COUPLED HBO AND NBO VARIATIONS IN THE Z SOURCE GX 5-1: INNER ACCRETION DISK AS THE LOCATION OF QPOs

K. Sriram1, A. R. Rao2, and C. S. Choi1

1 Korea Astronomy and Space Science Institute, Daejeon 305-348, Republic of Korea; astrosriram@yahoo.co.in
2 Tata Institute of Fundamental Research, Mumbai 400005, India

Received 2011 July 10; accepted 2011 November 11; published 2011 November 28

ABSTRACT

The simultaneous and coupled evolution of horizontal branch oscillation (HBO) and normal branch oscillation (NBO) in Z-type sources suggests that the production of HBO is connected to NBO and is caused by changes in the physical/radiative properties of the inner accretion disk, although there is a lack of substantial spectral evidence to support this. In this Letter, we present the results of an analysis of an RXTE observation of the Z source GX 5-1, where the 6 Hz NBO is simultaneously detected along with an HBO at 51 Hz. The variations in the intensity and the associated power density spectrum indicate that the HBO and NBO are strongly coupled, originating from the same location in the inner accretion disk. The absence of HBO and NBO in the lower energy bands, an increase in the rms amplitude with energy, and a smooth transition among them suggest that they are produced in the hot inner regions of the accretion disk. Based on a spectral analysis, we found a signature of changing or physically modified inner disk front during the coupled HBO and NBO evolution. We explore the various models to explain the observed phenomenon and propose that the NBO is affiliated to the oscillations in the thick/puffed-up inner region of the accretion disk.

Key words: accretion, accretion disks – binaries: close – stars: individual (GX 5-1) – X-rays: binaries

1. INTRODUCTION

Various mechanisms have been suggested to explain the quasi-periodic oscillations (QPOs) in neutron star low-mass X-ray binaries (NS LMXBs), but the location of their production region in the accretion disk and the connecting physical/radiative processes are not yet clarified. Of the two broad classifications of NS LMXBs, viz., atoll and Z-type sources, the latter has a high X-ray luminosity of $\sim 10^{38}$ erg s$^{-1}$ (close to the Eddington limit), which is secularly varying along three main branches forming a Z shape in the hardness intensity and color–color diagram. The associated branches from top to bottom are the horizontal branch (HB), normal branch (NB), and flaring branch (FB), and NB connects the other two (Hasinger & van der Klis 1989; Hasinger et al. 1990). Broad features in the power density spectra known as QPOs are often observed along the branches. Apart from twin kHz QPOs (van der Klis 1998), different low- and intermediate-frequency QPOs have been observed in Z-type NS LMXBs named after their branches, viz., horizontal branch oscillations (HBOs), normal branch oscillations (NBOs), and flaring branch oscillations (FBOs; van der Klis 2006). The systematic Z-track evolution and the different oscillations are considered to be caused by changes in the mass accretion rate but a few studies seem to rule out any relation to the accretion rate (Lin et al. 2009; Homan et al. 2010).

As the Z sources traverse from HB to NB, the HBO smoothly changes to NBO (typically a $\sim 50$ Hz peak is converted into a $\sim 6$ Hz peak), though the physical causes in the accretion disk, responsible for this variation, are unknown. There are two main models which generally explain the observed features of NBO. In the radiation-hydrodynamical model (Fortner et al. 1989; Miller & Lamb 1992), NBO is associated with the oscillations in the optical depth of radially inflowing hot material. In the other model, NBO is a result of the Keplerian rotation of the thick accretion disk, with variations in its dynamical properties (Alpar et al. 1992).

Many models were proposed to explain the generation of HBOs. In the magnetospheric beat-frequency model, HBO arises due to the orbital motion at a suitable magnetospheric radius (Alpar & Shaham 1985; Lamb et al. 1985). The sonic-point beat-frequency model, an extension of the magnetospheric beat-frequency model, was proposed to explain the simultaneous presence of HBOs and kHz QPOs (Miller et al. 1996, 1998). In the relativistic precession model (Stella & Vietri 1999; Stella et al. 1999), HBOs and kHz QPOs are caused by the relativistic frame dragging and relativistic periastron precession of an eccentric ring. In the two-oscillator model (Titarchuk & Osherovich 1999; Titarchuk et al. 1999), HBO and kHz QPOs are the result of oscillations in a hot blob and the Keplerian motion of the disk.

Both NBO and HBO are observed on numerous occasions, but much importance has been given to the timing domain analysis (Cir X-1, Soleri et al. 2009; GX 340+0, Penninx et al. 1991; GX 17+2, Wijnands et al. 1996; Homan et al. 2002; Cyg X-2, Wijnands et al. 1997; GX 5-1, Dotani 1988). Yu (2007) found HBO and NBO along with twin kHz QPOs in the source Sco X-1 and suggested that NBO resulted from the outward disk movement, but there was no systematic spectral study to support this idea. In this Letter, we present the timing and spectral analysis of an RXTE observation of GX 5-1 during which a smooth transition of HBO–NBO–HBO is observed. The spectral study indicates that the inner disk edge moves out radially or it gets thickened or puffed up, and the properties of the disk are substantially modified when compared to the properties of the disk with HBO.

GX 5-1 is the second brightest Z source (Bradt et al. 1968), located at a distance of 9.0 $\pm$ 2.7 kpc (Christian & Swank 1997) with a luminosity in the range of $6.0-7.6 \times 10^{38}$ erg s$^{-1}$ (1–30 keV; Jackson et al. 2009), and it resembles Cyg X-2 due to its HB nature (Kuulkers et al. 1994). This source exhibits HBO and NBO along with kHz QPOs (van der Klis et al. 1985; Lewin et al. 1992; Wijnands et al. 1998), but FBO has not
been detected yet. The kHz QPOs are not seen at NB and FB, which are often observed in Sco X-1. The detection of radio and infrared emission provides a clue for the existence of a jet (Fender & Hendry 2000; Jonker et al. 2000).

2. DATA ANALYSIS AND RESULTS

RXTE observed the source GX 5-1 on 1997 July 28 spanning two satellite orbits (ObsID 20055-01-04-00). We used the generic binned data (\( B_{250\mu s}, 4M_0 - 35, Q \)) for obtaining the power density spectrum (PDS) and the 16 s binned data (standard 2 data) from the Proportional Counter Unit 2 (PCU2) for spectral studies; PCU2 is the best calibrated among the PCUs (Jahoda et al. 2006). We added 0.5% systematic errors to the spectral data to account for the calibration uncertainties. During this observation GX 5-1 was in the upper NB and the intensity was nearly constant in the first orbit (14913 ± 50 counts s\(^{-1}\)) with an HBO at 49 ± 1 Hz but the intensity varied considerably in the second orbit, showing a dip-like feature.

The left panel in Figure 1 shows the light curve of the second orbit in the energy range 2–13 keV, which is divided into eight segments (a–h) for a detailed analysis. The intensity decreases to a lower state (≈14,000 counts s\(^{-1}\)) in about 1000 s and subsequently recovers to the initial state (≈15,000 counts s\(^{-1}\)), similar to the variation seen in the X-ray dips of LMXBs. The right panels in Figure 1 show the PDS in different energy bands, where the binned data are available in four energy bands, i.e., 1.94–3.70 keV, 4.05–5.82 keV, 6.18–8.68 keV, and 9.03–12.99 keV and the event mode for the 13.36–118.00 keV band. An NBO (6.0 ± 0.7 Hz with an rms 2.00% ± 0.22%) and an HBO (51.0 ± 1.0 with an rms 2.28% ± 0.30%) were found in the energy band 1.94–12.99 keV. The 6 Hz NBO and 51 Hz HBO were not present in the lower (<5.82 keV) and higher (>13.36 keV) energy bands and were prominent in the intermediate-energy bands i.e., 6.18–8.68 keV (7.1σ for HBO and 7.5σ for NBO) and 9.03–12.99 keV (3.2σ for HBO and 6.5σ for NBO). The HBO rms increased from 2.10% ± 0.30% (6.18–8.68 keV) to 4.94% ± 0.76% (9.03–12.99 keV) and NBO rms increased from 1.92% ± 0.23% to 4.07% ± 0.49%.

Figure 2 displays the best-fit PDS for the phases of ingress (or phase I: a+b+c), dip (II: d+e+f), and egress (III: g+h). In phase I, the HBO was detected at a significance level of 6.4σ (rms 2.58% ± 0.31%) and its strength decreased in phase II (rms 1.55% ± 0.35%) along with an appearance of NBO at 6 Hz (4.5σ; rms 1.92 ± 0.42) and HBO was later observed (4.2σ) in phase III. It is evident that the 6 Hz NBO is not present in phases I and III. To study the evolution of PDS during the intensity variation, we obtained the PDS of each segment...
Figure 2. Best-fit (dashed lines) PDS for the ingress (or phase I: a+b+c), the dip (II: d+e+f), and the egress (III: g+h) phase of the light curve. The Poisson level is not subtracted. The HBO and NBO rms and the errors (in brackets) are shown.

which is shown in Figure 3, along with the rms value and error. It is clear that the disappearance of HBO is almost balanced by the simultaneous appearance of NBO, indicating a common physical origin behind the observed phenomenon.

Both the eastern (a multi-color disk blackbody model plus a Comptonization model—diskbb+CompTT) and the western (a simple blackbody model, bbody, plus CompTT) approaches were used to fit the spectra of the three phases after excluding various other possible models such as a single power-law, CompTT, diskbb+power-law, bbody+power-law, etc. The hydrogen equivalent column density was fixed at $6.6 \times 10^{22}$ cm$^{-2}$ (Jackson et al. 2009). We confirmed that the allowance of the column density to be free does not improve the fit significantly, indicating that the observed intensity variation is not related to absorption by dense blobs intervening in the line of sight, as is often observed in dipping X-ray sources. The top left panels of Figure 4 show the best-fit spectra by the diskbb+CompTT model and the top right panels represent the residuals when we apply the best-fit parameters of the phase I spectrum to the spectra from other phases. The residuals in the phase II spectrum suggest that the accretion disk properties have significantly changed at this phase. The best-fit spectral parameters of the three phases are given in Table 1 for both adopted approaches. The source luminosity (in 2–10 keV) varied from $4.54 \times 10^{38}$ erg s$^{-1}$ (phase I) to $4.44 \times 10^{38}$ erg s$^{-1}$ (phase II).

It is difficult to meaningfully quantify the variations of spectral parameters because of the poor data statistics of the phase spectra, but residuals clearly indicate that there is a spectral difference between phases I and II. To discern the difference, we investigated the minimum set of parameters that are sufficient and significant to justify the spectral change between the phases. We first fitted the phase I and II spectra (using the eastern model) simultaneously with the phase II parameters tied to the best-fit parameters obtained from the phase I spectrum. The large value of $\chi^2$/dof (=2998/104) clearly indicated that the spectrum has changed during the intensity variation (Table 1). We then found a decrease in the value of $\chi^2$/dof as diskbb normalization ($N_{\text{disk}}$) and CompTT normalization were allowed to be free, but the values of reduced $\chi^2$ were still unacceptable, indicating the requirement of additional parameter variation. A substantial improvement of the fit was achieved by allowing the inner disk temperature ($kT_{\text{in}}$) to be free. After this step, any more significant improvement was not obtained even though all the other parameters were allowed to be free. The $F$-test values and probabilities indicate that the minimum set of spectral parameters needed to vary are the normalizations of diskbb and CompTT and the inner disk temperature (Table 1). The simultaneous fit results for all the three phases are summarized in Table 1. The analysis of the contour plot shows that the disk normalization, which is a close
measure of inner disk radius \( N_{\text{disk}} \propto R_{\text{in}}^2 \), varied significantly (at >99% confidence level, bottom left panel of Figure 4). We applied the same method to the phase II and III spectra and found similar results (Table 1 and bottom right panel of Figure 4). The study strongly suggests that the inner disk radius varied during the simultaneous evolution of HBO and NBO.

3. DISCUSSION AND CONCLUSION

We have presented a detailed systematic study of the RXTE observation of GX 5-1 when the powers of NBO and HBO were varying simultaneously (Figures 2 and 3). Yu (2007) found NBO, HBO, and twin kHz QPOs simultaneously in the source Sco X-1 and suggested that the generation of NBO is due to the radial outward movement of disk but this conclusion was not supported by any spectral signatures. In this Letter, we confirm such a disk movement during the evolution of the HBO–NBO–HBO transition and propose that the associated inner disk edge has either significantly moved or puffed up.

We found that the ratio of NBO to HBO rms is close to 2 (panel (d) in Figure 3), similar to the value of Sco X-1 (Yu 2007), and this ratio drops to 0.4 in panel (g) in Figure 3. The absence of HBO and NBO in low-energy bands, relatively high amplitude of NBO in 9.03–12.99 keV (Figure 1), and smooth transition of HBO–NBO–HBO (Figure 3) indicate that the QPOs are arising from a hot region in the inner accretion disk. The simultaneous spectral fit result suggests that the inner disk edge moves out when NBO is dominant and otherwise it moves in (Figure 4 and Table 1). The observed spectral variations can be explained in the framework of the radiation-hydrodynamical model: the disk material leaves the inner edge and falls on to the NS surface covered with a hot corona. The outward radiative pressure halts or pushes back the inner disk edge, which can cause the relative increase of the observed disk normalization. Alpar et al. (1992) pointed out that the rotation of a thick disk in the inner region could cause the observed NBOs. In this scenario, however, the twin kHz QPOs should not be seen because of the slow dynamical movement but are often observed, e.g., in Sco X-1 (where kHz QPO is also observed at normal and flaring branches). From the above discussion, we suggest that the oscillation frequency at the inner edge (at 51 Hz) is abated by the outward radiation pressure and results in a 6 Hz NBO. Since the vertical height and surface density of the disk are expected to increase during the process, the observed increase in the disk normalization could be explained.

In the two-oscillator model, the perpendicular mode \( (\nu_{LL}) \) of oscillating hot blob in magnetosphere generates the HBO (Titarchuk et al. 1999) and if the mass of the blob increases, frequency of that mode would shift to a lower frequency not much affecting the X-ray continuum. We speculate that whatever the oscillating mechanism may be the observed smooth transition of HBO to NBO could be due to an increase in the participating mass in the oscillations. Our spectral results suggest that when the disk inner front radius, which is the probable site for the transition boundary, is increased, it gets thickened or puffed up due to both the outward radiation pressure and the accumulation of matter coming from the outer region of the disk. In this scenario, it is quite possible that the
The Astrophysical Journal Letters, 743:L31 (7pp), 2011 December 20

Sriram, Rao, & Choi

Figure 4. Top (left): the unfolded spectra for phases I (top), II (middle), and III (bottom), using the diskbb+CompTT model are shown. Top (right): residuals resulting from modeling the spectra of all phases using the best-fit parameters for phase I spectrum. Bottom (left and right): significance contour plots between diskbb normalization ($N_{\text{disk}}$) of phase I and phase II, and phase III and phase II obtained during the simultaneous fit procedure (see the text). Contours show the 68%, 90%, and 99% confidence levels. Plots clearly suggests that $N_{\text{disk}}$ is different for the three phases at more than 99% confidence level.

The structure of the blob would be altered significantly and the quasi-coherent perpendicular motion of the blob might have been disturbed/randomized to produce the broad 6 Hz NBO instead of the 51 Hz HBO. The other possible scenario could be that the Keplerian motion of the disk became super-Keplerian, thus affecting the oscillations (Titarchuk et al. 1998) in the vertical structure of the disk and have respective dependency on the oscillation frequencies ($\nu_{v}$ (viscous oscillations) $\propto L^{-1}$ (thickness) and $\nu_{b}$ (break frequency) $\propto L^{-2}$; Titarchuk & Osherovich 1999). The NBOs are always found to be <20 Hz which implies that these flows would steeply affect these oscillations.

Casella et al. (2005) associated HBO, NBO, and FBO to C, B, and A type QPOs in black hole binaries (BHBs). In general, type B, A QPOs and their transitions are often observed during the very high (VH)/steep power-law (SPL) state (McClintock & Remillard 2004) or intermediate (IM) state (Belloni 2010). In this state, the accretion disk is considered to contain a compact corona (a low electron temperature with a high optical depth) along with a marginally truncated high-temperature Keplerian disk (Done & Kubota 2006; Sriram et al. 2007, 2010). A broad QPO at 6 Hz is often observed in a few BHBs, e.g., XTE J1550-564 (Homan et al. 2001), XTE J1859+226 (Casella et al. 2004), and GX 339-4 (Nespoli et al. 2003; Belloni et al. 2005). A similar transient variation from a type B to a type A QPO was also observed in H1743-322 (Homan et al. 2005) and GRS 1915+105 (Soleri et al. 2008). It was found that transient changes in QPOs are often associated with source intensity variations. The 6 Hz NBO is observed only during a characteristic transition in both Z-type sources and BHBs, which indicates that a common physical process is occurring at the inner region of the disk in both sources.

In a few atoll sources, similar QPOs varying between 5 and 14 Hz with a relatively high coherence were reported (Wijnands et al. 1999; Wijnands & van der Klis 1999; Belloni et al. 2004). These detections and a low mass accretion rate in atoll sources pose a distinct challenge to the models explaining the 6 Hz NBO in Z sources. It was found that in atoll sources and BHBs these
Note. The corresponding subscripts dbb and b denote the diskbb and bbody models. Errors are quoted at a 90% confidence level. The unabsorbed flux in 3.0–25.0 keV is given in units of \(10^{-8}\) erg cm\(^{-2}\) s\(^{-1}\). The simultaneous fit results between phases I and II, and phases II and III are shown. The best-fit parameter values from the simultaneous fit to the three phase spectra are also listed.

### Simultaneous Fit Result

| Parameters | I             | II            | III            |
|------------|---------------|---------------|---------------|
| \(kT_{\text{in}}\) (keV)\(^{a}\) | 2.13 ± 0.05   | ...           | 2.00 ± 0.04   | 2.17 ± 0.05 |
| \(N_{\text{disk}}\)\(^{b}\) | 45 ± 5        | ...           | 54 ± 6        | 47 ± 5     |
| \(kT_{\text{bb}}\) (keV)\(^{c}\) | ...           | 1.51 ± 0.06   | ...           | 1.43 ± 0.07 |
| \(N_{\text{bb}}\)\(^{d}\) | 0.079 ± 0.016 | ...           | 0.08 ± 0.015  | ...         |
| \(kT_{\text{CompTT}}\) (keV) | 3.21 ± 0.05   | 2.92 ± 0.15   | 3.13 ± 0.05   | 2.86 ± 0.14 |
| \(\Gamma\)\(^{e}\) | 8.17 ± 1.16   | 9.06 ± 0.68   | 8.21 ± 1.24   | 8.98 ± 1.30 |
| Total flux (diskbb + CompTT) | 3.63          | ...           | 3.53          | ...         |
| Total flux (bb + CompTT) | ...           | 3.74          | ...           | 3.57        |
| \(\chi^2/\text{dof}\) | 44/46         | 39/46         | 43/46         | 44/46       |

### Simultaneous Fit Result Phase I and II Spectra

| Parameters | \(\chi^2\) | dof | F-Stat Value | Probability |
|------------|------------|-----|--------------|-------------|
| All tied   | 2998       | 104 | ...          | ...         |
| Normalization’s (\(N_{\text{disk}}\), \(N_{\text{CompTT}}\)) free | 899 | 100 | 58 | 2.52 × 10\(^{-25}\) |
| \(kT_{\text{in}}\) along with Norms free | 105 | 98 | 370 | 2.01 × 10\(^{-46}\) |
| \(kT_{\text{in}}, kT_{\text{in}}\) along with Norms free | 92 | 96 | 6.7 | 1.72 × 10\(^{-2}\) |
| All free | 91 | 92 | 0.25 | 0.91 |

### Simultaneous Fit Result Phase II and III Spectra

| Parameters | \(\chi^2\) | dof | F-Stat Value | Probability |
|------------|------------|-----|--------------|-------------|
| All tied   | 2993       | 104 | ...          | ...         |
| Normalization’s (\(N_{\text{disk}}\), \(N_{\text{CompTT}}\)) free | 778 | 100 | 71 | 2.21 × 10\(^{-28}\) |
| \(kT_{\text{in}}\) along with Norms free | 100 | 98 | 332 | 2.19 × 10\(^{-44}\) |
| \(kT_{\text{in}}, kT_{\text{in}}\) along with Norms free | 86 | 96 | 7.8 | 7.17 × 10\(^{-3}\) |
| All free | 85 | 92 | 0.27 | 0.89 |

### Simultaneous Fit Result Phase I, II, and III Spectra

| Parameters | I             | II            | III            |
|------------|---------------|---------------|---------------|
| \(kT_{\text{in}}\) | 2.13 ± 0.01   | 1.96 ± 0.01   | 2.12 ± 0.01   |
| \(N_{\text{disk}}\) | 44 ± 2        | 66 ± 3        | 45 ± 2        |
| CompTT normalization | 8.95 ± 3.28   | 6.13 ± 2.86   | 7.54 ± 3.29   |

**Notes.**

The simultaneous fit results between phases I and II, and phases II and III are shown. The best-fit parameter values from the simultaneous fit to the three phase spectra are also listed.

\(a\) Inner disk temperature of the diskbb model.

\(b\) Normalization of the diskbb model.

\(c\) Temperature of the single-temperature blackbody model.

\(d\) Normalization of the blackbody model.

\(e\) Electron temperature.

\(f\) Optical depth of the Compton cloud.

**REFERENCES**

Alpar, M. A., Hasinger, G., Shaham, J., & Yancopoulos, S. 1992, A&A, 257, 627

Alpar, M. A., & Shaham, J. 1985, Nature, 316, 239

Belloni, T. 2010, in The Jet Paradigm (Lecture Notes in Physics, Vol. 794; Berlin: Springer), 53

Belloni, T., Homan, J., Casella, P., et al. 2005, A&A, 440, 207

Belloni, T., Parolin, I., & Casella, P. 2004, A&A, 423, 969

Bradt, H., Naranan, S., Rappaport, S., & Spada, G. 1968, ApJ, 152, 1005

Casella, P., Belloni, T., Homan, J., & Stella, L. 2004, A&A, 426, 587

Casella, P., Belloni, T., & Stella, L. 2005, ApJ, 629, 403

Christian, D. J., & Swank, J. H. 1997, ApJS, 109, 177

Done, C., & Kubota, A. 2006, MNRAS, 371, 1216

Dotani, T. 1988, PhD thesis, Univ. Tokyo

Fender, R. P., & Hendry, M. A. 2000, MNRAS, 317, 1

Fortner, B., Lamb, F. K., & Miller, G. S. 1989, Nature, 342, 775

Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79

Hasinger, G., van der Klis, M., Ebisawa, K., et al. 1990, A&A, 235, 131

Homan, J., Miller, J. M., Wijnands, R., et al. 2005, ApJ, 623, 383

Homan, J., van der Klis, M., Fridriksson, J. K., et al. 2010, ApJ, 719, 201

features are produced at the peak of their outburst when the inner disk edge is most probably located close to the compact object. We propose that the mass accretion rate is not the important criterion in producing NBO features. Instead it is the location of the inner disk that drives the NBO. If the disk edge is close to the compact object, the chances of getting affected by the outward radiation pressure is high which would generate or disturb the oscillation in the inner region of the disk. Similar studies concentrating on the correlated spectral and temporal variations in LMXBs would be helpful to get a clear picture of the accretion disk during the presence of NBO/NBO-like features.

We thank the anonymous referee for the useful comments. This research has made use of data obtained through HEASARC online service, provided by NASA/GSFC, in support of the NASA High Energy Astrophysics Programs.
Homan, J., van der Klis, M., Jonker, P. G., et al. 2002, \textit{ApJ}, 568, 878
Homan, J., Wijnands, R., van der Klis, M., et al. 2001, \textit{ApJS}, 132, 377
Jackson, N. K., Church, M. J., & Balucinska-Church, M. 2009, \textit{A&A}, 494, 1059
Jahoda, K., Markwardt, C. B., Raadeva, Y., et al. 2006, \textit{ApJS}, 163, 401
Jonker, P. G., van der Klis, M., Wijnands, R., et al. 2000, \textit{ApJ}, 537, 374
Kuulkers, E., van der Klis, M., Oosterbroek, T., et al. 1994, \textit{A&A}, 289, 795
Lamb, F. K., Shibazaki, N., Alpar, M. A., & Shaham, J. 1985, \textit{Nature}, 317, 681
Levin, W. H. G., Lubin, L. M., Tan, J., et al. 1992, \textit{MNRAS}, 256, 545
Lin, D., Remillard, R. A., & Homan, J. 2009, \textit{ApJ}, 696, 1257
McClintock, J. E., & Remillard, R. A. 2004, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press.), 157
Miller, G. S., & Lamb, F. K. 1992, \textit{ApJ}, 388, 541
Miller, M. C., Lamb, F. K., & Psaltis, D. 1996, \textit{BAAS}, 189, 4411
Miller, M. C., Lamb, F. K., & Psaltis, D. 1998, \textit{ApJ}, 508, 791
Nespoli, E., Belloni, T., Homan, J., et al. 2003, \textit{A&A}, 412, 235
Penninx, W., Lewin, W. H. G., Tan, J., et al. 1991, \textit{MNRAS}, 249, 113
Soleri, P., Belloni, T., & Casella, P. 2008, \textit{MNRAS}, 383, 1089
Soleri, P., Tudose, V., Fender, R., et al. 2009, \textit{MNRAS}, 399, 453
Sriram, K., Agrawal, V. K., Pendharkar, J. K., & Rao, A. R. 2007, \textit{ApJ}, 661, 1055
Sriram, K., Rao, A. R., & Choi, C. S. 2010, \textit{ApJ}, 725, 1317
Stella, L., & Vietri, M. 1999, \textit{Phys. Rev. Lett.}, 82, 17
Stella, L., Vietri, M., & Morsink, S. M. 1999, \textit{ApJ}, 524, L63
Titarchuk, L., Lapidus, I., & Muslimov, A. 1998, \textit{ApJ}, 499, 315
Titarchuk, L., & Osherovich, V. 1999, \textit{ApJ}, 518, L95
Titarchuk, L., Osherovich, V., & Kuznetsova, S. 1999, \textit{ApJ}, 525, L129
van der Klis, M., Jansen, F., van Paradijs, J., et al. 1985, \textit{Nature}, 316, 225
van der Klis, M. 1998, in The Many Faces of Neutron Stars, ed. R. Bucccheri, J. van Paradijs, & M. A. Alpar (Dordrecht: Kluwer Academic Publisher), 337
van der Klis, M. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 39
Wijnands, R., Mendez, M., van der Klis, M., et al. 1998, \textit{ApJ}, 504, L35
Wijnands, R., & van der Klis, M. 1999, \textit{ApJ}, 522, 965
Wijnands, R., van der Klis, M., Kuulkers, E., et al. 1997, \textit{A&A}, 323, 399
Wijnands, R., van der Klis, M., Psaltis, D., et al. 1996, \textit{ApJ}, 469, L5
Wijnands, R., van der Klis, M., & Rijkhorst, E. 1999, \textit{ApJ}, 512, L39
Yu, W. 2007, \textit{ApJ}, 659, L145