J. Astrophys. Astr. (1998) **19,** 55–61

Low Frequency Quasi-Periodic Oscillations in the Hard X-ray Emission from Cygnus X-1

B. Paul, P. C. Agrawal & A. R. Rao, *Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India.*
e-mail: bpaul@ tifr.res.in; pagrawal@ tifr.res.in; arrao@ tifr.res. in

Received 1998 June 5; accepted 1998 June 18

Abstract. The observations of the black hole binary Cygnus X-l were made in the energy band of 20-100keV with a balloon-borne Xenon-filled multiwire proportional counter telescope on 5th April 1992. Timing analysis of the data revealed the presence of Quasi-Periodic Oscillations (QPO) in the hard X-ray emission from the source. The QPO feature in the power density spectrum is broad with a peak at a frequency of 0.06 Hz. This result is compared with similar reports of QPOs in Cyg X-l in soft and hard X-rays. Short time scale random intensity variations in the X-ray light curve are described with a shot noise model.

Key words. X-rays: stars — stars: individual Cygnus Xl.

1. Introduction

Cyg X-l, the brightest hard X-ray source in the sky, is one of the best studied binary X-ray sources. The mass function of the companion star clearly indicates the presence of a massive compact object (about 16 $M_\odot$), and therefore is often referred to as the first source with observational evidence of a black hole (Webster & Murdin 1972; Bolton 1972). This X-ray source is noted for its peculiar features in several respects, like bimodal behaviour of the spectrum (Zhang *et al.* 1997a), large intensity variations over a wide range of time scales, time lag between soft and hard X-rays (Miyamoto & Kitamoto 1989), dependence of the shape and absolute value of the power density spectrum on the intensity states etc. (Belloni *et al.* 1996; Cui *et al.* 1997; Rao *et al* 1998). Most of the time the source is found to be in a low intensity and hard spectral state. Many of the X-ray properties of this source are also present in other black hole candidates and they are therefore considered to be the distinguishing characteristics of black hole binaries (Tanaka & Lewin 1995).

Black hole sources exhibit many different types of temporal variations in their X-ray intensity. Very rapid variability, flickering, irregular fluctuations and strong quasi-periodic oscillations (QPOs) are often observed in the X-ray light curves of black hole sources (see van der Klis 1995 for a review). Rapid and large amplitude variabilities in the intensity carry information about the irregular accretion flows in the vicinity of the compact object. Quasi-periodic oscillations in the X-ray flux have been observed in several black hole candidates in a wide frequency range. A variety of physical mechanisms have been considered which can produce the observed intensity variations in the black hole sources.

Cyg X-l shows X-ray intensity variations on time scales from milliseconds to months in both the soft X-rays and the hard X-rays. The intensity variations are found to be less pronounced in the high state of the source compared to the same in its low state. The X-ray variabilities have been explained as the sum of randomly occurring X-ray shots and a steady emission (Weisskopf *et al.* 1975). The shots are assumed to be symmetric in shape with exponential rise and decay, or asymmetric with sharp rise and exponential decay. The shots are probably due to the formation of local 'hot spots' in the accretion disks. The structure of the X-ray shots of Cyg X-l in its low state were studied in detail by Negoro *et al.* (1994) with the large area proportional counters onboard the GINGA satellite. Statistics of the X-ray shots including distributions of the shot duration and amplitude and also the temporal distribution of the shots were investigated in the Cyg X-l observations of GINGA (Negoro *et al.* 1995) and with the IXAE (Rao *et al.* 1998).

In some of the low state observations of Cyg X-l, in addition to the random variations, QPOs were also observed in the soft energy band with the EXOSAT (Angelini *et al.* 1992) and in the hard energy band with the SIGMA (Vikhlinin *et al.* 1992) and the BATSE experiments (Kouveliotou *et al* 1992). The QPO phenomena in Cyg X-l. is transient in nature and the peak frequency of the broad QPO signature lies between 0.04 and 0.07 Hz. Of the 13 observations of Cyg X-l with the EXOSAT ME detectors, QPOs were observed only on 4 occasions. The appearance of the QPOs in hard X-rays was found to be correlated with the energy flux whereas in soft X-rays no such correlation was observed. In the BATSE observations, the QPO feature in the power spectrum is broad, centered at a frequency of about 0.04 Hz, and was detected independently in several energy bands ranging from 20 to 320 keV. At high energy the fractional rms variation at the QPO frequency is about 10–15% of the total intensity.

We have performed hard X-ray observation of Cygnus X-l with a low background and good energy resolution telescope to study the energy spectrum and temporal properties of this source in detail. Here we report the detection of a low frequency QPO and random intensity variations in this source.

2. Observation and results

The observations were carried out with a balloon-borne hard X-ray telescope consisting of two xenonfilled multilayer proportional counters (XMPCs). The balloon flight was carried out on 5th April 1992, and the observation was made at a ceiling altitude corresponding toa residual atmospheric column density of 4 gm cm^{-2}. CygX-l was observed continuously for a duration of one hour followed by 4 cycles of 20 minutes source and 10 minutes background observations. The source was in a low state during our observation. The two identical xenon-filled proportional counters (XMPC) have a total effective area of 2400 cm^2 with a 5° × 5° field of view defined by a passive tin-copper graded collimator. The average detection efficiency in the energy range of 20 and 100keV is 50%. For details of the Xray telescope refer to Rao *et al.* (1991). The telescope, mounted on an orientation platform, can be preprogrammed to track a given source by an onboard automated tracking system.

The count rate profile of Cyg X-l and background observation is shown in Fig.1 where summed light curve from the two detectors is plotted. The background count rate was constant during the entire balloon flight. The source count rate changed with

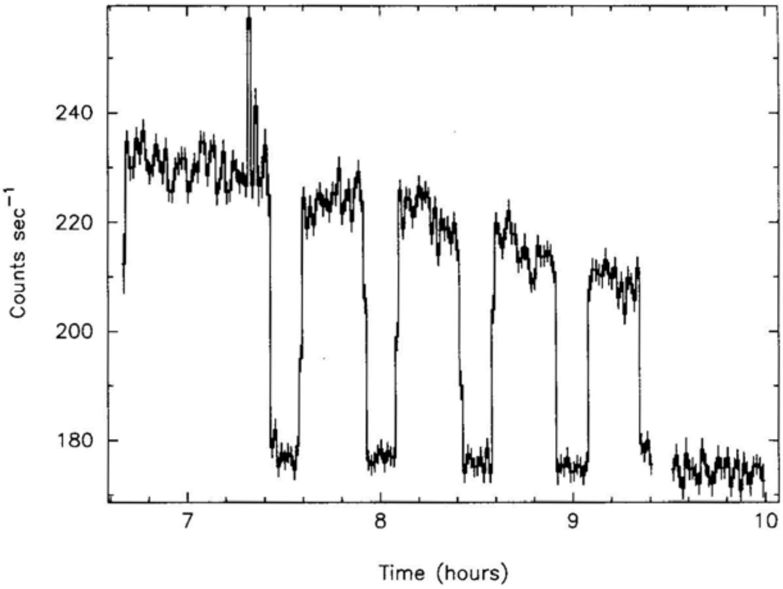

Figure 1. The 20–100 keV light curve of the 5th April 1992 observation of Cyg X-l showing the source and the background count rates in the two XMPC detectors.

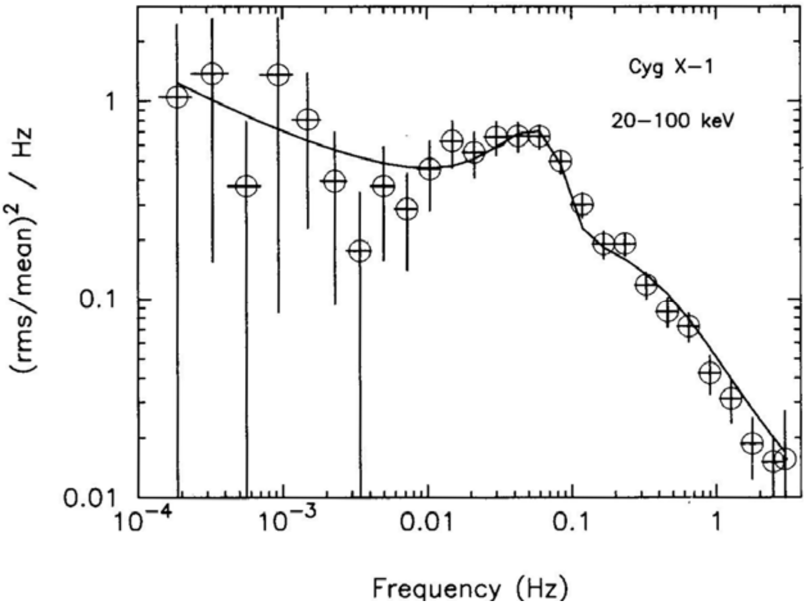

Figure 2. Power density spectrum of Cyg X-l in the 20–100 keV energy band.The continuous line shows the best fit which includes sum of three components, a zero centered Lorentzian, a Gaussian and a power-law component at very low frequency.

the zenith angle because of change in the atmospheric depth along the line of sight. Average Cygnus X-1 count rate near the meridian transit was 51.0 ± 0.8 counts s^{-1}. The energy spectrum in the 20–100 keV range has a power-law shape with a photon index 1.62 ± 0.07 (Chitnis *et al.* 1998).

2.1 *The power density spectrum*

To calculate the power density spectrum (PDS), we generated count rate profile of Cyg X-1 in the 20–100 keV band with a time resolution of 163 ms. The PDS, generated from this light curve in the frequency range of 10^{-4} to 3 Hz is shown in Fig. 2.

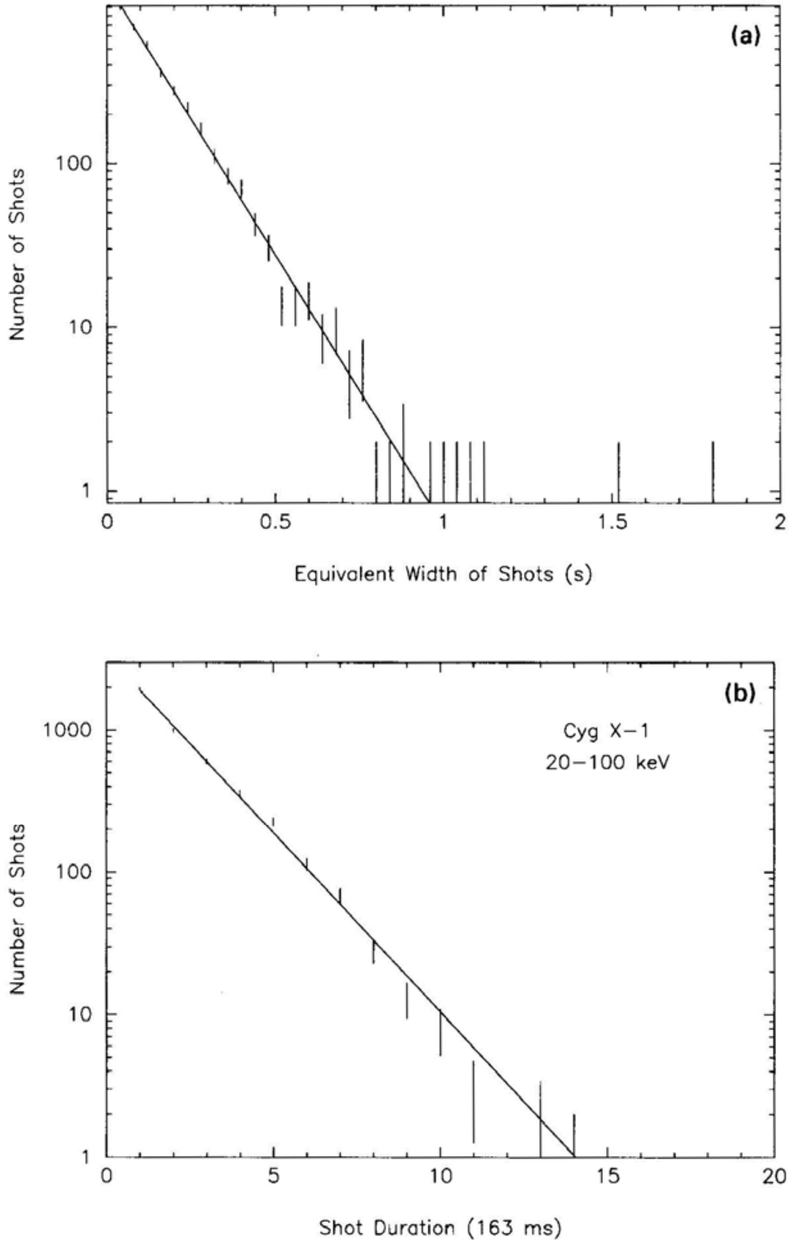

Figure 3. Statistics of the shots in the hard X-rays. (**a**) The number distribution of the shots as a function of equivalent width of the shots. The straight line shows the best fit exponential through the data points. (**b**) The number distribution of shots as a function of shot duration is also exponential in nature.

The PDS is white noise subtracted and is normalized to the mean count rate. Data from the two XMPC detectors were added to improve the statistics. A broad quasi-periodic oscillation peak centered around a frequency of 0.06 Hz is clearly observed in the figure. Apart from the QPO feature, the PDS appears to have a power-law shape which becomes steeper above a frequency of 0.2 Hz. The overall PDS fits well with a model comprising three components, a zero centered Lorentzian of width 0.7 Hz, a Gaussian of width 0.03 Hz centered at 0.06 Hz for the QPO peak and a power-law component of index —0.3 at lower frequencies with the following features:

- A power-law shape above 0.1 Hz with index of –0.96;
- A Gaussian type broad QPO peak centered at 0.06 Hz; and
- Increasing power towards very low frequency (< 0.01 Hz). The PDS is similar to the one obtained in other low state observations in hard X-rays (Vikhlinin *et al.* 1992, 1994; Kouveliotou *et al.* 1992; Angelini *et al.* 1992) of Cyg X-1.

2.2 *Shot noise description of the light curve*

We give here a statistical description of the rapid intensity variations observed in Cyg X-1 in its low state. The X-ray variability is assumed to be a result of randomly occurring X-ray shots with a steady emission. To quantify the variations in the intensity as a sum of shots in the light curve of Cyg X-1, we have adopted the following method. Every data bin of the light curve is compared to a running average around it, and if the successive data bins are found to be above the average, a shot is presumed to have occurred. The total excess counts in the individual shots above the average are calculated and the same divided by the averaged intensity gives the equivalent width of the shots. The number distribution of the shots as a function of the equivalent width is shown in Fig. 3(a). It is found that the distribution fits very well with an exponential function with a time scale of 0.13 s. The number distribution of the shots as a function of the duration of the shots is shown in Fig. 3(b), and it also has an exponential form with a time constant of 1.7 s.

The distribution of shots in the X-ray light curve of black hole candidates has been explained in the self-organized criticality (SOC) model (Mineshige *et al.* 1994). Negoro *et al.* (1995) have examined this model by analyzing the GINGA data for the hard state of Cyg X-1. Rao *et al.* (1998) found that in the soft X-ray band the shots have an exponential distribution in terms of their strength and duration. The time scales were found to be different in the two intensity states. In the present work we have found that in the hard X-ray band also the shots have similar exponential distribution.

3. Discussion

The QPOs and chaotic intensity variations in black hole sources are likely to provide better understanding of the physical processes taking place in the innermost part of the accretion disk. We have detected quasi-periodic oscillations with a frequency of ~0.06 Hz in the hard X-rays emitted from Cygnus X-1 in our observation on 5th April 1992. QPOs, in the frequency range of 0.04-0.07 Hz were observed from this source in the low intensity state on several occasions both in the hard X-ray band (Vikhlinin *et al.* 1994) and in the soft X-ray band (Angelini *et al.* 1994). Quasi-periodic oscilla tions-have also been observed in some other black hole sources LMC X-l, GX 339-4, GS 1124-68, GRO J0422+32 and GRS 1915+105 in the similar low frequency range. Some of these sources e.g. GX 339-4, *GS* 112468 and Cyg X-l also have shown higher frequency QPOs in the range of 1–12 Hz at different intensity states. The frequency of the QPOs detected in these sources is usually lower than the frequency of the QPOs observed in LMXBs and this appears to be characteristic of black hole candidates. There are two black hole candidates namely GRS 1915+105 (Morgan *et al.* 1997) and GRO 1655-40 (Remillard *et al.* 1997), both superluminal jets sources, in which high frequency transient QPOs (67 Hz and 300 Hz respectively) have been observed and are interpreted as signature of the Keplerian motion of material at the innermost stable orbit around the black hole.

Recently Cui *et al.* (1998) have brought into light the relation of QPOs with one very important aspect of the black hole accretion disks, namely dragging of the relativistic frame. They have suggested that QPOs can be produced by X-ray modulation at the precession frequency of the accretion disk. Given the mass of a black hole and the QPO frequency, the specific angular momentum (described as $a_* = J/mcr_g$, where J is the angular momentum and m is the mass) of the black hole can be determined. In the low state of Cyg X-l, the spectrum consists of a hard power-law component and a very low temperature (0.1–0.2 keV) black-body component whereas in the high state the black-body component becomes stronger and the temperature is also higher. In the case of Cygnus X-l, they suggested that the high and the low intensity states in this source are due to the presence of a prograde and retrograde disk respectively (Zhang *et al.* 1997b). The high frequency QPOs (9 Hz) observed in the high state suggests that for a black hole mass of $\sim 10M_\odot$, the specific angular momentum is $a_* \sim 0.5$. With this spin parameter, the QPO frequency for a retrograde disk (in the low state) is expected to be about 2 Hz, whereas the QPOs observed in the low state including the present observation, are in the frequency range of 0.04–0.07 Hz. Additionally, for this hypothesis to explain the observed intensity and spectral changes, the specific angular momentum of the black hole should be $a_* \sim 0.75$. These differences can be reconciled with the fact that there is a large uncertainty in the mass of the black hole and inclination of the system. One important point to note about this model is that the observed changes in the QPO frequency of the black hole sources can also be explained by moderate changes in the inner radius of the disk which may arise due to radiation pressure. Both the low and the high frequency QPOs, also observed in some other black hole sources, may arise due to similar change in the sign of rotation of the accretion disk. It is very important now to do a detailed study of the QPO properties of black hole candidates in different intensity levels which will lead to a better understanding of the disk precession phenomena around the black hole sources.

Acknowledgement

It is a pleasure to acknowledge the contributions of Shri M. R. Shah, Electronics Engineer-in-charge of this experiment, Shri D. K.Dedhia, Shri K. Mukherjee, Shri V. M. Gujar and Shri S. S. Mohite, for their support in the fabrication and testing of the payload and conducting the balloon experiment. We thank the Balloon Support

Instrumentation Group and the Balloon Flight Group led by Shri M. N. Joshi, under the overall supervision of Prof. S. V. Damle.

References

Angelini, L., White, N. E., Stella, L. 1992, *IAU Circ No. 5580.*
Angelini, L., White, N. E., Stella, L. 1994, *New Horizons of X-ray Astronomy: First results from ASCA,* Ed. F. Makino & T. Ohasi, (Tokyo, Japan: Universal Academy Press) p. 429.
Belloni, T., Mendez, M., van der Klis, M., *et al.* 1996, *Astrophys. J.,* **472,** L107.
Bolton, C. T. 1972, *Nature* (*London*), **235,** 271.
Chitnis, V. R., Rao, A. R., Agrawal, P. C. 1998, *Astr. Astrophys.,* **331,** 251.
Cui, W., Zhang, S. N., Focke, W, Swank, J. H. 1997, *Astrophys. J.,* **484,** 383.
Cui, W., Zhang, S. N., Chen, W. 1998, *Astrophys. J.,* **492,** L53.
Kouveliotou, C., Finger, M. H., Fishman, G. J., *et al.* 1992, *IAU Circ No. 5576.*
Morgan, E., Remillard, R., Greiner, J. 1997, *Astrophys. J.,* **482,** 993.
Mineshige, S., Takeuchi, M., Nishimori, H. 1994, *Astrophys. J.,* **435,** L128
Miyamoto, S., Kitamoto, S. 1989, *Nature* (*London*)*,* **342,** 773.
Negoro, H., Miyamoto, S., Kitamoto, S. 1994, *Astrophys. J.,* **423,** L127.
Negoro, H., Miyamoto, S., Kitamoto, S. 1995, *Astrophys. J.,* **452,** L49.
Rao, A. R., Agrawal, P. C, Manchanda, R. K., *et al.* 1991, *Astr. Astrophys.,* **241,** 127.
Rao, A. R., Agrawal, P. C, Paul, B., *et al.* 1998, *Astr. Astrophys.,* **330,** 181.
Remillard, R. A., Morgan, E. H., McClintock, J. E. *et al.* 1997, in *Proceedings of the 18th Texas Symposium on Relativistic Astrophysics,* Ed. A. Olinto, J. Frieman & D. Schramm (Chicago: Chicago University Press), in press.
Tanaka, Y., Lewin, W. H. G. 1995, in X-Ray Binaries, Ed. W. H. G. Lewin, jan van Paradijs & E. P. J. van den Heuvel, (Cambridge University Press) p 126.
Vikhlinin, A., Churazov, E., Gifanov, M. *et al.* 1994, *Astrophys. J.,* **424,** 395.
Vikhlinin, A., Finoguenov, A., Sitdikov, A. *et al.* 1992, *IAU Circ No. 5576.*
van der Klis, M. 1995, in *X-ray Binaries,* Ed. W. H. G. Lewin, jan van Paradijs & van den Heuvel, (Cambridge University Press) p 252.
Webster, B. L., Murdin, P. 1972, *Nature* (*London*), **235,** 37.
Weisskopf, M. C, Khan, S. M., Sutherland, P. G. 1975, *Astrophys. J.,* **199,** L147.
Zhang, S. N., Cui, W, Harmon, B. A. *et al.* 1997a, *Astrophys. J.,* **477,** L95.
Zhang, S. N., Cui, W, Chen, W. 1997b, *Astrophys. J.,* **482,** L155.