CHANDRA OBSERVATION OF LUMINOUS AND ULTRALUMINOUS X-RAY BINARIES IN M101

K. Mukai, W. D. Pence, and S. L. Snowden

NASA Goddard Space Flight Center, Code 662, Greenbelt, MD 20771

and

K. D. Kuntz

Joint Center for Astrophysics, Physics Department, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250

ABSTRACT

X-ray binaries in the Milky Way are among the brightest objects in the X-ray sky. With the increasing sensitivity of recent missions, it is now possible to study X-ray binaries in nearby galaxies. We present data on six luminous sources in the nearby spiral galaxy M101 obtained with the CHANDRA ACIS-S. Of these, five appear to be similar to ultraluminous sources in other galaxies, while the brightest source, P098, shows some unique characteristics. We present our interpretation of the data in terms of an optically thick outflow and discuss implications.

Subject headings: galaxies: individual (M101) — galaxies: spiral — X-rays: galaxies

1. INTRODUCTION

X-ray binaries in the Milky Way, with typical intrinsic luminosities in the range $10^{34}$–$10^{38}$ ergs $s^{-1}$ at a typical distance of 8 kpc, dominate our 2–10 keV sky. We therefore know a great deal about these Galactic X-ray binaries through many studies over the last several decades (see White, Nagase, & Parmar 1995 for a review). They are close binaries in which a neutron star or a black hole is accreting from a nondegenerate companion. They can be divided into low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs) depending on the spectral type of the mass donor. The HMXBs are young objects that are concentrated in the Galactic plane, preferentially in spiral arms. The LMXBs, on the other hand, appear to belong variously to the old disk, bulge, and globular clusters. Many neutron star LMXBs show thermonuclear flashes (i.e., type I bursts), suggesting a relatively low magnetic field; many HMXBs are coherent X-ray pulsars, containing highly magnetized neutron stars.

The Eddington limit for a $1.4 M_{\odot}$ object is $\sim 2 \times 10^{38}$ ergs $s^{-1}$. Significantly more luminous X-ray binaries can be considered black hole candidates on this argument alone, although HMXB pulsars SMC X-1 and LMC X-4 appear to exceed this limit at times (however, we do not know if they actually violate the Eddington limit, since the emission geometry of X-ray pulsars is not spherically symmetric). The definitive evidence for a black hole in X-ray binaries comes from radial velocity studies of the mass donor in the optical. In particular, over a dozen soft X-ray transients (SXTs, a subtype of LMXBs) have a measured mass function that exceeds 3 $M_{\odot}$, with inferred compact object masses typically in the $5$–$15 M_{\odot}$ range (Bailyn et al. 1998). In the X-ray regime, black hole binaries have characteristic spectral shapes, including a low/hard state dominated by a power-law spectrum and a high/soft state dominated by a $\sim 1$ keV thermal component, usually interpreted as arising from the inner disk (Tanaka & Shibazaki 1996). Although detailed studies have led to suggestions of additional spectral states (see, for example, Zycki et al. 2001), these spectral states are different from those of typical neutron star systems, either a $5$–$10$ keV bremsstrahlung-like spectrum (LMXBs) or a power law with an exponential cutoff (HMXBs).

Although a great deal is known about Galactic X-ray binaries, studies of extragalactic X-ray binaries offer complementary insights. In particular, a complete census of Galactic systems is difficult due to the extinction in the Galactic plane, and the luminosity estimates of Galactic systems are generally subject to large uncertainties. Study of a face-on galaxy such as M101 allows a study of a luminosity-limited sample with, on average, a low absorbing column.

In recent years, we have gained an additional motivation to study extragalactic X-ray source populations, in the form of off-nuclear point sources with luminosities greater than $10^{39}$ ergs $s^{-1}$ (hereafter ultraluminous X-ray sources, or ULXs) that have been found in many nearby galaxies (Colbert & Mushotzky 1999). One possible interpretation is that they are accreting intermediate-mass ($10^2$–$10^4 M_{\odot}$) black holes. This would be exciting if confirmed, because previously known black holes could be categorized into stellar ($\lesssim 10 M_{\odot}$) or supermassive ($>10^6 M_{\odot}$) subclasses. However, disk blackbody models of the ASCA spectra of ULXs (Makishima et al. 2000) suggest that they may have accretion disks as hot as several keV at their inner edges. In the standard model, it is difficult for a disk around an intermediate-mass black hole to achieve such high temperatures.

The superb angular resolution of CHANDRA allows the detection of point sources well below $10^{38}$ ergs $s^{-1}$ in nearby (say, closer than 10 Mpc) galaxies, thus sampling LMXBs, HMXBs, and both black hole and neutron star systems. Consequently, many groups are studying X-ray source populations in a considerable number of nearby galaxies as summarized, for example, in Prestwitch (2002). Here we present preliminary results of our observation of M101.

Sources with luminosities in the $10^{38}$–$10^{39}$ ergs $s^{-1}$ range have also been considered ULXs by some authors. They are likely to be related to ULXs, as well as to Galactic BHCs.
2. OBSERVATION AND SOURCE DETECTION

M101 is a nearby face-on spiral galaxy at an estimated distance of \( \sim 7.2 \) Mpc. It is an ideal galaxy for the observation of X-ray binaries, supernova/hypernova remnants (Snowden et al. 2001), and diffuse emission (Kuntz et al. 2002). We have therefore observed M101 with Chandra ACIS for 98.2 ks during 2000 March 26–27. The details of the observation, data reduction, source search, the catalog of 110 sources detected on the S3 chip, and their collective properties are described in Pence et al. (2001). Here we concentrate on the six brightest sources, listed in Table 1. We adopt the source number in Pence et al. (2001) as their names throughout this paper. Pence et al. (2001) argue on statistical grounds that about 75\% of the 110 sources detected on the S3 chip are intrinsic to M101. Therefore, we will assume that the majority of the six sources in question, if not all, are located in M101.

One of the sources, P098, is an order of magnitude brighter (as seen with ACIS-S) than the others and has other peculiar properties; this object will be the focus of this paper. However, we will first discuss the other five systems listed in Table 1 with observed luminosities in excess of \( 10^{38} \) ergs s\(^{-1}\). The inferred bolometric luminosities are higher, almost certainly exceeding the Eddington limit for a 1.4 \( M_\odot \) object. These five systems (three of which have been discussed in Snowden et al. 2001 as likely binaries, rather than hypernova remnants) are therefore black hole candidates (BHCs), even though they do not qualify as ULXs using the threshold of \( 10^{39} \) ergs s\(^{-1}\).

3. THE FIVE BRIGHT BLACK HOLE CANDIDATES

We have attempted a simple continuum spectral fit to the five BHCs, using power-law, bremsstrahlung, blackbody, and disk blackbody (diskBB, as implemented in XSPEC) models. The spectrum of P104 is best fitted with a power-law model, while the diskBB model works best for the others. The best-fit models do not resemble typical spectra of Galactic X-ray pulsars (flat power law) or of bright neutron star LMXBs (Comptonized spectra that can be approximated as a 5 keV bremsstrahlung; White et al. 1995). We have also examined the timing properties of these sources; their light curves in 5000 s bins are shown in Figure 1. Of the five, P104, the power-law source, is highly variable on a relatively short timescale (e.g., note the factor of \( \sim 2 \) drop in count rate in one 5000 s bin near the end of the observation). This is also one of the hypernova candidates of Wang (1999), since it is coincident with a optically detected supernova remnant MF83 (Matonick & Fesen 1997), but the observed variability excludes the hypernova interpretation (Snowden et al. 2001). The power-law index of P104, \( \sim 2.6 \), is unusually steep for a black hole binary in a low/hard state. Although such an index is often seen in the power-law component of high/soft state (e.g., 2.2–2.7 in GS 1124–68: Ebisawa et al. 1994), a soft component is not obvious in the Chandra spectrum of P104; a single power-law model fit \( (\chi^2 = 1.1) \) is clearly favored over a diskBB model fit \( (\chi^2 = 2.2) \) and also over a power-law plus disk blackbody model fit \( (\chi^2 = 1.2) \), although the last is extremely sensitive to initial guesses and thus is not reliable. Nevertheless, the rapid variability clearly establishes P104 as an X-ray binary in M101.

According to a \( \chi^2 \) test for constancy of the light curves of these five sources, only P104 is found to be significantly variable, in the total Chandra band. Of the remaining four sources, P76 is a possible exception; when its light curve in the 2–8 keV band is tested for constancy, we obtain \( \chi^2 = 24.9 \) for 19 degrees of freedom. The probability of a

![Fig. 1.—Chandra ACIS-S (0.125–8.0 keV) light curves of the five bright normal ULXs.](image-url)
constant source displaying this level of apparent variability is \(-16\%\) (in the total Chandra band, we obtain \(\chi^2 = 16.1\) and a chance probability of 65% for P076).

We also detect an apparent emission line in the spectrum of P104 at 1.02 keV, probably the Ne x Ly\(\alpha\) line (Fig. 2). This line may be intrinsic to the binary, since it is present in one Galactic X-ray binary, 4U 1626–67 (Angelini et al. 1995). However, another likely origin of the line is the hot plasma in MF83. The total luminosity in this line is of order \(10^{37}\) erg s\(^{-1}\) at the distance of 7.2 Mpc. Other lines are not required or excluded by the data. Similarly, in the spectrum of P005, there is an apparent line at 1.34 keV with an inferred line luminosity of \(-4 \times 10^{37}\) erg s\(^{-1}\) and another possible line at 1.85 keV. It is interesting to note that P005 is one of the eight “interarm” sources detected in the S3 chip (Pence et al. 2001), which coincides with the ROSAT HRI source H18 of Wang, Immler, & Pietsch (1999). The latter authors suggested a blue optical counterpart, interpreted as an active galactic nucleus (AGN); however, the Chandra and optical positions are about 5" apart (Wang et al. 2001, private communication), and therefore this source may turn out to be in M101 after all. The analogy with P104 suggests a combination of a luminous X-ray binary, responsible for the optically thick continuum, and a supernova remnant, responsible for the line emission.

The spectra of the three remaining BHCs (P076, P070, and P110) can be characterized as a disk blackbody with inferred temperatures at the inner edge of the disk in the 0.6–1.6 keV range, with no obvious emission lines. Their luminosities in the Chandra band are inferred to be \(1.7–4.0 \times 10^{38}\) erg s\(^{-1}\). Together with P104, these four sources appear to be accreting black holes in high/soft states, similar to the ULXs and other bright BHCs observed with ASCA (Makishima et al. 2000). For the interpretation of the diskBB model parameters as disk inner radius and temperature to be viable, P076 and P005 need to be relatively low-mass (\(<3M_\odot\)) black holes accreting at the Eddington limit.

4. THE PECULIAR ULX P098

The brightest source we have discovered in M101, P098, stands out from others in luminosity, variability, and spectral shape. We have already noted the clear variability in P098 (Pence et al. 2001). Furthermore, the variability is far more pronounced in the 0.8–2.0 keV range than in the lower energy ranges (Fig. 3). We have extracted spectra of P098 at three time intervals (indicated in Fig. 3) and fitted them with simple models (Fig. 4). Even during interval (a), when P098 had the highest count rate and the hardest spectrum, most of the flux is in the soft band (\(E < 1\) keV). It is clear that LMXB-like (\(-5\) keV bremsstrahlung) or HMXB pulsar-like (flat power law with photon index \(-1.5\)) models are inappropriate. In fact, we find that no single component model fits the interval (a) spectrum satisfactorily over the entire ACIS-S band. The diskBB model did best with \(\chi^2 \approx 2.0\), which fits the data below \(\sim 1.5\) keV adequately but leaves residuals above 2 keV.

When we restrict ourselves to fitting data below 1.5 keV only, either blackbody or diskBB models work well for the bright state, giving a reduced \(\chi^2\) of 1.1 (for blackbody) and 1.3 (for diskBB) in this range. The high energy excess can then be fitted using an additional power-law component. In a similar attempt at fitting the spectra for intervals (b) and (c), we find no formally acceptable models; however, again, the blackbody and diskBB models provide the “best” fits, with \(\chi^2 \approx 2\). The residual patterns are complex and are not dominated by obvious features, although a high energy excess component can reduce \(\chi^2\). We therefore use the blackbody and diskBB models to characterize the spectral...
changes from rate (b) to intermediate (c) to high (a) count rate states of P098.

Using the blackbody model, the inferred temperature ranged from 0.09 to 0.17 keV and the radius changed from ~20,000 to ~5000 km, while the bolometric luminosity (calculated analytically from the model normalization and the distance to M101 of 7.2 Mpc, assuming all absorptions are external to the X-ray emission region) stayed near ~3 \times 10^{39} \text{ ergs s}^{-1} (see Table 2). This is in contrast to the behavior of the luminosity in the 0.2–1.5 keV band, which changed by nearly a factor of 3. With the diskBB model, the

temperature range was 0.1–0.2 keV, the inner radius of the disk changed from ~20,000 to ~4000 km, while the bolometric luminosity (from model parameters) stayed at ~5 \times 10^{39} \text{ ergs s}^{-1}. The differences between parameters derived using these two different models give some indications of true uncertainties in derived parameters. Using either model, the inferred radii are anticorrelated with the temperatures and are far larger than the typical inner disk radius (Table 1).

The apparent variability in the Chandra band can be described as changes in high-energy cutoff of the spectrum, while the count rates in the 0.2–0.5 keV band changed little. This cannot be explained by a cold absorber; we also consider a highly ionized absorber to be unlikely, as we do not see warm absorber edges such as due to O vii and O viii. The variability above 0.8 keV may be due to appearance and disappearance of a hot continuum source. Since such a continuum source also contributes lower energy (0.2–0.5 keV) flux as well, there must be compensating change in the lower temperature continuum source to keep the low energy counts unchanged. This is exactly what the diskBB fits imply. An alternative interpretation is a simple change of temperature of the emission region, as parameterized by the blackbody fits. Therefore, even though neither model provides a statistically satisfactory fits for intervals (b) and (c), they are likely to reflect the kind of changes taking place in P098. We therefore consider the implications of the blackbody and diskBB model fits.

In many other ULXs, we have a puzzle in that the black hole mass inferred from the Eddington limit argument is high, while that inferred from using the disk blackbody model is low. This is particularly severe if a Schwarzschild black hole is assumed; even the assumption of Kerr black holes may not completely solve this puzzle (Ebisawa, Życki, & Kubota 2001). In P098, however, the situation is very different. Both the low temperature and the large luminosity can be accommodated in the framework of an intermediate-mass black hole accreting at much less than the Eddington rate. The problem with this picture is the large disk radius changes inferred by the fit (roughly by a factor of 4), while the inferred bolometric luminosity changes little. It is difficult to understand how a slight change in the mass accretion rate (as suggested by the near-constant luminosity) can trigger such a drastic change in inner radius of the accretion
of classical novae in the constant bolometric luminosity models in which the blackbody-like component originates a black hole mass of $\sim 0.5$. Thus, if we take the diskBB model fits at face value, P098 must have lost the inner part of the disk, while the temperature at $R = 20,000$ km increased by 0.5/0.3 $\sim$ 1.67, or the luminosity of the remaining part of the disk by a factor of $\sim 8$. This seems rather contrived for any potential models in which the blackbody-like component originates in the accretion disk; we therefore prefer an alternative interpretation.

The behavior of P098 is reminiscent of the slow evolution of classical novae in the constant bolometric luminosity phase (Balman, Krautter, & Ogelman 1998) and of the X-ray variability of supersoft sources (Southwell et al. 1996). In these systems, nuclear burning on the surface of an accreting white dwarf keeps the radiative luminosity at or near the Eddington limit. The nuclear energy also drives a strong outflow; this wind is optically thick, hence the observed spectrum is determined by the radius of last scattering. When the outflow rate is higher, the effective photospheric radius is large; hence, the observed temperature is low. When the outflow rate is lower, the photosphere is smaller; hence, a higher temperature is seen. The situation in P098 may be analogous.

The relative lack of variability in bolometric luminosity of P098 suggests the existence of a limiting mechanism; we postulate that this is the Eddington limit, therefore implying a black hole mass of $\sim 1.67$, or the luminosity of the remaining part of the disk by a factor of $\sim 8$. This seems rather contrived for any potential models in which the blackbody-like component originates in the accretion disk; we therefore prefer an alternative interpretation.

Within this framework, we observe X-ray photons scattered in the mass outflow from P098, at a typical radius of 10,000 km. Fluctuations in the mass-loss rate and/or the outflow velocity result in varying radius of this effective photosphere, while the total radiative luminosity remains constant at about the Eddington limit. The changing radius of the effective photosphere drives the correlated change in the temperature and model normalization. It is possible that such a mechanism is responsible for most of the variability of P098 down to the fastest timescale detected (Fig. 3), not just the spectral changes between intervals a, b, and c, although we cannot prove this with the available data. If the dominant source of the variability is mass-loss rate rather than the velocity, it is likely that higher accretion rate leads to higher mass-loss rate, a larger photosphere, a lower X-ray temperature, and hence a lower count rate with Chandra ACIS-S.

A detection of P Cygni profile, particularly in the X-rays where the mass donor does not contribute a significant flux, would be a strong evidence for the mass outflow interpretation, similar to what has been achieved for Cir X-1 (Brandt & Schulz 2000); however, this probably requires a future generation of X-ray observatory, such as Constellation-X. If the optical counterpart can be identified and is not dominated by the mass donor, X-ray and optical brightness of P098 may be anticorrelated. On the other hand, if future X-ray observations reveal that the bolometric luminosity is far from constant, we will be forced to rethink our interpretation.

### 5. Implications for other ULXs

We have studied the six brightest sources detected in our Chandra ACIS-S observation of M101. We briefly consider the possible implications of our findings on the nature of ULXs in general.

Of the five non-ULX BHCs that we have studied, one (P104) is spatially coincident with a supernova remnant (MF83). Another source, P005, although located in the interarm region and originally suspected of being a background AGN, may also be a combination X-ray binary/supernova remnant in M101. In our own Galaxy, the jet source SS 443 is in the supernova remnant W50 (Seward et al. 1976), while the super-Eddington neutron star binary Cir X-1 has tentatively been linked to the nearby supernova remnant G321.9-0.3 (Stewart et al. 1993). The case of P104 may point toward an interesting link between bright extra-
galactic BHCs and some of the unique and extreme X-ray binaries in our Galaxy.

The ULX P098 is highly variable, particularly above 0.8 keV, and has a soft blackbody-like spectrum. Fitting of spectra from P098 extracted from three time intervals shows that the bolometric luminosity may have been relatively constant. The apparent violent variability appears to reflect anticorrelated changes in the source temperature and size. We have therefore presented an interpretation based on optically thick outflow, because we find it unlikely that the inner radius of the accretion disk can change by a factor of 4 on such a short timescale, without a commensurate change in bolometric luminosity.

Yet the spectrum of P098 can be fitted with a disk blackbody model and a power-law excess, a traditional model for black hole candidates, which is also applied to ULXs (e.g., Ebisawa 1991; Merloni, Fabian, & Ross 2000; Ebisawa et al. 2001). While our Chandra data of P098 can be fitted with the diskBB model, we have questioned the standard interpretation. It is important to note that a variety of physical pictures can reproduce a diskBB-like X-ray spectral shape, provided that the emission region is optically thick, has a size similar to the inner disk and has a slight temperature gradient. That is, the optically thick disk interpretation of ULX spectra (Makishima et al. 2000) is almost certainly not unique. An additional argument for caution is provided by Zycki et al. (2001), who show that the soft component in Galactic BHCs are often too broad to be fitted by models of an optically thick disk. They argue that an intermediate temperature material is likely present, providing either additional blackbody contributions or additional Comptonization. Unfortunately, existing X-ray spectra of extragalactic ULXs are not sufficiently constraining to allow discrimination between pure disk models, Comptonized disk models, and models of X-rays scattered in a strong outflow.

We may be able to sidestep the problem of disks that appear to be too small and too hot for the black hole mass by abandoning the “pure disk” assumption for the ULX spectra. However, it leaves the question of the black hole mass unresolved: either ULXs are unbeamed objects containing intermediate-mass black holes, or they are beamed objects containing stellar-mass black holes. Our contributions to this debate are twofold. First is that no object we have detected in M101 requires an intermediate-mass black hole. Even the most luminous object, P098, can be an Eddington-limited, unbeamed X-ray source with a $\sim 20 M_\odot$ black hole. This is somewhat larger than the typical mass of stellar black holes but not so large as to require a new class of objects, at least in M101.

Our second contribution to this debate comes from the strong variability seen in P098 and P104. The very fact that variability can be detected with less than 1000 photons suggests an impressive degree of variability in P104, perhaps favoring a beamed model for ULXs, such as suggested by King et al. (2001). In addition, the energy-dependent light curves of P098 suggest the possibility that the true variability of other ULXs may have been underestimated; similar analyses of light curves of P076 proved suggestive, but not conclusive. It would be very important to search for similar energy-dependent variability characteristics in other ULXs, whenever counting statistics permit; existing studies may have severely underestimated the true variability of ULXs if they are often variable predominantly at higher energies, because observed counts are generally weighted heavily toward lower energies.

REFERENCES

Angelini, L., White, N. E., Nagase, F., Kallman, T. R., Yoshida, A., Takeshima, T., Becker, C., & Paerels, F. 1995, ApJ, 449, L41
Balmer, S. Krautter, J, & Ogelman, H. 1998, ApJ, 499, 395
Bailyn, C. D., Jain, R. K., Coppi, P., & Orosz, J. A. 1998, ApJ, 499, 367
Brandt, W. N., & Schulz, N. S. 2000, ApJ, 544, L123
Colbert, E. J. M., & Mushotzky, R. F. 1999, ApJ, 519, 89
Ebisawa, K. 1991, Ph.D. thesis, Univ. Tokyo
Ebisawa, K., Zycki, P., & Kubota, A. 2001, in X-Ray Emission from Accretion onto Black Holes, ed. T. Yaqoob & J. H. Krolik, 19E
Ebisawa, K., et al. 2000, ApJ, 535, 632
Gallemore, M., et al. 2001, ApJ, 552, L109
Kuntz, K. D., Pence, W., Snowden, S. L., & Mukai, K. 2002, ApJ, 561, 189
King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., & Elvis, M. 2001, ApJ, 552, L109
Kuntz, K. D., Pence, W., Snowden, S. L., & Mukai, K. 2002, ApJ, submitted
Makishima, K., et al. 2000, ApJ, 535, 632
Matonick, D. M., & Fesen, R. A. 1997, ApJS, 112, 49
Merloni, A., Fabian, A. C., & Ross, R. R. 2000, MNRAS, 313, 193
Pence, W. D., Snowden, S. L., Mukai, K., & Kuntz, K. D. 2001, ApJ, 561, 189
Seward, F. D., Page, C. G., Turner, M. J. L., & Pounds, K. A. 1976, MNRAS, 175, 39P
Snowden, S. L., Mukai, K., Pence, W. D., & Kuntz, K. D. 2001, AJ, 121, 3001
Southwell, K. A., Livio, M., Charles, P. A., O'Donoghue, D., & Sutherland, W. J. 1996, ApJ, 460, 483
Stewart, R. T., Caswell, J. L., Haynes, R. F., & Nelson, G. J. 1993, MNRAS, 261, 593
Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607
Wang, Q. D. 1999, ApJ, 517, L27
Wang, Q. D., Immler, S., & Pietsch, W. 1999, ApJ, 523, 121
White, N. E., Nagase, F., & Parmar, A. N. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. van den Heuvel (Cambridge: Cambridge Univ. Press), 1
Zycki, P. T., Done, C., & Smith, D. A. 2001, MNRAS, 326, 1367

Prestwich, A. H. 2002, in ASP Conf. Ser. 262, X-Rays at Sharp Focus: Chandra Science Symposium, ed. S. Vrtilek, E. M. Schlegel, & L. Kuhi (San Francisco: ASP), in press
Seward, F. D., Page, C. G., Turner, M. J. L., & Pounds, K. A. 1976, MNRAS, 175, 39P
Snowden, S. L., Mukai, K., Pence, W. D., & Kuntz, K. D. 2001, AJ, 121, 3001
Southwell, K. A., Livio, M., Charles, P. A., O'Donoghue, D., & Sutherland, W. J. 1996, ApJ, 470, 1065
Stewart, R. T., Caswell, J. L., Haynes, R. F., & Nelson, G. J. 1993, MNRAS, 261, 593
Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607
Wang, Q. D. 1999, ApJ, 517, L27
Wang, Q. D., Immler, S., & Pietsch, W. 1999, ApJ, 523, 121
White, N. E., Nagase, F., & Parmar, A. N. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. van den Heuvel (Cambridge: Cambridge Univ. Press), 1
Zycki, P. T., Done, C., & Smith, D. A. 2001, MNRAS, 326, 1367