THE ASTROPHYSICAL JOURNAL, 676:1184–1188, 2008 April 1

A STUDY OF THE LONG-TERM EVOLUTION OF QUASI-PERIODIC OSCILLATIONS IN THE ACCRETION-POWERED X-RAY PULSAR 4U 1626−67

RAMANPREET KAUR,[1] BISWAJIT PAUL,[2] BRIJESH KUMAR,[1] AND RAM SAGAR[1]
Received 2007 July 18; accepted 2007 December 20

ABSTRACT

We report here a study of the long-term properties of quasiperiodic oscillations (QPOs) in an unusual accreting X-ray pulsar, 4U 1626−67. This is a unique accretion-powered X-ray pulsar in which we have found the QPOs to be present during all sufficiently long X-ray observations with a wide range of X-ray observatories. In the present spin-down era of this source, the QPO central frequency is found to be decreasing. In the earlier spin-up era of this source, there are only two reports of QPO detections, in 1983 with *EXOSAT* and 1988 with *Ginga* with an increasing trend. The QPO frequency evolution in 4U 1626−67 during the last 22 years changed from a positive to a negative trend, somewhat coincident with the torque reversal in this source. In the accretion-powered X-ray pulsars, the QPO frequency is directly related to the inner radius of the accretion disk, as per the Keplerian frequency model (KFM) and the beat frequency mdel (BFM). A gradual depletion of accretion disk is reported earlier from the X-ray spectral, flux, and pulse profile measurements. The present QPO frequency evolution study shows that X-ray flux and mass accretion rate may not change by the same factor; hence the simple KFM and BFM are not able to explain the QPO evolution in this source. This is the only X-ray pulsar to show persistent QPOs and is also the first accreting X-ray pulsar in which the QPO history is reported for a long timescale relating it with the long-term evolution of the accretion disk.

Subject headings: binaries: close — pulsars: individual (4U 1626−67) — stars: neutron — X-rays: binaries

1. INTRODUCTION

The X-ray source 4U 1626−67 was discovered with the *Uhuru* satellite (Giacconi et al. 1972) in 2–6 keV band. Pulsations, with a period of 7.68 s, were first discovered by Rappaport et al. (1977) with SAS-3 observations and has been extensively monitored since then, especially with the BATSE detectors on board the *Compton Gamma Ray Observer* (*CGRO*; Chakrabarty et al. 1997; Bildsten et al. 1997). Optical counterpart of the pulsar was identified as KZ TrA, a faint blue star ($V \approx 18.5$) with little or no reddening (McClintock et al. 1977; Bradt & McClintock 1983). Optical pulsations with 2% amplitude were detected at the same frequency as the X-ray pulsations (Ilovaisky et al. 1978) and are understood to be due to reprocessing of the pulsed X-ray flux by the accretion disk (Chester 1979). A faint optical counterpart and the observed optical pulsed fraction requires the companion star to be of very small mass (McClintock et al. 1977, 1980). The X-ray light curve does not show any orbital modulation or eclipse. However, from the reprocessed pulsed optical emission and a close sideband in the power spectrum of optical light curve, an orbital period of 42 minutes was inferred (Middleditch et al. 1981). Therefore, it falls under the category of ultracompact binaries ($P_{\rm orb} < 80$ minutes), which have hydrogen-depleted secondaries to reach such short periods (Paczyński & Sienkiewicz 1981; Nelson et al. 1986).

Despite extensive searches, the orbital motion of this binary has never been detected in the X-ray pulse timing studies (Rappaport et al., 1977; Levine et al. 1988; Jain et al. 2007). A very low mass secondary, in a nearly face-on orbit can possibly account for the lack of pulse arrival time delay. Recently Jain et al. (2007) have also proposed this source to be a candidate for a neutron star with a supernova fall-back accretion disk. From the extensive timing and spectral observations both in optical and X-ray bands, it has not yet been possible to establish the presence of a binary companion, and the upper limit of the companion mass has been determined to be very low. However, the presence of an accretion disk in 4U 1626−67 is beyond any doubt. Optical spectral and timing studies confirm that most of the optical emission is strongly dominated by the accretion disk (Grindlay 1978; McClintock et al. 1980). The X-ray spectrum also shows bright hydrogen-like and helium-like oxygen and neon emission lines with red- and blueshifted components, a certain sign of accretion disk origin (Schulz et al. 2001; Krauss et al. 2007). Another direct evidence of an accretion disk in 4U 1626−67 is found from the detection of quasi-periodic oscillations, at a frequency of 40 mHz, from *Ginga* observations (Shinoda et al. 1990) and subsequently at a higher frequency of about 48 mHz from *BeppoSAX*, *ASCA*, *RXTE*, and *XMM-Newton* (Owens et al. 1997; Angelini et al. 1995; Kommers et al. 1998; Krauss et al. 2007). The QPOs have also been detected in reprocessed optical emission from both ground-based and *Hubble Space Telescope* observations (Chakrabarty 1998; Chakrabarty et al. 2001).

For more than a decade since its discovery, 4U 1626−67 was found to be spinning up with a characteristic timescale $P/\dot{P} \approx$ 5000 yr. It was found to be spinning down at about the same rate by BATSE on board *CGRO* in the beginning of 1991 (Chakrabarty et al. 1997). Even though the torque reversal was abrupt, the decrease in bolometric X-ray flux has been gradual and continuous over the past ≈30 yr (Chakrabarty et al. 1997; Krauss et al. 2007). Recently, from a set of *Chandra* monitoring observations, Krauss et al. (2007) have established that the bolometric X-ray flux and various emission line fluxes have decreased continuously over the last few years, indicating a gradual depletion of the accretion disk. The X-ray flux and mass accretion rate are directly related, and these are likely to be related to the mass and extent of the material in the accretion disk. Therefore, the observed gradual decrease in X-ray flux indicates a depletion of material in the accretion disk of the pulsar. Another signature of this is seen by Krauss et al. (2007) as a change in the pulse profile of the pulsar as compared to the earlier observations.

[1] Aryabhatta Research Institute of Observational Sciences, Manora Peak, NainiTal 263 129, India.
[2] Raman Research Institute, C. V. Raman Avenue, Sadashivanagar, Bangalore 560 080, India.

TABLE 1
Log of Observations of 4U 1626−67

Telescope	Year	ObsID	No. of Pointings	Observation Span[a] (ks)	Time on Source (ks)
EXOSAT ME	1983	128	1	27	27
ASCA GIS	1993	40021000	1	72	40
ASCA SIS	1993	40021000	1	70	25
BeppoSAX MECS	1996	10017001	1	162	116
BeppoSAX LECS	1996	10017001	1	128	35
RXTE PCA	1996	P10101	9	395	147
	1996	P10144	1	13	10
	1997	P20146	14	33125	13
	1998	P30058	3	9167	40
		P30060	10	2758	44
XMM-Newton pn	2001	0111070201	1	17	16
	2003	0152620101	1	84	84

[a] End time − start time.

In the present work, we investigate the QPO frequency evolution of 4U 1626−67 over a long period and discuss the relation of the change in QPO frequency with the a possible recession of the inner accretion disk.

2. OBSERVATIONS AND ANALYSIS

4U 1626−67 has been observed with various X-ray telescopes over different epochs of time. Table 1 lists the log of observations of 4U 1626−67 that were found to be useful for the present study. Details of individual observations described below are in chronological order. Detection of QPOs at around 48 mHz have been mentioned from some of these observations, sometimes from a different instrument also (*Ginga* [Shinoda et al. 1990], *ASCA* [Angelini et al. 1995], *BeppoSAX* [Owens et al. 1997], *RXTE* [Kommers et al. 1998; Chakrabarty 1998], and *XMM-Newton* [Krauss et al. 2007]). However, the QPO frequencies measured from these observations are often not reported with good enough accuracy to investigate a slow frequency evolution. For the present study, we have therefore reanalyzed the data and measured the QPO parameters with the highest possible accuracy.

An *EXOSAT* medium energy (ME) proportional counter light curve of 4U 1626−67 was obtained from HEASARC archive with the time resolution of 0.3125 s for an observations made on 1983 August 30 for 27 ks. The ME light curve of another observation made by *EXOSAT* on 1986 March 30 for ≈84 ks and reported earlier by Levine et al. (1988) is not available in the HEASARC Archive.

ASCA observations of 4U 1626−67 were made on 1993 August 11 with the two Gas Imaging Spectrometers (GIS2 and GIS3) and the two Solid State Imaging Spectrometers (SIS0 and SIS1) and light curves with total useful exposures of 40 and 25 ks were obtained for the GIS and SIS, respectively. During the *ASCA* observation, the GIS detectors were operated in Pulse Height mode and SIS detectors were operated in Fast mode and the light curves were extracted from the unscreened high bit mode data with the minimum time resolution of 0.125 s for both GIS and SIS detectors. The light curves from the pairs of GIS and SIS instruments were added and a single power spectra is generated with the summed light curves.

4U 1626−67 was observed with *BeppoSAX* on 1996 August 9 for 116 ks by the three units of Medium Energy Concentrator Spectrometer (MECS) and for 35 ks by the Low Energy Concentrator Spectrometer (LECS). Light curves were extracted from all the instruments with 0.125 s. A single summed light curve was generated from three light curves of the MECS instruments to increase the signal-to-noise ratio.

RXTE PCA pointed observations of the source were made from 1996 February to 1998 August. In 1996, the observations were made in the beginning of the year and at the end of the year under ObsIDs P10101 and P10144, respectively. The observations made under ObsID P10101 covers a time span of almost 5 days from MJD 50123 to 50128. There were nine observations in this ObsID each lasting for 4–8 hr. A single observation was made under ObsID P10144 for ≈5 hr on MJD 50445. In 1997, all the observations were made under ObsID P20146 and cover a time range of almost a year, from MJD 50412 to MJD 50795, but individual observations were made only for a few minutes. In 1998, *RXTE* PCA made observations under two ObsIDs, P30058 and P30060. There were three observations made under ObsID P30058, out of which two observations were made on MJD 50926 and the third observation was made on MJD 51032. In ObsID P30060, there were 10 short observations of about an hour each. For almost all the observations of *RXTE*, all five PCUs were on. Light curves were extracted from observations of 4U 1626−67 with a time resolution of 0.125 s using the Standard-1 data, which cover the entire 2–60 keV energy range of the PCA detectors. We divided all the *RXTE* PCA observations from 1996 to 1998 into three segments, from MJD 50123 to 50128, 50412 to 50795, and 50926 to 51032. The signal-to-noise ratio of the power spectra generated from the individual observations made between MJD 50412 and MJD 50795 was too poor to detect QPO except on MJD 50445, so a single power spectrum was produced by combining power spectra of all observations made between MJD 50412 and MJD 50795.

XMM-Newton has observed 4U 1626−67 four times, but a significant amount of science data was present only in two of these observations, made under ObsIDs 0111070201 and 0152620101, listed in Table 1. We have analyzed data only from the pn detector of European Photon Imaging Camera (EPIC) on board *XMM-Newton*, which operates in the energy band of 0.15–15 keV. Light curves were extracted with a time resolution of 0.125 s for both the observations.

All the light curves were divided into small segments, each of length 1024 s, and a power density spectrum of each segment was generated. The power spectra were normalized such that their integral gives the standard rms fractional variability, and the expected white noise was subtracted. A final power spectrum was generated with the average of all the power spectra generated for

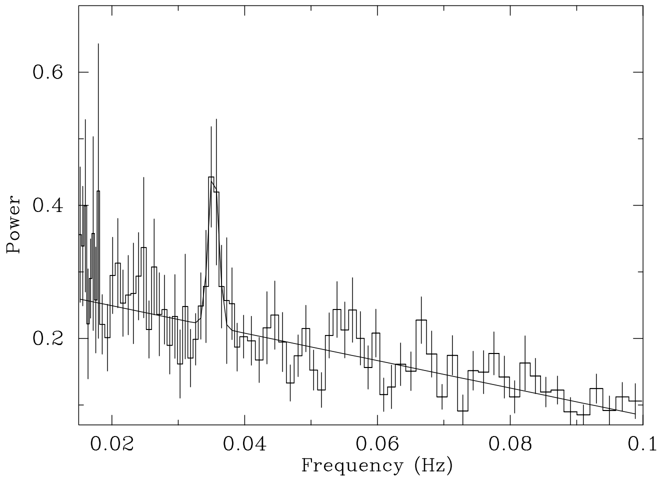

FIG. 1.—Power density spectrum generated from the light curve obtained from the *EXOSAT* observation made on 1983 August 30.

each of the observations listed in Table 1. Flares with duration of 1000 s are clearly seen in the *EXOSAT* data, as mentioned by Levine et al. (1988). However, these flares are not detected in rest of the data mentioned in Table 1. A QPO at a frequency of ∼48 mHz is clearly seen in the power spectra of all the data sets except that from *EXOSAT* observations, during which it is detected at ∼36 mHz. Figure 1 shows the QPO detection from the *EXOSAT* observations made on 1983 August 30 in the range of 15–100 mHz. A Gaussian model is fitted to the QPO feature to determine its central frequency and width (FWHM of Gaussian) for all the data sets. The continuum of the power spectrum in the band of 20–80 mHz is fitted with a constant or a linear model. The uncertainty of the Gaussian model peak at 1 σ confidence interval is quoted as an error on the Gaussian center.

The QPO feature detected in the power spectrum of *EXOSAT* data is quite narrow ∼2 mHz as compared to the QPOs seen in rest of the data with a width of ∼4–5 mHz. Figure 2 shows power spectra in the frequency range 26–72 mHz for the observations listed in Table 1 except the *EXOSAT* observations. Different constant numbers were added to each plot for clarity. A best-fitted Gaussian model for the QPOs and a constant model or a linear model for the continuum is shown on each plot with a solid line. A dotted vertical line at the best-fitted Gaussian center to the *ASCA* 1993 data is plotted in the same figure. A shift of ∼2 mHz is clearly seen from bottom to the top plot shown in Figure 2.

The evolution of the QPO central frequency as observed by various X-ray telescopes in both spin-up and spin-down eras is shown in Figure 3. An error bar plotted on each point in Figure 3 represents 1 σ error estimates. We could not find *Ginga* observations of 4U 1626−67 made in 1988 July from archive data; thus the central frequency of QPOs and error estimate on it is taken from Shinoda et al. (1990) and is also shown in Figure 3. To confirm the consistency of QPO frequency for each data set listed in Table 1, the QPO frequencies were measured from smaller segments of the data, 10 each for the 1996 *RXTE* observation and the 2004 *XMM-Newton* observation. The values determined from smaller segments have larger uncertainties, but within the uncertainties these values are consistent with the QPO frequency measured using the complete data sets in each case. It can be clearly seen in Figure 3 that the QPO central frequency has increased from 1983 to 1993 and that it gradually decreased from 1993 to 2004. However, the lack of observations does not allow us to define an exact time when the QPO frequency evolution changed from an increasing trend to a decreasing trend. The observations

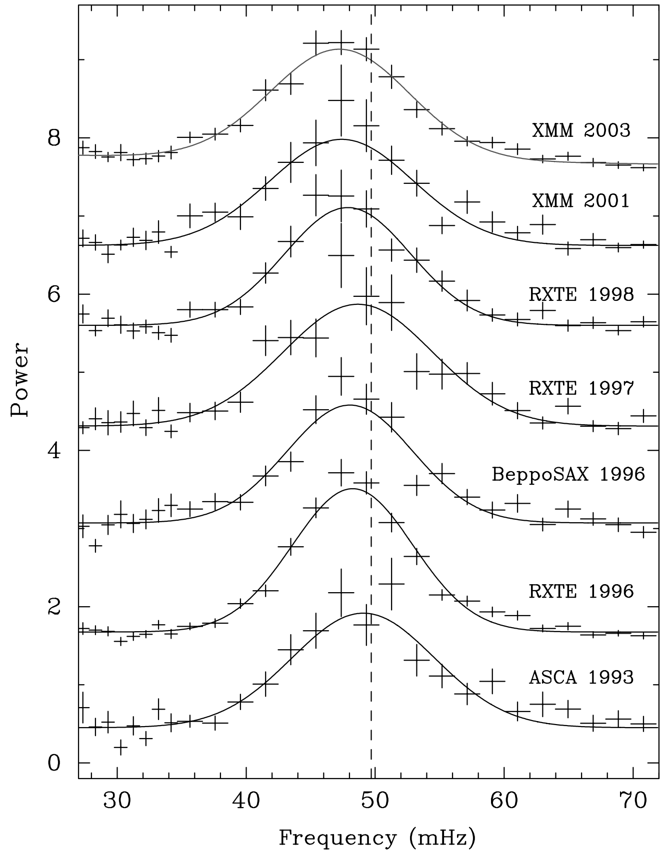

FIG. 2.—All power density spectra are generated from the light curves obtained from observations listed in Table 1. in chronological order. Different constant numbers were added to each plot for clarity. The year of observations is written along with each power density spectrum. A vertical line is drawn at 49.77 mHz, QPO frequency of *ASCA* 1993 observations, to clearly show the decrease in QPO frequency with time.

from 1993 to 2004 showed a frequency decrease of ∼2.3 mHz, while the error bars on all the data points during this era are within 0.4 mHz, except the *ASCA* 1993 data point, for which the error bar is 0.6 mHz, confirming the real decrease in QPO frequency with time. The QPO frequency derivative during spin-down era is $\sim(0.2 \pm 0.05)$ mHz yr^{-1}. A linear fit is shown on the data points with a solid line in the spin-down era in Figure 3. The reduced χ^2 of the linear fit is 1.07 for 5 degrees of freedom. To

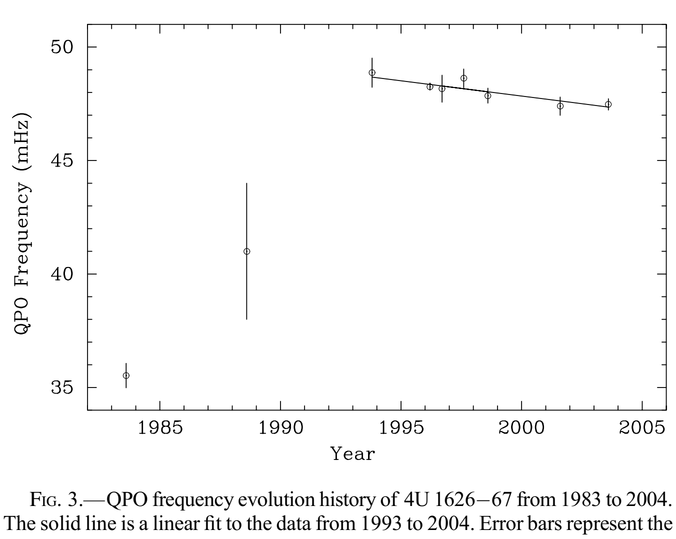

FIG. 3.—QPO frequency evolution history of 4U 1626−67 from 1983 to 2004. The solid line is a linear fit to the data from 1993 to 2004. Error bars represent the 1 σ confidence intervals.

further confirm the linearity, a constant model is also fitted to the data from 1993 to 2004. The reduced χ^2 for a constant model is 3.22 for 6 degrees of freedom, indicating a poor fit as compared to the linear fit.

3. DISCUSSION

In high magnetic field X-ray pulsars, the QPO frequency is in the range of a few mHz to a few Hz (Kaur et al. 2007). The QPOs are known to occur sporadically only in a few percent of the X-ray observations. For example, QPOs are detected in only 15% of the out-of-eclipse observations of Cen X-3 (Raichur & Paul 2007). Our independent investigation of the *RXTE* PCA light curves of several persistent sources show that the QPOs are quite rare. Exceptions to this are some of the transient sources, such as 3A 0535+262 (Finger et al. 1996) and XTE J1858+034 (Paul & Rao 1998), which showed QPOs during most of the observations made during their outbursts. In the present study, using light curves of 4U 1626−67 taken with various observatories over a period of more than 20 years, we have detected QPOs in every single observation of sufficient length. This is the first accretion-powered pulsar for which the QPO study has been made over a long timescale. In this regard, 4U 1626−67 is unique among persistent high magnetic field accreting X-ray pulsars. It shows that the accretion disk of the pulsar is quite stable, holding this feature for years. However, in a few cases, the observation duration was not long enough to make accurate measurements of the QPO parameters.

QPOs in accretion-powered X-ray sources are widely believed to arise due to inhomogeneities near the inner accretion disk. The QPO frequency is the Keplerian frequency at the inner disk radius and is therefore positively related to the mass accretion rate or the X-ray luminosity. If the compact object is a neutron star, the inner disk is coupled with the central object through the magnetic field lines and QPOs corresponding to the beat frequency between the spin frequency and the Keplerian frequency of the inner disk can also be seen. In accretion-powered high magnetic field X-ray pulsars, the two different QPOs are never seen to occur in the same source. In some of the sources, such as 4U 1626−67, the QPO frequency is lower than the spin frequency, and therefore the QPOs can only be explained by the BFM.

According to both KFM and BFM, the radius of the QPO production area, $r_{\rm QPO}$, is defined as

$$r_{\rm QPO} = \left(\frac{GM_{\rm NS}}{4\pi^2\nu_k^2}\right)^{1/3}, \qquad (1)$$

where G is the gravitational constant, $M_{\rm NS}$ is the mass of the neutron star, and ν_k is the Keplerian frequency of the inner accretion disk.

The radius of the inner accretion disk, r_M can be defined as

$$r_M = 3\times 10^8 L_{37}^{-2/7}\mu_{30}^{4/7}, \qquad (2)$$

where L_{37} is the X-ray luminosity in units of 10^{37} ergs s^{-1} and μ_{30} is magnetic moment in units of 10^{30} cm^3 gauss. If the QPOs are as per Keplerian frequency model ($\nu_k = \nu_{\rm QPO}$, where $\nu_{\rm QPO}$ is QPO frequency of the pulsar), then we expect $\nu_k \propto L_{37}^{3/7}$ or $\nu_{\rm QPO} \propto L_{37}^{3/7}$. The flux of 4U 1626−67 has decreased from 0.32 to 0.15 units from 1993 to 2004 (Krauss et al. 2007), which implies that the change in QPO frequency is expected to be ∼27% from 1993 to 2004. The present QPO observations have shown only 4% decrease in QPO frequency during the same time. However, the KFM is not valid in this source. In the BFM ($\nu_k = \nu_{\rm QPO} + \nu_s$, where ν_s is pulsar spin frequency), the inner disk frequency is higher as compared to KFM, and the relative change in QPO frequency is expected to be even larger. Therefore, we see that the evolution of QPO frequency and the decrease of X-ray flux cannot be explained by the standard QPO generation mechanism and the usual relation between the inner disk and X-ray luminosity. We can consider two possibilities. One is that the QPOs are not generated from the inner disk, but are generated due to reprocessing in some outer structure of the disk. This is not very likely due to the large (up to 15%) rms in the QPO feature. The second possibility is that the observed X-ray flux change is not due to a change of mass accretion rate by the same factor. Many X-ray sources show X-ray flux variation at long timescales of up to a few months due to obstruction provided by a complex accretion disk mechanism.

The earlier study by Chakrabarty et al. (1997) concluded that there was an abrupt torque reversal in 1990 and that the system moved from spin-up to spin-down era with a characteristic timescale $P/\dot{P}$ of ∼5000 yr. The two QPO detections with *EXOSAT* (35 mHz in 1983) and *Ginga* (40 mHz in 1988) are during the spin-up era of this pulsar, with an increasing trend, while the observations from 1993 to 2004, in the spin-down era, showed a slow decreasing trend in QPO frequency with time, somewhat coincident with the torque reversal in this source, shown in Figure 3. QPO frequency is found to be decreasing in the spin-down era with a frequency derivative of $\sim(0.2 \pm 0.05)$ mHz yr^{-1}. The X-ray spectral and flux evolution studies, along with pulse profile changes of 4U 1626−67 by Krauss et al. (2007), have indicated that the accretion disk in this source is depleting with a timescale of 30–70 yr. Krauss et al. (2007) also estimated the long-term average accretion rate to be $3\times 10^{-11}\ M_\odot$ yr^{-1} for a distance ≥3 kpc. However, a gradual change in mass accretion rate cannot explain the unique torque reversal phenomena of this source (Li et al. 1980).

4. CONCLUSIONS

Our main conclusions are the following:

1. We have detected very persistent quasi-periodic oscillations in the unique accretion-powered X-ray pulsar 4U 1626−67.
2. Using data from several observatories, we have detected a gradual evolution of the oscillation frequency over a period of 22 years.
3. The frequency evolution indicates a possible recession of the accretion disk of the pulsar during the present spin-down era.

We thank an anonymous referee for valuable comments and suggestions that helped us to improve the paper. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

REFERENCES

Angelini, L., White, N. E., Nagase, F., Kallman, T. R., Yoshida, A., Takeshima, T., Becker, C. M., & Paerels, F. 1995, ApJ, 449, L41
Bildsten, L., Chakrabarty, D., et al. 1997, ApJS, 113, 367
Bradt, H. V. D., McClintock, J. E. 1983, ARA&A, 21, 13
Chakrabarty, D. 1998, ApJ, 492, 342
Chakrabarty, D., Homer. L., Charles, P. A., & O'Donoghue, D. 2001, ApJ, 562, 985
Chakrabarty, D., et al. 1997, ApJ, 474, 414

Chester, T. J. 1979, ApJ, 227, 569
Finger, M. H., Wilson, R. B., & Harmon, B. A. 1996, ApJ, 459, 288
Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., & Tananbaum, H. 1972, ApJ, 178, 281
Grindlay, J. E. 1978, ApJ, 225, 1001
Ilovaisky, S. A., Motch, C., & Chevalier, C. 1978, A&A, 70, L19
Jain, C., Paul, B., Joshi, K., Dutta, A., & Raichur, H. 2007, J. Astrophys. Astron., submitted
Kaur, R., Paul, B., Raichur, H., & Sagar, R. 2007, ApJ, 660, 1409
Kommers, J. E., Chakrabarty, D., & Lewin, W. H. G. 1998, ApJ, 497, L33
Krauss, M. I., Schulz, N. S., & Chakrabarty, D. 2007, ApJ, 660, 605
Levine, A., Ma, C. P., McClintock, J., Rappaport, S., van der Klis, M., & Verbunt, F. 1988, ApJ, 327, 732
Li, F. K., Joss, P. C., McClintock, J. E., Rappaport, S., & Wright, E. L. 1980, ApJ, 240, 628
McClintock, J. E., Bradt, H. V., Doxsey, R. E., Jernigan, J. G., Canizares, C. R., & Hiltner, W. A. 1977, Nature, 270, 320
McClintock, J. E., Li, F. K., Canizares, C. R., & Grindlay, J. E. 1980, ApJ, 235, L81
Middleditch, J., Mason, K. O., Nelson, J. E., & White, N. E. 1981, ApJ, 244, 1001
Nelson, L. A., Rappaport, S. A., & Joss, P. C. 1986, ApJ, 311, 226
Owens, A., Oosterbroek, T., & Parmar, A. N. 1997, A&A, 324, L9
Paczyński, B., & Sienkiewicz, R. 1981, ApJ, 248, L27
Paul, B., & Rao, A. R. 1998, A&A, 337, 815
Raichur, H., & Paul, B. 2007, ApJ, submitted
Rappaport, S., Markert, T., Li, F. K., Clark, G. W., Jernigan, J. G., & McClintock, J. E. 1977, ApJ, 217, L29
Schulz, N. S., Chakrabarty, D., Marshall, H. L., Canizares, C. R., Lee, J. C., & Houck, J. 2001, ApJ, 563, 941
Shinoda, K., Kii, T., Mitsuda, K., Nagase, F., Tanaka, Y., Makishima, K., & Shibazaki, N. 1990, PASJ, 42, L27