AQUILA X-1 IN OUTBURST AND QUIESCEANCE

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ABSTRACT

We present photometry and spectroscopy of the soft X-ray transient Aql X-1. Optical photometry during an active state shows a strong (0.6 mag peak-to-peak) modulation at a period of 19 hr. Infrared (K′ band) photometry during a quiescent state limits any ellipsoidal variations to less than 0.07 mag (peak-to-peak), which implies an inclination i < 31° (90% limit). Spectroscopy in a quiescent state shows at most very small radial velocity variations, which implies a very low inclination of i < 12° (90% limit). The low inclination is rather unexpected given the large photometric modulation seen in the active state. The upper limit to the equivalent width of the anomalous Li 6707 Å line is less than 0.3 Å, which is similar to the measured strength of this line in several other X-ray transients.

Subject headings: binaries: close — stars: individual (Aquila X-1) — stars: neutron — X-rays: stars

1. INTRODUCTION

Aql X-1 is the most active of the soft X-ray transients (SXTs), having outbursts nearly once per year (Kaluzienski, Holt Boldt, & Serlemitsos 1977; Friedhorsky & Terrell 1984). The accreting object is known to be a neutron star (NS) because of the detection of type I X-ray bursts (Czerny, Czerny, & Grindlay 1987). During outbursts, the optical counterpart (V1333 Aql) brightens by several magnitudes to V ~ 17, or occasionally to V ~ 15. Between outbursts the system fades to V ~ 19, and the spectrum shows K–3 V absorption features as well as emission lines typical of low-mass X-ray binaries (LMXBs; Thorstensen, Charles, & Bowyer 1978; Shahbaz, Casares, & Charles 1997). The reddening and distance to the optical counterpart have variously been estimated at E(B–V) ~ 0.4, or ~ 0.35, and d ~ 2.5 or 2.3 kpc, based on the observed quiescent colors and spectral type (Thorstensen et al. 1978; Shahbaz et al. 1996, 1998a).

A photometric modulation at ~ 19 hr is sometimes found during quiescence and minioutburst. SXT often show modulations at the orbital period during quiescence due to ellipsoidal effects, and in outburst due to X-ray heating of the accretion disk and/or the secondary (van Paradijs & McClintock 1995). Interestingly, there are two disparate determinations of the period: Shahbaz et al. (1998b) find P = 19.30 ± 0.05 hr, while Chevalier & Ilovaïsky (1998) find P = 18.9479 ± 0.0002 hr. This latter modulation was first found during outburst (Chevalier & Ilovaïsky 1991) and appears to be stable over several outburst cycles. Recent quiescent data appear to show a modulation at the same period, and the phase of the quiescent and outburst minima are in agreement (Chevalier & Ilovaïsky 1998). If this result is confirmed, the modulation is very likely at the orbital period. The former modulation was found over a seven day period when the system was quiescent. Effects that could produce periodicities offset from the orbital period (i.e., outburst superhumps) should therefore be absent, and the modulation should be at the orbital period. Therefore the discrepancy between the two periods is hard to understand.

Shahbaz et al. (1998b) measure a very small ellipsoidal modulation at I band during quiescence and use this to estimate the inclination 20° < i < 31°. However, they also caution that a nearby comparison star shows a similar (but smaller) modulation at the same period and that their Aql X-1 measurement may also be interpreted as an upper limit of i < 31°. Shahbaz et al. (1997) measure the rotational velocity of the secondary star to be V_rot sin i = 62 ± 35 km s⁻¹, and also note that the secondary contributes 94% of the quiescent light at 6000 Å.

The X-ray decay light curve and changes in the X-ray spectrum during the 1997 February–March outburst provide good evidence that the propeller effect dominates the accretion flow in Aql X-1 at X-ray luminosities below ~ 10^36 ergs s⁻¹ (Campana et al. 1998; Zhang, Yu, & Zhang 1998).

The rapid outburst cycle makes Aql X-1 an ideal test object for theories of SXT outbursts. One possible explanation for the rapid outburst cycle of Aql X-1 is offered by van Paradijs (1996), who points out that Aql X-1 lies at the boundary of the (in)stability line of the accretion disk limit cycle (Smak 1983).

The dominance of the secondary during quiescent intervals provides an opportunity to determine the evolutionary state of the system, the orbital period, and the mass function. A determination of the mass of the NS (which requires accurate knowledge of the mass function and the inclination) is of particular interest, as the current inventory of NS mass measurements is based largely on massive systems (van Kerkwijk, van Paradijs, & Zuidervijk 1995). Given that the NSs in low-mass systems have different evolutionary histories, and may have formed via different methods (accretion-induced collapse is often mentioned; van Paradijs et al. 1997), there is a possibility their masses may differ. Three low-mass systems in which NS masses have been measured are PSR 1012 + 5307 (Callanan, Garanivich, & Koester 1998), Cen X-4 (Shahbaz, Naylor, & Charles 1993), and Cyg X-2 (Casares, Charles, & Kuulkers 1998). While the NS in the former two systems have masses consistent with the canonical 1.4 M₆, the latter may have a mass greater than 1.88 M₆.
2. OBSERVATIONS

2.1. Outburst Photometry at the FLWO 1.2 m

On the nights of 1996 July 17, 18, and 19 (UT), we obtained V-band photometry of Aql X-1 from the Fred Lawrence Whipple Observatory (FLWO) 1.2 m telescope and “1-shooter” CCD camera. The XTE/ASM rates show that Aql X-1 was in a flat-topped, weak outburst for an ~80 day period in 1996 June–July. The mean flux as measured by the ASM was ~18 mcrab, but the rate is clearly variable.

The data were de-biased and flat-fielded with IRAF, and magnitudes were determined with the aid of IRAF/DAOPHOT. As observing conditions were non-photometric, our magnitude zero point has been set via stars h and k from Lyutyi & Shugarov (1979).

This photometry folded on the 18.9479 hr period of Chevalier & Ilovaisky (1998) is shown in Figure 1. There is a marked modulation with a peak-to-peak amplitude of ~0.6 mag. While the data do not provide interesting constraints on the period, they do determine the time of minimum light T(0) = 2,450,282.220 ± 0.003 HJD.

2.2. Quiescent Photometry at the KPNO 2.1 m

We used the IRIM on the KPNO 2.1 m on the nights of 1997 July 8–12 (UT) to obtain J-, H-, and K'-band photometry of V1333 Aql. This imager uses an HgCdTe, NICMOS3 device that provides 256 × 256 pixels of 1.1 size on the 2.1 m telescope. Conditions were variable but often photometric with ~1.5 seeing. We observed the Aql X-1 field using a 3 × 3 dither pattern with variable ~10° slews between each dither. At each position we exposed for 10 s using six co-adds. The background was derived using the median of the nine images and subtracted from each frame. Each were then flat-fielded, registered, and co-added. Both the image reduction and photometry (see below) were performed using IRAF/DAOPHOT. We note that the background images show systematic variations that appear to be caused by the combination of the large pixel size and the relatively crowded field. These systematics are included in our errors. The magnitude scale was set via observations of various stars from the UKIRT Faint Standard catalog (Casali & Hawarden 1992).

The K'-band light curve for Aql X-1 and a nearby (presumed constant) star of similar magnitude is shown in Figure 2. Each light curve has been folded on the orbital period determined by Chevalier & Ilovaisky (1998) of P = 18.9479 hr, using the T(0) determined above for phase zero. The mean magnitudes for Aql X-1 were J = 16.50 ± 0.15, H = 15.90 ± 0.15, and K' = 15.74 ± 0.15. These errors are indicative of the observed scatter in the Aql X-1 K' observations and include the variations found in repeated observations of the standards over the run.

We then binned these two datasets into 12 equally sized phase bins, determining the magnitude error for each bin from the observed variance in the bin. These data where then fitted to models of the expected ellipsoidal light curve using the model of Avni (1978) as described by Orosz & Bailyn (1997). This code computes the orbital variations in the projected area of the star in the Roche geometry, along with limb and gravity darkening, in order to predict the light curve. For q (ratio of secondary mass to primary mass) between 1 and 0.1, the best-fit inclination ranges between 10° < i < 12°. The 68% error range includes zero and is bounded by i < 22°; the 90% error range is bounded by i < 31°. Similar fits to the presumed constant star show minima within a few degrees of zero, and 68% and 90% upper limits at i < 22° and i < 30°, respectively. We note that mean variability in the binned data is higher for the standard star than that for Aql X-1: 7.3% versus 6.4%. This indicates that the variability is dominated by systematic effects, likely due to the large (~1°) pixel size and the very crowded Aql X-1 field.

2.3. MMT Spectroscopy

We obtained 26 spectra of Aql X-1 on the nights of 1997 June 7, 8, and 9 using the MMT and Blue Channel spectrograph. The spectra cover the wavelength range 3600–7200 Å with 3.6 Å resolution. Conditions were clear and seeing was ~1'. Exposure times were 20 minutes, and each exposure was bracketed by an exposure of an HeNeAr comparison lamp in order to reduce the spectra to a common velocity. The dispersion is 1.2 Å/pixel−1, and the signal-to-noise ratio (S/N) in each continuum pixel is ~5. Aql X-1 was near quiescence at this time, as evidenced by photometry with the FLWO 1.2 m telescope, which finds V = 18.68 ± 0.03 on 1997 June 7, and nondetection by the XTE ASM.

The images were reduced with standard IRAF routines, and spectra were extracted with the IRAF longslit package. Velocities were determined via cross-correlations computed with the IRAF/IFCOR package run against a range of late-type standard stars. We found that a late K star produced the strongest correlations, and we therefore used GJ 9698 (spectral type K8 V, HCV = −28.2 km s−1; Bopp & Meredith 1986) in subsequent velocity determinations. We limited our correlations to the wavelength ranges 4900–5850 Å and 5915–6470 Å in order to avoid the possible interstellar medium (ISM) contribution in the NaD line and
the Hα and Hβ emission lines. The more heavily reddened SXT GS 2000+25 shows weak interstellar lines at 5778, 6177, and 6284 Å (Harlaftis, Horne, & Filippenko 1996), but we find our results are unchanged if we shorten our wavelength intervals to exclude these lines.

In order to estimate the errors we also extracted the spectrum of a second star that was in the slit and had a magnitude similar to Aql X-1. If the velocity errors are only due to statistical effects, one expects the errors to scale with the \( r \) values like \( c/(1 + r) \) (Tonry & Davis 1979), with \( c \) set such that the \( \chi^2/r = 1 \) under the assumption of a constant velocity for this star. If the errors are set by systematic effects, then there should be no difference in the scatter for high (or low) \( r \) values. In order to test for systematic effects, we first culled out one deviant velocity (\( -700 \text{ km s}^{-1} \)), which also had \( r < 4 \). We then separated the remaining 25 velocities into two groups based on whether the \( r \) values were above or below the median value. We find no significant difference in the variance of the velocity data for the high \( r \) value (\( r > 12, \sigma = 28.0 \text{ km s}^{-1} \)) or low \( r \) value (\( 4 < r < 12, \sigma = 29.6 \text{ km s}^{-1} \)) groups, and therefore adapt a uniform error for the Aql X-1 velocities of \( \sigma = 29.6 \text{ km s}^{-1} \).

We fitted a constant plus a sine wave with a period of 18.9479 hr (Chevalier & Ilovaisky 1998) to the 22 Aql X-1 velocities with correlation coefficients \( r > 3.0 \). The \( \chi^2 = 15 \), indicating an acceptable fit, and we find a best fit \( K_c = 21 \text{ km s}^{-1}, \gamma = 19 \text{ km s}^{-1}, \text{ and } T(0) = 2,450,606.8666 \text{ HJD} \). Here \( T(0) \) is defined as the time for which the sine component of the fit equals zero, which should occur when the secondary is in front of the primary. This best fit sinusoid is plotted in Figure 3. The 68% confidence limits (Lampton, Margon, & Bowyer 1976) are \( K_c \leq 41 \text{ km s}^{-1}, 2 < K_c < 41 \text{ km s}^{-1}, \) and \( 2,450,606.6992 < T(0) < 2,450,606.9755 \text{ HJD} \), and 90% limits are \( 2 < \gamma < 39 \text{ km s}^{-1}, K_c < 48 \text{ km s}^{-1} \) [the phase of \( T(0) \) is not bounded within the 90% limits]. These results are unchanged if we instead fit to the 19.30 hr period reported by Shahbaz et al. (1998b).

We can determine more restrictive limits on \( K_c \) if we first limit \( T(0) \) by accepting the 18.9479 hr period as orbital and projecting the time of optical minimum found in \( T(0) \) forward to the epoch of our radial velocities, e.g., \( T(0) = 2,450,606.703 \pm 0.006 \text{ HJD} \). Note that this \( T(0) \) is consistent with that found above, although one should not assign too much significance to this since the radial velocity data alone only provide an \( \sim 30\% \) restriction on the phase of \( T(0) \). These fits show \( K_c < 24 \text{ km s}^{-1} \) (68% limits) and \( K_c < 29 \text{ km s}^{-1} \) (90% limits).

In order to measure the velocities of the Hα line, we fitted the individual spectra to a single Gaussian emission line with an FWHM and amplitude equal to that measured in
the averaged spectrum. The S/N in the Hα line is high enough that the statistical error in the fitting procedure is typically \( \sim 5 \text{ km s}^{-1} \). However, as can be seen in Figure 4, the scatter around the best fit is much larger than 5 km s\(^{-1}\), possibly because the intrinsic shape of the line is variable. In order to estimate errors on the Hα velocity curve, we have rescaled the errors until the scatter around the best fit is much larger than 5 km s\(^{-1}\). Allowing all three parameters to vary, we then find 68% error ranges of \( T(0)_{\text{ref}} = 70 \pm 20 \text{ km s}^{-1} \), \( \gamma = 150 \pm 20 \text{ km s}^{-1} \), and \( T(0)_{\text{HJD}} = 2,450,607.10 \pm 0.05 \text{ HJD} \). The 90% error ranges are 50% larger. As before, \( T(0)_{\text{fit}} \) is defined to occur when the sine component of the fit equals zero, which in this case should be when the primary is in front of the secondary, assuming that the Hα velocities accurately trace the motion of the primary [i.e., 0.5 cycles from \( T(0) \)].

The averaged spectrum of Aql X-1 is shown in Figure 5. H-Balmer, He i, and He ii lines are seen in emission. The Hα emission has a measured FWHM of \( 845 \pm 25 \text{ km s}^{-1} \). Correcting for the instrumental resolution by subtracting it in quadrature, we estimate the intrinsic FWHM of the line is \( 830 \pm 25 \text{ km s}^{-1} \). We estimate FWZI \( ~2100 \text{ km s}^{-1} \) at Hα, although this is a lower limit due to the S/N in the spectrum. The He ii 4686 Å line does not show the double-peaked accretion disk profile often seen in LMXB and CVs, and it has an intrinsic FWHM = \( 640 \pm 70 \text{ km s}^{-1} \), and an FWZI \( \sim 2000 \pm 500 \text{ km s}^{-1} \).

We do not find any evidence for an Li i 6707 Å line in the summed spectrum. The noise level in the summed spectrum corresponds to 0.1 Å EW per resolution element, so we set a 3 \( \sigma \) upper limit to the EW of this line of 0.3 Å. We also note that several photospheric lines with EW \( \sim 0.2 \text{ Å} \) are readily detectable in the spectrum; for example, the Ca i 6717 Å line has EW \( \sim 0.2 \text{ Å} \).

3. DISCUSSION

What causes the observed modulations?—Based on analogy to other LMXB, the 0.6 mag optical modulation seen during outburst in 1996 July is likely due to reprocessing of X-rays in a nonaxisymmetric disk and/or in the heated face of the companion (van Paradijs & McClintock 1995). As both effects create minima at the same phase, we are not able to distinguish between these two possibilities. The relative phasing of the outburst and quiescent light curves found by Chevalier & Ilovaisky (1998) most likely supports either of these interpretations. Additionally, the agreement between the time of 1996 July optical minimum and the \( T(0) \) found from our radial velocity data supports these interpretations, but we caution the significance of this agreement is low.

Any modulation found during quiescence is likely to be ellipsoidal, since the K star is very dominant during quiescence. However, our data does not allow us to clearly detect any quiescent modulation. Shahbaz et al. (1998b) may detect a quiescent modulation and are able to determine a time of minimum light. Based on the standard model of X-ray reprocessing during outburst and ellipsoidal modulations during quiescence, the time of the outburst and quiescent minima should differ by 0.5 cycles. The accuracy of the
period determination of Chevalier & Ilovaisky (1998) is sufficient to allow meaningful comparison of the time of minimum light of our outburst modulation to that found in quiescence (Shahbaz et al. 1998b). This difference, 432.212 ± 0.004 cycles, is unexpected if the period is orbital in origin. This implies that either the orbital period or the time of minimum light in quiescence may be in error.

What is the inclination?—The empirical relation between the inclination and the amplitude of outburst modulation found in ~12 LMXB (van Paradijs & McClintock 1995; van Paradijs, van der Klis, & Pedersen 1988) leads one to predict an inclination of ~70° from our observed 0.6 mag modulation. This high inclination is unexpected given the much lower inclinations implied by the very small modulations found during quiescence at I band (Shahbaz et al. 1998b) and at K band (this paper).

The radial velocity amplitude $K_r$ can provide a measurement of the inclination of the system if we make the assumption that the component masses in Aql X-1 are similar to those in the well-studied NS SXT Cen X-4. This may be a reasonable assumption, since Cen X-4 has an orbital period and spectral type ($P_{orb} = 15.098$ hr, Chevalier et al. 1989; spectral type K5–7 V, McClintock & Remillard 1990) similar to Aql X-1. Previous studies of Cen X-4 find that $K_r = 146$ km s$^{-1}$ and $i = 40°$ (McClintock & Remillard 1990; Shahbaz, Naylor, & Charles 1993). Since $K_r$ scales directly with sin (i) via the mass function, the limits we derive from the radial velocity data alone imply $i = 5°$ ± 4° (68%), or $i < 12°$ (90% confidence limit). Accepting the 18.9479 hr period as orbital allows even more restrictive limits of $i < 6°$ (68%) or $i < 7°$ (90%). These limits are much more restrictive than those placed by the quiescent ellipsoidal modulations and imply that Aql X-1 is the lowest inclination SXT known.

What are the binary parameters?—Optical photometry and spectroscopy indicate the secondary star in Aql X-1 is of early K V spectral type (Thorstensen et al. 1978; Shahbaz et al. 1997). Dereddening our IR magnitudes assuming $E(B-V) = 0.4$, we find $D(J-K) = 0.55 ± 0.21$, consistent with G0 V–K6 V spectral types (Tokunaga 1999).

Secondaries in SXT are generally undermassive for their spectral type; for example, the secondary in Cen X-4 has been estimated to have a mass $M_s \sim 0.1 M_{\odot}$ (McClintock & Remillard 1990), so for Aql X-1 we expect $M_s \leq 0.8 M_{\odot}$ (Allen 1973). Combining the equation for rotational velocity of the secondary ($V_{rot}$) from Wade & Horne (1988) with that for the Roche lobe radius from Eggleton (1983) allows one to approximate

$$V_{rot} \sin (i) = 0.52 K_r (1 + q)^{1/3} q^{1/2}$$.

Assuming $M_s = 1.4 M_{\odot}$, our 90% upper limit of $K_r < 48$ km s$^{-1}$ then allows us to approximate $V_{rot} \sin (i) \leq 27$ km s$^{-1}$. The more restrictive limits allowed by using the 18.9479 hr period imply $V_{rot} \sin (i) \leq 16$ km s$^{-1}$ (90% confidence). The one previously published measurement of the rotational speed of the secondary finds $V_{rot} \sin (i) = 62^{±20}_{-30}$ km s$^{-1}$ (68% limits; Shahbaz et al. 1997). This may be consistent with our upper limits at the ~2σ level.

The assumptions above imply a mass ratio $q = M_s/M_1 \leq 0.6$. The mass ratio may also be estimated from the orbital velocity of the Hα line if we assume that $K_{H\alpha} = K_r$. This yields $q_{H\alpha} = K_{H\alpha}/K_r = 3.3^{+14.7}_{-2.0}$, or assuming $K_r < 48$ km s$^{-1}$, $q_{H\alpha} > 0.8$. While this is inconsistent with the assumed masses for the components at the 90% level, it is consistent at the 95% error level. One should be wary of mass ratios computed using orbital velocity of emission lines, as they may not always correctly indicate the velocity amplitude of the primary. Certainly many studies have found that the phase of the Hα radial velocity curve is not that expected if it accurately tracked the motion of the primary (Orosz et al. 1994; Filippenko, Matheson, & Ho 1995).

Caveats.—As an aside, we note that these results assume that the period of Aql X-1 is ~19 hr. While there is clearly optical modulation at 19 hr both in outburst and quiescence, the fact that the two independent determinations of the period disagree (Chevalier & Ilovaisky 1998; Shahbaz et al. 1998b) sheds some doubt on its orbital origin.

Some of the apparent discrepancies between the inclination as implied in outburst and in quiescence would be explained if there was an “interloper” along the line of sight to Aql X-1, or if the system was triple. The probability of an interloper within a 1″ radius of Aql X-1 is rather small at 1.6%, based on the density of stars with $V < 19$ in the Aql X-1 field.

3.1. Lithium

The nondetection of the Li 6707 Å line in Aql X-1 is interesting in comparison to the quite high equivalent width EW = 0.480 ± 0.065 Å found in Cen X-4 (Martin et al. 1994, 1996). Because Li is quickly destroyed in the stellar interiors of SXT companions, its detection implies that it is actively being created in these systems. It may be produced during X-ray outbursts (Martin et al. 1996), or also in the hot advection-dominated accretion flow (ADAF) during quiescent periods (Yi & Narayan 1997). In the latter case, truncation of the ADAF at the Alfvén radius decreases the Li production, and it is necessary to postulate a propeller in order to eject detectable quantities of Li into the photosphere of the secondary. Aql X-1 has recently been found to contain an efficient propeller consisting of an NS with a $P_{spin} = 1.8$ ms and $B \sim 10^8 G$ (Zhang et al. 1998; Campana et al. 1998). If Cen X-4 contains a 31 ms pulsar (Mitsuda 1996), then its Li production should be much less efficient (Yi & Narayan 1997) and the strength of the Li 6707 Å line relative to Aql X-1 is difficult to explain. In the former case, the fact that Aql X-1 has outbursts much more frequently than all other SXTs would lead one to expect a substantial Li 6707 Å line, so its nondetection is once again difficult to explain. A possible explanation may lie in the radio observations: Martin et al. (1994) postulate that nonthermal radio emission seen in outbursts of SXT (including Cen X-4; Hjellming & Han 1995) is evidence of strong particle acceleration and that these particles produce Li via spallation. Despite sensitive radio observations during numerous Aql X-1 outbursts, radio emission has been detected only once, at a level of ~1 mJy during the 1992 outburst (Hjellming & Han 1995). More typically radio observations set upper limits of ~0.5 mJy (Biggs & Lyne 1996; Geldzahler 1983). This may indicate that Aql X-1 is relatively inefficient at producing nonthermal particles, as scaling the observed flux of Cen X-4 at $d = 1.2$ kpc (McCintock & Remillard 1990) to the distance of Aql X-1 leads one to expect ~2 mJy during an outburst. As a word of caution, we note that...
Martin et al. (1996) show that the strength of the Li 6707 Å line changes with orbital phase in X-ray Nova Muscae 1996. Our phase coverage of Aql X-1 is incomplete, so we cannot discount the possibility that the line is stronger at phases we were not able to cover.

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REFERENCES

Allen, C. W. 1973, Astrophysical Quantities (London: Athlone)
Avni, J. 1978, in Physics and Astrophysics of Neutron Stars and Black Holes, ed. R. Giacconi & R. Ruffini (Amsterdam: North-Holland), 42
Biggs, J. D., & Lyne, A. G. 1996, MNRAS, 282, 691
Bopp, B. W., & Meredith, R. 1986, PASP, 98, 772
Callanan, P. J., Garnavich, P. M., & Koester, D. 1998, MNRAS, 298, 207
Campana, S., Stella, L., Mereghetti, S., Colpi, M., Tavani, M., Ricci, D., Dal Fiume, D., & Belloni, T. 1998, ApJ, 499, L65
Casali, M. M., & Hawarden, T. G. 1992, JCMT-UKIRT Newsletter 3, 33
Casares, J., Charles, P. A., & Kuulkers, E. 1998, ApJ, 493, L39
Chevalier, C., & Ilovaisky, S. A. 1991, A&A, 251, L11
———. 1998, IAU Circ. 6806
Chevalier, C., Ilovaisky, S. A., van Paradijs, J., Pedersen, H., & van der Klis, M. 1989, A&A, 210, 114
Czerny, M., Czerny, B., & Grindlay, J. E. 1987, ApJ, 312, 122
Eggleton, P. P. 1983, ApJ, 268, 368
Filippenko, A. V., Matheson, T., & Ho, L. C. 1995, ApJ, 455, 614
Geldzahler, B. J. 1983, ApJ, 264, L49
Harlaftis, E. T., Horne, K., & Filippenko, A. V. 1996, PASP, 108, 762
Hjellming, R., & Han, X. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press)
Kaluzienski, L. J., Holt, S. S., Boldt, E. A., & Serlemitsos, P. J. 1977, Nature, 265, 606
Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 177
Lyutyi, V. M., & Shugarov, S. Yu. 1979, Soviet Astron. Lett., 5, 206
Martin, E. L., Casares, J., Molnar, P., Rebolo, R., & Charles, P. A. 1996, New Astronomy, 1, 197
Martin, E. L., Rebolo, R., Casares, J., & Charles, P. A. 1994, ApJ, 435, 791
McClintock, J. E., & Remillard, R. A. 1990, ApJ, 350, 386
Mitsuda, K., Asai, K., Vaughan, B., & Tanaka, Y. 1996, in Proc. X-Ray Imaging and Spectroscopy of Cosmic Hot Plasmas, Int. Symp. X-Ray Astron., ed. F. Makino & K. Mitsuda (Tokyo: UAP)

Orosz, J. A., & Bailyn, C. D. 1997, ApJ, 477, 876
Orosz, J. A., Bailyn, C. D., Remillard, R. A., McClintock, J. E., & Foltz, C. B. 1994, ApJ, 436, 848
Priedhorsky, W. C., & Terrell, J. 1984, ApJ, 280, 661
Shahbaz, T., Bandyopadhyay, R. M., Charles, P. A., Wagner, R. M., Muhli, P., Hakala, P., Casares, J., & Greenhill, J. 1998a, MNRAS, 300, 1035
Shahbaz, T., Casares, J., & Charles, P. A. 1997, A&A, 326, L5
Shahbaz, T., Naylor, T., & Charles, P. A. 1993, MNRAS, 265, 655
Shahbaz, T., Smale, A. P., Naylor, T., Charles, P. A., van Paradijs, J., Hassall, B. J. M., & Callanan, P. 1996, MNRAS, 282, 1437
Shahbaz, T., Thorstensen, J. R., Charles, P. A., & Sherman, N. D. 1998b, MNRAS, 296, 1004
Smak, J. 1983, ApJ, 272, 234
Thorstensen, J., Charles, P. A., & Bowyer, S. 1978, ApJ, 220, L131
Tokunaga, A. T. 1999, in Astrophysical Quantities (Revised), ed. A. Cox (New York: Springer), in press
Tonry, J., & Davis, M. 1979, AJ, 84, 1511
van Kerkwijk, M. H., van Paradijs, J., & Zuiderwijk, E. J. 1995, A&A, 303, 497
van Paradijs, J. 1996, ApJ, 464, L139
van Paradijs, J., & McClintock, J. E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 87
van Paradijs, J., van den Heuvel, E. P. J., Kouveliotou, C., Fishman, G. J., Finger, M. H., & Lewin, W. H. G. 1997, A&A, 317, L9
van Paradijs, J., van der Klis, M., & Pedersen, H. 1988, A&A, 76, 185
Wade, R. A., & Horne, K. 1988, ApJ, 324, 411
Yi, I., & Narayan, R. 1997, ApJ, 486, 363
Zhang, S. N., Yu, W., & Zhang, W. 1998, ApJ, 494, L71