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THE OPTICAL COUNTERPART OF THE ACCRETING MILLISECOND PULSAR SAX J1808.4−3658 IN OUTBURST: CONSTRAINTS ON THE BINARY INCLINATION

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ABSTRACT

We present multiband optical/IR photometry of V4580 Sgr, the optical counterpart of the accretion-powered millisecond pulsar SAX J1808.4−3658, taken during the 1998 X-ray outburst of the system. The optical flux is consistent with emission from an X-ray–heated accretion disk. Self-consistent modeling of the X-ray and optical emission during the outburst yields a best-fit extinction of $A_V = 0.68^{+0.37}_{-0.15}$ and an inclination of $\cos i = 0.65^{+0.23}_{-0.33}$ (90% confidence), assuming a distance of 2.5 kpc. This inclination range requires that the stellar companion of the pulsar has extremely low mass, $M_c = 0.05$–$0.10\ M_\odot$. Some of the IR observations are inconsistent with disk emission and are too bright to be from either the disk or the companion, even in the presence of X-ray heating.

Subject headings: accretion, accretion disks — binaries: close — pulsars: individual (SAX J1808.4−3658) — stars: individual (V4580 Sagittarii) — stars: neutron

1. INTRODUCTION

It is generally believed that millisecond radio pulsars are formed during sustained mass transfer onto neutron stars in X-ray binaries (e.g., Bhattacharya & van den Heuvel 1991). Only one example of a presumed progenitor, an accretion-powered millisecond X-ray pulsar, is currently known. The X-ray transient SAX J1808.4−3658 ($l = 355^\circ.4$, $b = -8^\circ.1$) was discovered in 1996 September by the *BeppoSAX* Wide Field Cameras during an approximately 20 day transient outburst (in 't Zand et al. 1998). Based on the detection of Eddington-limited thermonuclear X-ray bursts during these observations, the source distance is estimated to be 2.5 kpc (in 't Zand et al. 2001). A second source outburst was detected with the *Rossi X-Ray Timing Explorer* (*RXTE*) in 1998 April (Marshall 1998). Timing analysis of the 2–30 keV *RXTE* data revealed the presence of a 401 Hz pulsar in a 2 hr binary with a low-mass companion (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998).

Shortly after the initial *RXTE* detection of the 1998 X-ray outburst, we observed a $V \approx 16$ star located 19″ from the center of the *BeppoSAX* error circle; this star was not present on the Digitized Sky Survey image of the field to a limiting magnitude of $V \gtrsim 19$, leading to its identification as the optical counterpart of SAX J1808.4−3658 (Roche et al. 1998). The optical intensity of this source faded as the X-ray source declined, and a 2 hr orbital modulation was marginally detected in the optical flux (Giles, Hill, & Greenhill 1999). This 2 hr optical modulation was subsequently confirmed in observations during quiescence (Homer et al. 2001). The optical counterpart has been designated V4580 Sagittarii (Kazarovets, Samus, & Durlevich 2000). In this Letter, we report on optical/IR photometry obtained during the 1998 outburst.

2. OBSERVATIONS AND RESULTS

We obtained multiband optical photometry of the SAX J1808.4−3658 field at several epochs during the 1998 X-ray outburst using the f/15 Cassegrain CCD imager on the 1 m Jacobus Kapteyn Telescope (JKT) at the Observatorio del Roque de los Muchachos, La Palma, Canary Islands, Spain. Additional optical observations were obtained at various epochs during the outburst using the Keck 10 m telescope in Mauna Kea, Hawaii, the 3.5 m New Technology Telescope (NTT) at the European Southern Observatory in La Silla, Chile, and the 1.9 m telescope at the South African Astronomical Observatory (SAAO). IR photometry was also obtained at several epochs using the 3.8 m United Kingdom Infrared Telescope (UKIRT). A summary of these observations is given in Table 1. For completeness, we have included the photometry obtained by other groups as well (Giles et al. 1999; Percival et al. 1998; Homer et al. 2001).

The *V*-band flux history is shown in Figure 1, along with the X-ray flux history measured by the *RXTE* Proportional Counter Array (Gilfanov et al. 1998). On both plots, we have also indicated the quiescent flux levels measured well after outburst (Wijnands et al. al. 2001; Homer et al. 2001). It is interesting to compare the behavior of the X-ray and optical light curves. In the X-ray band, the intensity shows a steady exponential decay ($\tau = 10.9$ days) until about MJD 50,929, when there is a sharp break to a steeper decay ($\tau = 2.2$ days), as shown previously by Gilfanov et al. (1998). The optical *V*-band light curve also shows an initially exponential decay in intensity ($\tau = 8.4$ days) until MJD 50,936, when it abruptly reaches a plateau lasting at least 30 days. Despite the fact that the optical light curve appears to roughly follow the X-ray light curve early in the outburst, the breaks from the initial decay are spaced by a week, and the behavior after the break is quite different in the two bands.

The broadband optical/IR spectrum is shown in Figure 2 for several epochs during the outburst, as well as a quiescent measurement. The shape of the *BVRI* spectrum during the outburst

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TABLE 1
OPTICAL/IR PHOTOMETRY OF SAX J1808.4−3658

			MAGNITUDES							
UT DATE	MJD	TELESCOPE	*B*	*V*	*R*	*I*	*J*	*H*	*K*	REFERENCE
1998 Apr 16.6	50,919.6	Keck 10 m	...	...	16.19(3)	...	...	...	...	1
1998 Apr 18.2	50,921.2	JKT 1 m	...	16.51(9)	16.19(15)	15.89(13)	...	...	...	1
1998 Apr 18.6	50,921.6	UKIRT 3.8 m	...	...	...	...	15.06(2)	14.34(1)	13.76(3)	1
1998 Apr 18.7	50,921.7	Mount Canopus 1 m	...	16.72	...	16.11(5)	...	...	...	2
1998 Apr 22.7	50,925.7	Mount Canopus 1 m	...	16.77	...	...	...	...	...	2
1998 Apr 24.2	50,927.2	JKT 1 m	17.43(10)	17.12(7)	16.82(6)	16.50(8)	...	...	...	1
1998 Apr 27.7	50,930.7	Mount Canopus 1 m	...	17.81	...	17.36(13)	...	...	...	2
1998 Apr 28.0	50,931.0	SAAO 1.9 m	...	17.74(8)	...	17.13(11)	...	...	...	1
1998 Apr 29.7	50,932.7	Mount Canopus 1 m	...	18.17(6)	...	17.67(6)	...	...	...	2
1998 May 2.6	50,935.6	UKIRT 3.8 m	...	...	...	...	...	...	17.17(4)	3
1998 May 2.7	50,935.7	Mount Canopus 1 m	...	18.58(11)	...	17.83(10)	...	...	...	2
1998 May 4.6	50,937.6	UKIRT 3.8 m	...	...	...	...	...	...	17.33(4)	3
1998 May 4.7	50,937.7	Mount Canopus 1 m	...	18.36(7)	...	17.83(13)	...	...	...	2
1998 May 5.1	50,938.1	JKT 1 m	18.67(18)	18.51(15)	18.06(14)	17.92(25)	...	...	...	1
1998 May 5.7	50,938.7	Mount Canopus 1 m	...	18.50(9)	...	18.12(15)	...	...	...	2
1998 May 16.7	50,949.7	Mount Canopus 1 m	...	18.36(14)	...	17.80(15)	...	...	...	2
1998 May 17.5	50,950.5	Mount Canopus 1 m	...	18.44(5)	...	17.84(6)	...	...	...	2
1998 Jun 2.4	50,966.4	NTT 3.5 m	...	18.59(5)	...	...	...	...	...	1
1998 Jun 27.7	50,991.7	Mount Canopus 1 m	...	>20.5	...	...	...	...	...	1
1998 Sep 7.6	51,063.6	UKIRT 3.8 m	...	...	...	...	>19.3	...	>18.3	1
2000 Jul 3	51,728	SAAO 1.9 m	22.0(1)	21.5(1)	20.9(1)	...	...	...	...	4

NOTE.—Where multiple measurements were obtained on the same day from a given observatory, we present the average value. Measurement uncertainties are quoted at the 1 σ level.

REFERENCES.—(1) This work; (2) Giles et al. 1999; (3) Percival et al. 1998; (4) Homer et al. 2001.

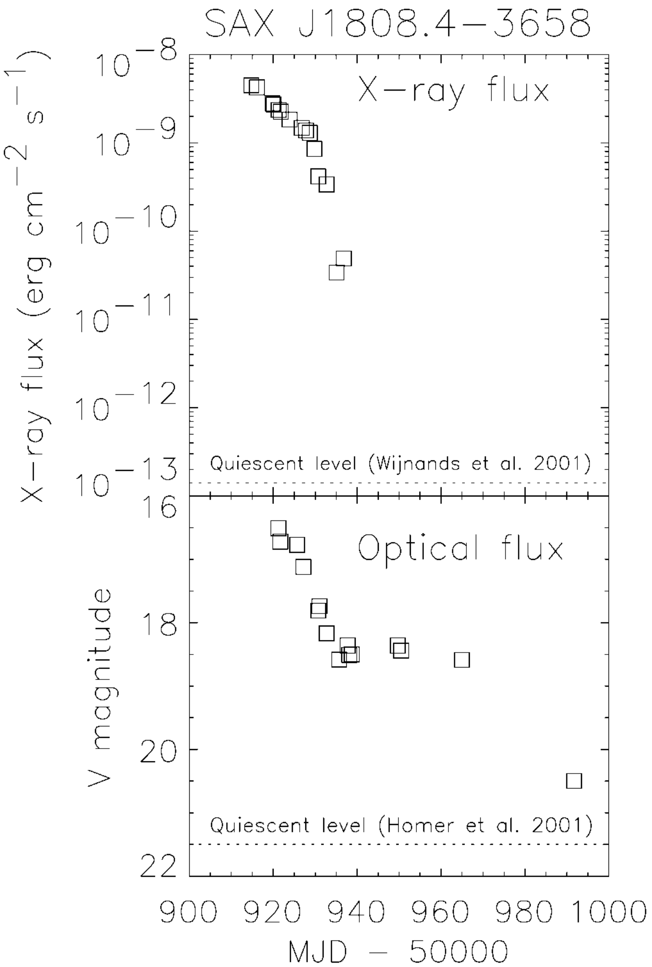

FIG. 1.—X-ray (3–150 keV) and optical flux histories during the 1998 outburst of SAX J1808.4−3658. Quiescent levels well after the outburst are also indicated. The X-ray history (taken from Gilfanov et al. 1998) contains a sharp break at MJD 50,929, while the optical history shows a break at MJD 50,936.

remains roughly constant, and we show below that this shape is easily consistent with an X-ray–heated disk model. There is an obvious IR excess on MJD 50,921, with the *JHK* points lying well above an extrapolation of the *BVRI* spectrum. By contrast, the *K* point for MJD 50,938 is consistent with the extrapolated optical spectrum. Since the origin of the IR excess early in the outburst is unclear, we restrict our accretion disk

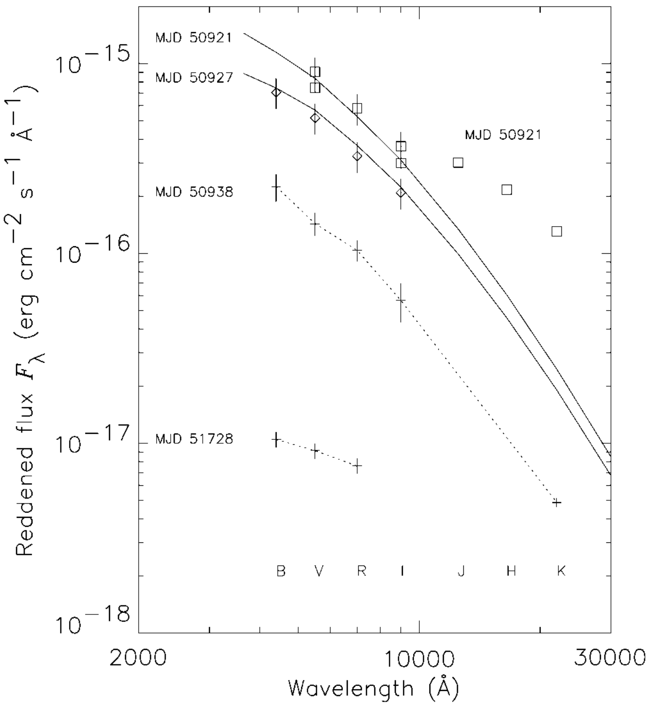

FIG. 2.—Broadband optical/IR spectra of SAX J1808.4−3658 at various epochs during the 1998 outburst. Solid curves are model fits, while dotted curves simply indicate a rough interpolation of the data. There is a clear IR excess with respect to an accretion disk model on MJD 50,921 but not on MJD 50,938.

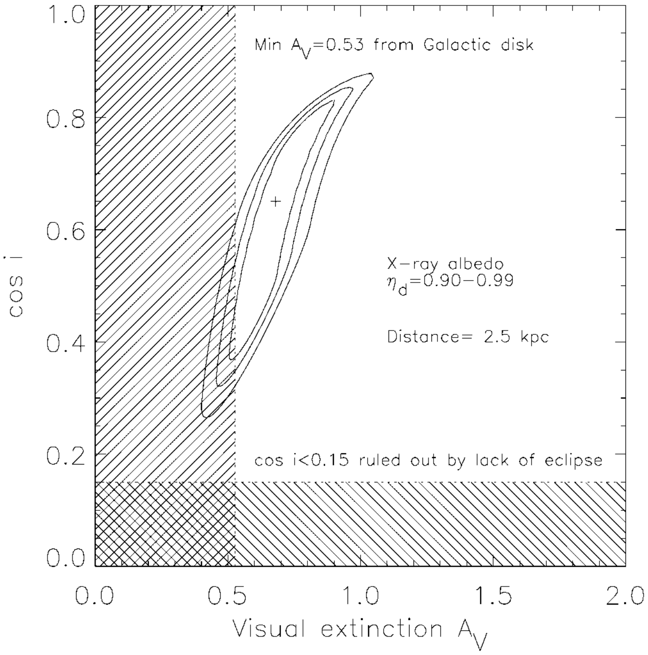

FIG. 3.—Confidence regions for cos i and A_V from spectral fitting. The best fit (cos $i = 0.65$, $A_V = 0.68$) is indicated by the cross, while the solid contours denote $\Delta\chi^2 = 1.0$, 2.3, and 4.6 (corresponding to confidence levels of 39%, 68%, and 90%). Hashed regions indicate addition limits from the line-of-sight extinction in the Galactic disk and the lack of an X-ray eclipse.

fitting in the § 3 to the optical *BVRI* bands, which (along with the ultraviolet and soft X-ray) is where most of the disk emission from a low-mass X-ray binary (LMXB) accretion disk is expected.

One point of concern is the discrepancy between optical intensities measured at different observatories a short time apart. This is particularly evident in the JKT and Mount Canopus observations on MJD 50,921, which were spaced by half a day but differ by 0.2 mag in *V* and *I*. One possible contribution to this discrepancy is the 2 hr orbital flux modulation reported by Giles et al. (1999), with an amplitude of ≃0.07 mag. To account for this in our fits, we added a systematic uncertainty of this size in quadrature to the statistical uncertainties quoted in Table 1. However, even this systematic uncertainty is insufficient to explain the discrepancy, which we conclude largely arises from further systematic errors due to calibration uncertainties in the JKT data. In particular, several of the JKT service observations suffered from limited or insufficient calibration measurements. We therefore adopt a systematic uncertainty of 0.2 mag for all the JKT measurements in our model fitting.

3. SPECTRAL FITTING

The optical data during outburst are well fitted by an X-ray–heated accretion disk model (see Vrtilek et al. 1990; Chakrabarty 1998 and references therein). We summarize this model here. The observed flux from the accretion disk at frequency ν can be written as

$$F_\nu = \frac{4\pi h\nu^3 e^{-A_\nu/1.086}\cos i}{c^2D^2}\int_{r_{\rm in}}^{r_{\rm out}} \frac{r\,dr}{\exp\,[h\nu/kT(r)] - 1}, \quad (1)$$

where D is the source distance, A_ν is the (frequency dependent) interstellar extinction in magnitudes, r is the midplane disk radius coordinate, $r_{\rm in}$ and $r_{\rm out}$ are the inner and outer radii of the disk, and the surface temperature profile $T(r)$ of the disk is given by

$$T^4(r) = \frac{3GM_{\rm X}\dot{M}}{8\pi\sigma r^3} + \frac{L_{\rm X}(1-\eta_d)}{4\pi\sigma r^2}\left(\frac{dH}{dr} - \frac{H}{r}\right). \quad (2)$$

Here $M_{\rm X}$ is the neutron star mass, $\dot{M}$ is the mass transfer rate through the disk, $L_{\rm X}$ is the X-ray luminosity of the neutron star, η_d is the X-ray albedo of the disk, and H is the scale height of the disk. $H(r)$ may be determined from the condition of hydrostatic equilibrium, as in a standard Shakura-Sunyaev disk model (see, e.g., Frank, King, & Raine 1992). The first term in equation (2) is due to internal viscous heating in the disk, and the second term is due to X-ray heating.

For SAX J1808.4−3658, many of these model parameters are well constrained. We may adopt the distance $D = 2.5$ kpc inferred from radius expansion X-ray bursts (in 't Zand et al. 2001). Since this is a disk-accreting pulsar, we may assume that the inner disk is truncated by the magnetosphere of the pulsar at a radius $r_{\rm in}$ on the order of the corotation radius $r_{\rm co} = (GM_{\rm X}P_{\rm spin}^2/4\pi^2)^{1/3} \approx 30$ km (Psaltis & Chakrabarty 1999); in fact, the optical spectrum is not very sensitive to the exact value of this parameter since the optical emission primarily arises from radii in excess of 10^8 cm. The outer disk will be cut off sharply near the tidal radius of the neutron star, approximately equal to $R_{\rm Roche}$ (Frank et al. 1992), which will in turn depend upon the mass ratio and thus the binary inclination (Eggleton 1983). We may infer the X-ray luminosity from the X-ray flux through $L_{\rm X} = 4\pi D^2 F_{\rm X}$ and hence deduce the mass transfer rate $\dot{M}$. Finally, for the X-ray albedo of the disk, we use the results of previous studies of X-ray reprocessing in LMXBs, which found that $\eta_d \gtrsim 0.90$, indicating that only a small fraction of the incident X-ray flux is absorbed by the accretion disk and reprocessed into the optical band (Kallman, Raymond, & Vrtilek 1991; de Jong, van Paradijs, & Augusteijn 1996).

With the model parameters set as described above, we fitted the heated disk model to the observed photometry with two free parameters: cos i and the optical *V*-band extinction A_V. We computed our model fits on a grid with 99 values of cos i in the range 0.01–0.99 and 501 values of A_V in the range 0.00–5.00. We computed the extinction in the other bands using the interstellar reddening law of Rieke & Lebofsky (1985). For each (A_V, cos i) grid point, we fitted the data for 10 different values of η_d in the range 0.90–0.99 and used only the best-fit value for that grid point. In order to ensure that we were working in the regime where X-ray heating is important (and the X-ray flux is well determined), we confined our fitting to the optical data prior to the break in the X-ray light curve at MJD 50,929. The fitting was performed simultaneously to all the *BVRI* data in Table 1 prior to that date.

Our simple disk model was able to provide a good simultaneous solution to these data. The best-fit parameters were $A_V = 0.68^{+0.37}_{-0.28}$ and cos $i = 0.65^{+0.23}_{-0.38}$, with reduced $\chi^2 = 0.81$ (9 degrees of freedom), where the uncertainties are quoted at the 90% confidence level. The spectral model for two epochs is shown by the solid curves in Figure 2, and a contour plot of the allowed parameter space is shown in Figure 3. The confidence levels indicated by the contours in Figure 3 are determined as described by Lampton, Margon, & Bowyer (1976). The hashed regions in Figure 3 reflect the additional lower limit of $A_V > 0.53$ set by the measured Galactic dust extinction through the Galactic disk along the line of sight (Schlegel, Finkbeiner, & Davis 1998) and the additional lower limit of cos $i > 0.15$ set by the absence of a deep X-ray eclipse of the source (Chakrabarty

& Morgan 1998). (We note that the system must lie outside the Galactic disk, given its distance and Galactic latitude.) Accounting for these additional independent limits, the best-fit parameter values are $A_V = 0.68^{+0.37}_{-0.15}$ and $\cos i = 0.65^{+0.23}_{-0.33}$. The allowed parameter space is relatively narrow in A_V, with a central value only slightly larger than the Galactic value.

To investigate how sensitive our conclusions are to the adopted source distance $D = 2.5$ kpc, we refit the data for distances of 2 and 3 kpc as well. For the larger distance, the confidence contours in Figure 3 were slightly displaced upward and to the right, with best-fit parameter values $A_V = 0.74^{+0.39}_{-0.34}$ and $\cos i = 0.80^{+0.14}_{-0.38}$ and with reduced $\chi^2 = 0.80$. For the smaller distance, the contours were more elongated and displaced downward and to the left, with best-fit parameter values $A_V = 0.63^{+0.31}_{-0.22}$ and $\cos i = 0.39 \pm 0.35$ and with reduced $\chi^2 = 0.85$. In both cases, the fit values are quoted without accounting for the addition-independent limits discussed above. The assumed distance clearly plays a significant role in determining the fit parameters, although the qualitative results of an extinction value slightly greater than Galactic and an intermediate inclination are robust.

4. DISCUSSION

We have shown that the optical spectrum of SAX J1808.4−3658 during its 1998 outburst is well fit by an X-ray–heated accretion disk model. The derived inclination range for the binary requires that the companion mass is 0.05–0.10 $M_\odot$ (Chakrabarty & Morgan 1998). This is consistent with the low companion mass deduced from the long-term average $\dot{M}$ for gravitational radiation driven mass transfer (Chakrabarty & Morgan 1998) and thus supports the recent prediction that the mass donor is a low-mass brown dwarf (Bildsten & Chakrabarty 2001). This inclination range is also consistent with the orbital phase flux variability observed from the source in both the X-ray (Chakrabarty & Morgan 1998; J. C. Lee, D. Psaltis, & D. Chakrabarty 2001, in preparation) and optical (Giles et al. 1999; Homer et al. 2001) bands.

The strong IR excess measured on MJD 50,921 is clearly inconsistent with emission from the X-ray heated disk (see Fig. 2). It is also orders of magnitude too bright to be due to the companion; even X-ray heating does not mitigate this because of the small solid angle subtended by the star. On the other hand, the IR emission on MJD 50,938 is consistent with disk emission, indicating that the cause of the earlier IR excess is transient in nature. It is interesting to note that the flux density of the IR excess is comparable to the radio flux density measured from the source a week later (Gaensler, Stappers, & Getts 1999). Radio/IR emissions due to synchrotron processes have been previously detected from some X-ray binaries during outburst (see, e.g., Fender 2001). The possibility of a synchrotron origin for the IR excess on MJD 50,921 (as well as the radio emission) will be explored in detail elsewhere (D. Chakrabarty, B. M. Gaensler, & B. W. Stappers 2001, in preparation).

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REFERENCES

Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1
Bildsten, L., & Chakrabarty, D. 2001, ApJ, 557, 292
Chakrabarty, D. 1998, ApJ, 492, 342
Chakrabarty, D., & Morgan, E. H. 1998, Nature, 394, 346
de Jong, J. A., van Paradijs, J., & Augusteijn, T. 1996, A&A, 314, 484
Eggleton, P. P. 1983, ApJ, 268, 368
Fender, R. 2001,Ap&SS, 276, 69
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (2d ed.; Cambridge: Cambridge Univ. Press)
Gaensler, B. M., Stappers, B. W., & Getts, T. J. 1999, ApJ, 522, L117
Giles, A. B., Hill, K. M., & Greenhill, J. G. 1999, MNRAS, 304, 47
Gilfanov, M., Revnivtsev, M., Sunyaev, R., & Churazov, E. 1998, A&A, 338, L83
Homer, L., Charles, P. A., Chakrabarty, D., & van Zyl, L. 2001, MNRAS, 325, 1471
in 't Zand, J. J. M., Heise, J., Muller, J. M., Bazzano, A., Cocchi, M., Natalucci, L., & Ubertini, P. 1998, A&A, 331, L25
in 't Zand, J. J. M., et al. 2001, A&A, 372, 916
Kallman, T. R., Raymond, J. C., & Vrtilek, S. D. 1991, ApJ, 370, 717
Kazarovets, E. V., Samus, N. N., & Durlevich, O. V. 2000, Inf. Bull. Variable Stars, 4870, 1
Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 177
Marshall, F. E. 1998, IAU Circ. 6876
Percival, W., Charles, P., Kuulkers, E., Miller, L., Shahbaz, T., McLure, R., & Dunlop, J. 1998, IAU Circ. 6902
Psaltis, D., & Chakrabarty, D. 1999, ApJ, 521, 332
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Roche, P., Chakrabarty, D., Morales-Rueda, L., Hynes, R., Slivan, S. M., Simpson, C., & Hewett, P. 1998, IAU Circ. 6885
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Vrtilek, S. D., Raymond, J. C., Garcia, M. R., Verbunt, F., & Hasinger, G. 1990, A&A, 235, 162
Wijnands, R., Kuiper, L., in 't Zand, J., Dotani, T., van der Klis, M., & Heise, J. 2001, ApJ, submitted (astro-ph/0105421)
Wijnands, R., & van der Klis, M. 1998, Nature, 394, 344