical features of this state.

4. *Intermediate State:* There are some states of XRBs which cannot be classified into either of the above types. Such states are included in intermediate states.

3.4 Radio Jets in Microquasars

Superluminal[8] radio jets are observed to come out of microquasars, particularly when the microquasar is in SPL or hard state. The exact causes of these jets in BH binaries are not well understood, although they seem to be related to the magnetic field and rotation of the BH[9]. Historically, the name 'microquasar' was coined due to this feature, which is also seen in quasars.

4 Observation and Data Analysis

4.1 Introduction

As mentioned, the X-ray band falls roughly in the 0.1 keV - 50 keV range (wavelengths $\sim$ 0.1 - 120 Å). These wavelengths are absorbed by the earth's atmosphere, making it impossible to observe astronomical X-ray sources from Earth. Thus, any X-ray detector must go above the atmosphere to conduct observations. The earliest X-ray observations started in the 1970's and made use of hot air balloons. Today, advanced technology allows us to place satellites (*Chandra* X-Ray Observatory, RXTE *etc.*) into space for long-term observation of X-ray sources.

4.2 Procedure

In Observational Astronomy, there are mainly three catagories of observations, *viz. imaging, timing analysis* and *spectral analysis.* Out of these, only timing and spectral analysis of the source were carried out since RXTE is not equipped for X-ray imaging. RXTE data for the X-ray transient 4U1630-47 was used. The data represented the BHB in its outburst phase (2002-2006). Xanadu[10]

---

[8] motion at speeds *apparently* greater than light.

[9] http://curious.astro.cornell.edu/blackholes.php

[10] http://heasarc.gsfc.nasa.gov/lheasoft/xanadu/

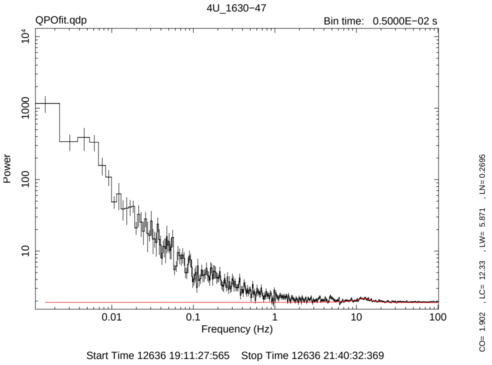
was used to obtain light curves, Power Density Spectra (PDS) and energy spectra from the data. Using the software *Powspec*, PDS for the source were studied. Quasi-Periodic Oscillations (QPOs), seen as peaks in the PDS, were fitted using Lorentzian profiles and their essential parameters were found. Using the Proportional Counter Array (PCA) data, the energy spectra of the source were analysed over a period of a week using the Xspec software.

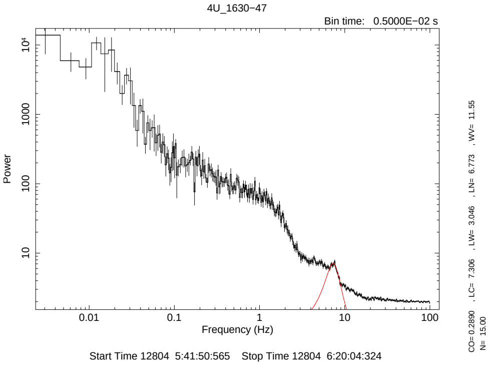
4.3 Timing Analysis

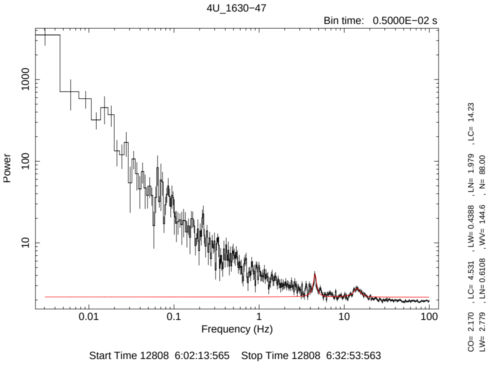
The study of variation of the observables of a system *(e.g.* flux, Doppler Shift) over time is known as timing analysis. In the project, the light curves of the X-ray binary 4U1630-47 were studied. In a complicated time profile, the existing periodicities may not be apparent. In such cases, the technique of Fourier Transform is very useful since it transfers the function from the time domain to the frequency domain. Thus, the periodicities appear as peaks in the Fourier Transformed function and hence can be noted easily. In the project, the *Powspec* software was used to Fourier Transform the light curves into PDS. Given below is a table of the series of observations for the source.

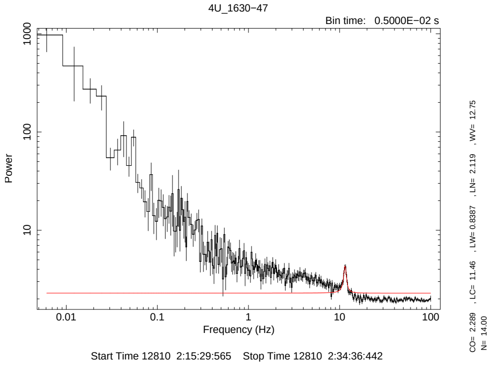
Observation ID	Start Time (MJD)	Stop Time (MJD)	Time Duration (h:m:s)
70417-01-09-00	12636 19:11:27.565	12636 21:40:32.369	02:29:04.804
80117-01-07-00	12804 05:41:50.565	12804 06:20:04.324	00:38:13.759
80117-01-07-02	12808 06:02:30.565	12808 06:32:53.563	00:00:30.398
80117-01-08-00	12810 02:15:29.565	12810 02:34:36.442	00:19:06.877
80117-01-08-01	12812 06:26:16.565	12812 06:44:54.562	00:18:37.997
80117-01-12-10	12834 12:02:14.565	12834 12:24:05.284	00:21:50.719
-	09353 00:01:00.184	09353 00:35:08:184	00:34:08.000

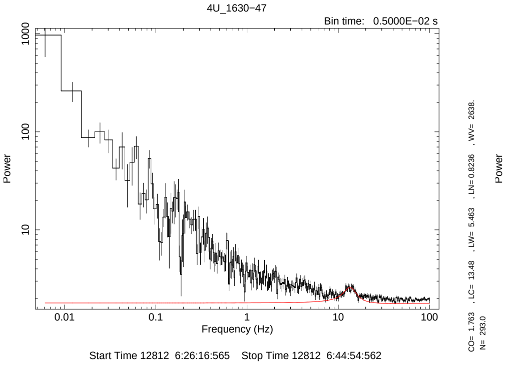
The PDS of different series of observations are presented below.

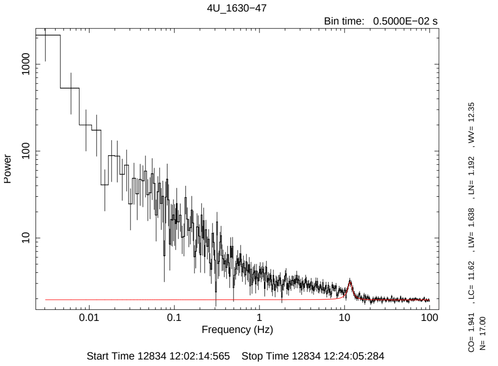


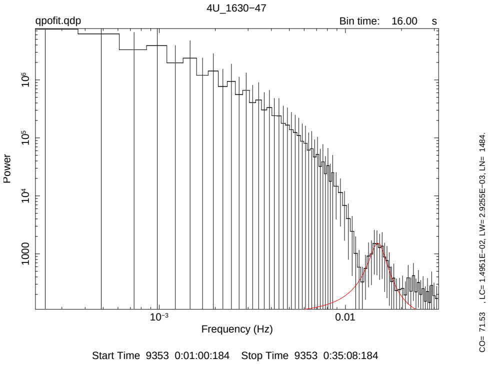


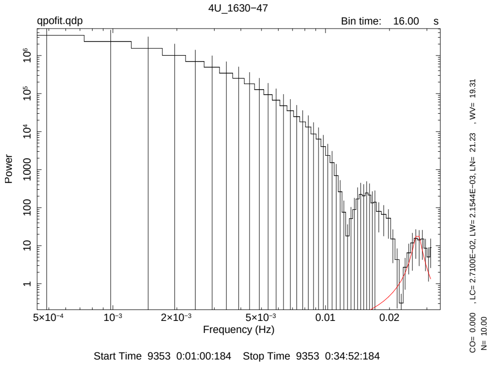












From the graphs, it can be seen that in every PDS, there are one or more peaks in the high-end frequency region. These are the QPOs mentioned in section 4.2. As the name suggests, QPOs are temporary periodicities observed in the light curves of microquasars. The parameters obtained from the above Lorentzian models are presented below.

Observation ID	QPO parameters		
	Peak Frequency(Hz)	Peak Power $(\text{rms/mean})^2$/Hz	FWHM (Hz)
70417-01-09-00	12.33	2.172	5.871
80117-01-07-00	7.306	7.06	3.046
80117-01-07-02	4.532, 14.22	4.16 ,2.78	0.44,2.78
80117-01-08-00	11.46	4.4075332	0.8387
80117-01-08-01	13.49	2.59	5.463
80117-01-12-01	11.62	3.13	1.638

4.4 Spectral Analysis

Spectral analysis is the study of the Energy spectrum of an astronomical object to obtain information about it. In this project, energy spectra of 4U1630 -47 in the energy band of ∼ 5 - 50 keV , obtained from the PCA, were analysed. Since the channel response for energies beyond 30 keV was not good, these spectra were fitted with a single multicomponent model consisting of disk blackbody which is dominant at lower energies, power law at high energies, gaussian for Fe line emission and interstellar absorbtion. The following is a table of the different spectral data-sets against the models they were fitted by and the important model parameters.

Observation ID	Photon Absorption	Disc Blackbody	Gaussian	Power Law	χ^2
	nH	T_{in}(K)	Fe K line (eV)	Photon Index	
80117-01-08-00	5.72±4.26	1.85 ± 0.09	6.4 ± 0.1	1.95 ± 0.25	1.083
80117-01-08-01	8.52 ± 0.42	1.92 ± 1.5	6.4 ± 0.2	1.60 ± 0.52	1.052
80117-01-12-01	11.10 ± 0.65	1.89 ± 1.1	6.5 ± 0.1	3.11 ± 0.56	1.134

4.5 Calculation of BH luminosity

The following section is aimed at calculation of luminosity of BHs using the energy spectrum and compare it with the EL. Xspec software was used to calculate flux in the range of 0.5-50 keV. Since X-rays fall in the high energy band and since 4U1630-47 emits largely in X-rays, most of the energy is contributed by X-rays (contribution of radio waves to energy may be neglected). Thus the energy flux (F_E) turns out to be $2.76 \cdot 10^{-11} W/m^2$.

The EL (L_{edd}) for 4U1630-47 was found out using equation (6). In doing so, it was assumed that the mass of the BH is 3.4-5.6$M_\odot$ and its distance from the earth is 10kpc (Yukiko Abe, Yasushi Fukazawa and Aya Kubota 2004). It was obtained that L_{edd} for the BH lies in the range $4.3 \cdot 10^{31}$ to $7.0 \cdot 10^{31}$.

The absolute luminosity (L) of the source can be obtained from its apparent luminosity, *i.e.* energy flux obtained above and its distance from the earth (d).

$$L = 4\pi d^2 F_E \tag{7}$$

Thus, $L/L_{edd} \sim 0.4 - 0.7$

5 Conclusions and Discussion

The main aim of this project, understanding X-ray binary systems, was achieved by reading theory and analysing a specific microquasar, 4U1630-47. This involoved reading about mathematical techniques like Fourier Transforms and physics of the compact binary systems. After gaining a background about the subject, data analysis was carried out to determine certain observable quantities of the source. From the PDS, it was found that the QPO pairs obeyed a 3:1 or 3:2 resonance, which is in accordance with existing results (Remillard & McClintock 2006). Modelling of the energy spectra provided important parameters, like the Fe line frequency and width and the photon index for the power law fit.

5.1 Astronomical Importance of Microquasars

1. The phenomenon of accretion makes the BH "visible", which otherwise does not allow radiation to escape; hence, microquasars can be used extensively to study BHs.
2. Microquasars have a very high gravitational field, so these sources offer the opportunity to experimentally verify the General Theory of Relativity.
3. The proximity of microquasars makes the study of lobes of the outflowing radiojets more feasible. Extensive observations of the jet properties provide more accurate understanding of quasars.
4. The dynamical time scales in the flow of matter in microquasars are also scaled down proportional to the BH masses in microquasars and quasars. Hence long-term (∼100-1000 years) phenomena in AGN correspond to a period of few hours to few days in microquasars. Therefore, monitoring a microquasar for a few days may sample phenomena not possible to observe in quasars.

5.2 Significance of QPOs

1. It is observed that QPO frequencies do not change significantly with change in X-ray luminosity. Moreover, the typical high-frequency QPOs have a frequency that closely matches the frequency of the Innermost Stable Circular Orbit (ISCO) of a typical Schwarzschild BH. It is speculated that QPO frequencies are mainly dependent on the spin and mass of the

BH. Hence, they can potentially be used to deduce these fundamental parameters which define a BH completely.

2. QPOs are oscillations which occur under extreme physical conditions. Hence their study can help us understand the behaviour of matter in relativistic conditions and to verify the existing hypotheses.

5.3 Quantitative Deductions

The total luminosity can be obtained by integrating the energy spectrum over the frequency range if mass of the compact object and its distance from earth are known. Thus, the fraction of EL being emitted by the X-ray source can be found out as demonstrated in section 4.4. The L/L_E ratio for 4U1630-47 was found out to be $\sim 0.4 - 0.7$.

Although the model parameters were not used extensively for calculations, an idea about how they could be used to quantitatively understand the system was obtained. This topic of Astronomy is still open to research, and many questions still remain unanswered. This project provided a glimpse of these new and exciting problems.

6 Acknowledgements

Our sincere thanks to Dr. Manojendu Choudhury, without whose invaluable guidance and support, this project would have been impossible. We are very grateful to the Homi Bhabha Centre for Science Education (HBCSE), for providing a conducive atmosphere for this project. In particular, we are indebted to Dr. Aniket Sule for organising the Astronomy Nurture Program 2009.

References

[1] Hard X-ray and Gamma Ray Properties of Cosmic Sources, Manojendu Choudhury 2004.

[2] Introduction to High Energy Astrophysics, Stephan Rosswog and Markus Brüggen 2007.

[3] High Energy Astrophysics, Volume II, Malcolm S. Longair 1997.

[4] X-ray Properties of Black Hole Binaries, Ronald A. Remillard and Jeffrey E. McClintock 2006, *Annu. Rev. Astron. Astrophys. 44:49-92.*

[5] http://curious.astro.cornell.edu/blackholes.php

[6] http://heasarc.gsfc.nasa.gov

[7] Introduction to Fourier Transfroms in Physics, K.A.I.L. Wijewardena Gamalath 2007.