THE QUIESCENT OPTICAL AND INFRARED COUNTERPART TO EXO 0748–676 = UY VOL

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ABSTRACT

We present optical and infrared photometry of the low-mass X-ray binary EXO 0748–676 in quiescence for the first time in 24 years since it became X-ray active in 1985. We find the counterpart at average magnitudes of $R = 22.4$ and $J = 21.3$. We monitored the source approximately nightly from 2008 November to 2009 January. During this time there was considerable night-to-night optical variability but no long-term trends were apparent. The night-to-night variability reveals a periodicity of $P = 0.159331 \pm 0.000012$ d, consistent with the X-ray orbital period to within 0.01%. This indicates that the quiescent optical modulation is indeed orbital in nature rather than a superhump. Interestingly, the modulation remains single-peaked with a deep minimum coincident with the times of X-ray eclipse, and there is no indication of a double-peaked ellipsoidal modulation. This indicates that even in “quiescence,” emission from the accretion disk and/or X-ray heated inner face of the companion star dominate the optical emission, and implies that obtaining an accurate dynamical mass estimate in quiescence will be challenging.

Key words: binaries: eclipsing – stars: individual: (UY Vol) – X-rays: binaries

1. INTRODUCTION

The low-mass X-ray binary (LMXB) EXO 0748–676 was discovered in 1985 as a transient X-ray source (Parmar et al. 1985) and rapidly associated with an optical counterpart, UY Vol (Wade et al. 1985). Unlike most X-ray transients, however, it did not decay back to a quiescent state, but remained active and for the last two decades has been considered part of the persistent LMXB population. In 2008 August–September, Wolff et al. (2008a) found EXO 0748–676 unusually faint, at a factor of two below its typical RXTE brightness and suggested that a transition to quiescence might finally be impending. In late September, Swift found the source at a low luminosity consistent with quiescence and in early October RXTE failed to detect the source at all, confirming that it had dropped to quiescence (Wolff et al. 2008b). Degenaar et al. (2009) presented five Swift and two Chandra observations spanning late September to early November, including the Swift data previously reported by Wolff et al. (2008b). They found the source declining during this period from $16 \times 10^{33}$ erg s$^{-1}$ to $8.3 \times 10^{33}$ erg s$^{-1}$ with the spectrum dominated by thermal emission from the neutron star surface.

The optical counterpart, UY Vol, was originally discovered around 17th magnitude (Wade et al. 1985). Subsequent studies found pronounced orbital modulation arising from a combination of eclipses of the accretion disk and X-ray heating of the companion star. The brightness spanned $17.7 > B > 16.9$ (Crampton et al. 1986; Schmidtke & Cowley 1987) with $\sim 0.2$ mag variations between epochs, and $17.8 > V > 17.1$ (van Paradijs et al. 1988). This brightness was typical of later observations. By 2008 October, the source had substantially faded to $R \sim 22$ (Hynes & Jones 2008; Torres et al. 2008) reinforcing the conclusion that it was now quiescent.

EXO 0748–676 is an intriguing object for a number of reasons. It is unusual among neutron star LMXBs in being a quasi-persistent source for which we have observed the entire period of activity and furthermore have estimates of the pre-eruption luminosity (Garcia & Callanan 1999). This makes it a fascinating system in which to study the post-eruption cooling curve and investigate the physics of neutron star interiors (Degenaar et al. 2009).

It also has an optimal inclination angle yielding total X-ray eclipses of the neutron star without being an accretion disk corona source, shows periodic X-ray dips, and also exhibits type I X-ray bursts (Parmar et al. 1986; Gottwald et al. 1986). The possible detection of gravitationally redshifted absorption lines during X-ray bursts offered tantalizing prospects for constraining the neutron star equation of state (Cottam et al. 2002), although this detection could not be reproduced in subsequent observations (Cottam et al. 2008). Independently, Özel (2006) argued that soft equations of state can be ruled out based on observations of other characteristics of X-ray bursts in EXO 0748–676.

Since our optical observation at the end of 2008 October (Hynes & Jones 2008), we have been following the source nightly in the optical. We report here on the optical behavior in quiescence over the following three months.

2. OBSERVATIONS

Optical and infrared photometry of UY Vol were obtained approximately nightly from 2008 October 28 to 2009 February 5 using Andicam on the SMARTS 1.3 m telescope. Each night, three 450 s $R$-band images were taken together with 20 50 s $J$-band images. During this period, data were obtained on 71 out of 101 nights. We show our combined optical image in Figure 1.

Optical data were supplied with pipeline reductions applied and these were satisfactory. The three images from each night were aligned and combined to produce a single average before performing aperture photometry on UY Vol and a comparison star (both shown in Figure 1). All photometry was done differentially relative to the comparison star using standard IRAF techniques, and this star was then calibrated separately relative to standard stars A, C, and D in the field of T Phe observed on multiple photometric nights (Landolt 2009). Our estimate of the calibrated magnitude of the comparison is $R = 14.66 \pm 0.03$. The uncertainty quoted is the night-to-night standard deviation. Systematic errors may be larger as color...
corrections were not possible since only $R$-band observations were performed.

Our deduced average magnitude for UY Vol is $R = 22.39 \pm 0.04$. This is the formal error on the mean and systematic uncertainties in the calibration may be larger. We show the long-term light curve in Figure 2. Considerable night-to-night variability is present but there is no obvious long-term trend. We will quantify this statement after removing some of the intrinsic variability in Section 4. To verify the significance of the variability seen we also show a light curve for another nearby star at $R = 22.42 \pm 0.04$. The standard deviation of the individual UY Vol data is 0.36 mag, while that for the nonvariable star is 0.26 mag.

IR data were obtained in a 7-point dither pattern. $3 \times 50$ s images were taken at six of the seven positions, and two at the other. For each night, a sky image derived from the median of the dithered images was subtracted, and flat fields were applied. We excluded images with the highest sky values and those with a sky value significantly deviating from the nightly mean to minimize residuals in the background subtraction. We then filtered the remaining images based on visibility of the faintest stars in the field. Our final combination of these best images used 422 individual frames, all of which had been individually checked. The target is marginally detected in this combined IR image at a position consistent with that measured from optical images. Photometry relative to several Two Micron All Sky Survey stars in the field yields $J = 21.3 \pm 0.2$. At this level, we caution that systematic errors in background subtraction are likely to be larger than the formal statistical error quoted.

3. PERIOD SEARCH

It was immediately apparent that the data appeared consistent with modulation on the published orbital period of 3.82 hr = 0.1593 d (Wolff et al. 2002) with a single-humped modulation. To verify this we fitted the full data set with a sinusoidal modulation of variable period, allowing the phasing, amplitude and mean brightness to vary freely. We find several strong minima in the 0.10–0.25 d period range (Figure 3). One of these is consistent with the orbital period, and the others are consistent with one-day aliases of the orbital period, as expected given our once-per-day sampling. No significant minima are seen other than these aliases.

Choosing the alias corresponding to the X-ray period, we derive an optical period of $P = 0.159331 \pm 0.000012$ d. The $1\sigma$ uncertainty quoted corresponds to the range of periods with which $\chi^2 \leq \chi^2_{\text{min}} + 1$. This period is consistent with the secure X-ray orbital period of 0.159338 d to within errors. The uncertainty is $\sim 0.01\%$ of the orbital period, so the optical period is indeed orbital not significantly longer as would be expected from a superhump modulation.

4. LIGHT CURVES

Since the dominant photometric variations are orbital, we fold the data on the X-ray orbital ephemeris of Wolff et al. (2002) and show the folded data in Figure 4. The orbital modulation is very apparent, with a minimum at phase 0.0 and a maximum at phase 0.5. The light curve is rather similar to those seen in brighter states (Crampton et al. 1986; Schmidtke & Cowley 1987; van Paradijs et al. 1988) and attributed there to a combination of eclipses of a hot accretion disk and irradiation of the inner face of the companion star. The amplitude of the modulation is about the same as seen earlier.

We use the folded light curve to remove the orbital modulation and better search for long-term trends. In particular, we expect fading if the optical light is due to heating by the cooling neutron star. To do this we construct a coarsely phase-binned version of the light curve, shown plotted over the data in Figure 4. After
removing the orbital modulation, no long-term trend emerges and a formal fit yields a gradient of less than 0.005 mag per day, and consistent with zero.

5. DISCUSSION

The lower range of the observed modulation provides an upper limit to the unheated brightness of the companion star. Muñoz-Darias et al. (2009) discuss the system parameters and nature of the companion star based on outburst data. They argue that the companion mass is $0.16 M_\odot \leq M_2 \leq 0.42 M_\odot$, with the upper limit corresponding to a main-sequence mass donor and lower masses to somewhat evolved stars. The upper-limit suggests an M2V classification, for which we expect $R = 22.8$ at 7.7 kpc (Cox 2000). The 7.7 kpc distance was estimated from a photospheric radius expansion burst by Wolff et al. (2005) assuming a 1.4 $M_\odot$ neutron star burning helium rich material. Assuming a heavier neutron star or hydrogen rich material, the effective temperature for the quiescent emission around 5000 K, effective temperature for the cool neutron star) could still dominate the light curve and hence the companion should be cooler, so that the companion should receive a larger fraction of the X-ray flux. This means they will also shield the companion and lower masses to somewhat evolved stars. The upper-limit of the observed modulation provides an upper limit to the unheated brightness of the companion star.

The evolved case would be smaller, due to the smaller mass ratio and hence smaller Roche lobe, and is likely to be cooler, so would be at $R > 22.8$. Given uncertainties in the distance, the main-sequence case cannot be ruled out based on the current brightness of the source, although could be if it fades below this level.

The modulation seen is clearly orbital in origin. The period agrees with the X-ray one to within 0.01%, and the minimum coincides with the minimum of the X-ray ephemeris. This rules out superhumps as a possible alternative modulation mechanism. Superhumps may be common in LMXBs (Haswell et al. 2001) and have been seen in the black hole system XTE J1118+480 near quiescence (Zurita et al. 2002). The superhump period should exceed the orbital period by a few percent, however, and this is clearly not the case.

The modulation is single-peaked with a pronounced minimum near phase zero. It actually looks rather similar to those observed in bright states, especially in the data of Schmidtke & Cowley (1987) where the peak appears slightly skewed to phases earlier than 0.5. Even the amplitude is similar to the 0.5–0.6 mag amplitude seen in outburst. This suggests that the light curve is still dominated by X-ray heating of the companion and/or eclipses of the accretion disk.

The extent of X-ray heating of the companion star can readily be estimated. For a period of 3.82 hr and assuming a typical neutron star mass, 1.4 $M_\odot$, and a typical LMXB mass ratio of one-third, we expect a binary separation $a \sim 10^{11}$ cm. Assuming an isotropic X-ray luminosity $L_X = 8.3 \times 10^{33}$ erg s$^{-1}$ (Degenaar et al. 2009), we then deduce an X-ray flux at the companion star of $f_X = 6 \times 10^{10}$ erg cm$^{-2}$ s$^{-1}$ and an irradiation temperature of $T_{irr} \approx 6000$ K for normal incidence. Of course, the true geometry does not provide normal incidence, and thermal reprocessing of X-rays is likely to be less than 100% efficient, but it would still be reasonable to expect an irradiation temperature above 5000 K over a significant area of the inner face of the companion, well in excess of its likely photospheric temperature. It is therefore plausible that X-ray heating (by the cooling neutron star) could still dominate the light curve as seems to be observed, though this is likely marginal at this point, and the unheated portions of the photosphere may be contributing non-negligible flux. We note that the deduced color, $R - J = 1.1$ also independently suggests an average effective temperature for the quiescent emission around 5000 K, consistent with these calculations.

While the heating of the companion star can account for the observations, some heating of the accretion disk may be occurring as well. This is harder to quantify as it depends sensitively on the disk geometry. In general, we would expect irradiation of the disk to be less important in quiescence. Cooler disks should be less vertically extended so will intercept less X-ray flux. This means they will also shield the companion star less, so that the companion should receive a larger fraction of the X-ray luminosity than in outburst. The similarity of the light-curve shape and amplitude to that in outburst certainly is suggestive that the disk may still be contributing, but heating of the companion alone is sufficient to explain the observations, so we cannot make a firmer statement on the extent of the disk contribution.

A single-humped irradiation dominated light curve is not unprecedented in quiescent objects. This is what is seen in the optically bright accreting millisecond pulsars in quiescence: SAX J1808.4–3658 (Burderi et al. 2003; Campana et al. 2004)
and IGR J00291+5934 (D’Avanzo et al. 2007; Jonker et al. 2008). In those systems, however, the observed X-ray luminosity was two orders of magnitude too low to explain the observed heating, and instead a turned-on pulsar wind was invoked. In EXO 0748–676 thermal emission from the cooling neutron star is sufficient to explain the modest level of heating of the companion that is needed.

While the neutron star appears to still be cooling (Degenaar et al. 2009), pre-eruption X-ray observations suggest that it may already be close to the true-quiescent X-ray level, corresponding to the crust quickly returning to thermal equilibrium with an unusually hot core (Garcia & Callanan 1999; Degenaar et al. 2009). In this case, we would not expect the optical counterpart to dim significantly more, and that the X-ray heating may remain a persistent feature in the quiescent light curve. This is supported by our lack of apparent long-term decay.

This means there may be limited prospect for measuring ellipsoidal variations. Fortunately, since UY Vol is an eclipsing system we already have good constraints on the binary inclination without ellipsoidal variations. Obtaining a radial velocity curve is in principle still possible, as the X-ray heating is at a low level and is likely not completely overwhelming photospheric emission. Other X-ray active systems have yielded photospheric radial velocity curves, e.g., V395 Car (Shahbaz et al. 1999), although concerns are then raised about whether the photospheric absorption lines are present across the whole companion star surface and hence whether the radial velocity curve determined truly traces the motion of the companion star center of mass. In any case, with a brightness of 22 < R < 23, UY Vol will be an extremely challenging target for radial velocity studies.

6. CONCLUSIONS

We have obtained optical photometry of EXO 0748–676 = UY Vol since its X-ray decline to quiescence in late 2008. We find an average brightness of R = 22.4, with substantial intrinsic variability. The variations are orbital in origin and define a single-humped light curve similar to that seen in outburst. This suggests that X-ray heating by the cooling neutron star is still dominating the optical emission and that obtaining a reliable dynamical mass estimate may be challenging for this object.

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REFERENCES

Burderi, L., Di Salvo, T., D’Antona, F., Robba, N. R., & Testa, V. 2003, A&A, 404, L43
Campana, S., et al. 2004, ApJ, 614, L49
Cottam, J., Paerels, F., & Mendez, M. 2002, Nature, 420, 51
Cottam, J., Paerels, F., Méndez, M., Boïtin, L., Lewin, W. H. G., Kuulkers, E., & Miller, J. M. 2008, ApJ, 672, 504
Cox, A. N. (ed.) 2000, Allen’s Astrophysical Quantities (4th ed., New York: AIP Press)
Crampton, D., Stauffer, J., Hutchings, J. B., Cowley, A. P., & Ianna, P. 1986, ApJ, 306, 599
D’Avanzo, P., Campana, S., Covino, S., Israel, G. L., Stella, L., & Andreuzzi, G. 2007, A&A, 472, 881
Degenaar, N., et al. 2009, MNRAS, in press
Garcia, M. R., & Callanan, P. J. 1999, AJ, 118, 1390
Gottwald, M., Haberl, F., Parmar, A. N., & White, N. E. 1986, ApJ, 308, 213
Haswell, C. A., King, A. R., Murray, J. R., & Charles, P. A. 2001, MNRAS, 321, 475
Hynes, R., & Jones, E. 2008, Astron. Tel., 1816
Jonker, P. G., Torres, M. A. P., & Steeghs, D. 2008, ApJ, 680, 615
Landolt, A. U. 1992, AJ, 104, 340
Muñoz-Darias, T., Casares, J., O’Brien, K., Steeghs, D., Martinez-Pais, I. G., Cornelisse, R., & Charles, P. A. 2009, MNRAS, 394, L136
Özel, F. 2006, Nature, 441, 1115
Parmar, A. N., White, N. E., Giommi, P., & Gottwald, M. 1986, ApJ, 308, 199
Parmar, A. N., White, N. E., Giommi, P., Haberl, F., Pedersen, H., & Mayor, M. 1985, IAU Circ., 4039
Schmidteke, P. C., & Cowley, A. P. 1987, AJ, 93, 374
Shahbaz, T., Kuulkers, E., Charles, P. A., van der Hooft, F., Casares, J., & van Paradis, J. 1999, A&A, 344, 101
Torres, M. A. P., Jonker, P. G., Steeghs, D., & Seth, A. C. 2008, Astron. Tel., 1817
van Paradijs, J., van der Klis, M., & Pedersen, H. 1988, A&AS, 76, 185
Wade, R. A., Quintana, H., Horne, K., & Marsh, T. R. 1985, PASP, 97, 1092
Wolff, M. T., Becker, P. A., Ray, P. S., & Wood, K. S. 2005, ApJ, 632, 1099
Wolff, M. T., Hertz, P., Wood, K. S., Ray, P. S., & Bandyopadhyay, R. M. 2002, ApJ, 575, 384
Wolff, M. T., Ray, P. S., & Wood, K. S. 2008, Astron. Tel., 1736
Wolff, M., Ray, P., Wood, K., & Wijnands, R. 2008, Astron. Tel., 1812
Zurita, C., et al. 2002, MNRAS, 333, 791