THE REAPPEARANCE OF THE TRANSIENT LOW-MASS X-RAY BINARY X1658–298

STEFANIE WACHTER
Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile

ALAN P. SMELE
Laboratory for High-Energy Astrophysics/Universities Space Research Association, Code 662, NASA/Goddard Space-Flight Center, Greenbelt, MD 20771

AND

CHARLES BAILYN
Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101

Received 1999 November 5; accepted 1999 December 22

ABSTRACT

In April 1999 the transient low-mass X-ray binary X1658–298 resumed its strong and persistent X-ray emission after a 21 yr interval of quiescence. We present RXTE data obtained soon after the reappearance, including four eclipses with a mean duration of 901.9 ± 0.8 s and ingress/egress times of 6–13 s. Our updated ephemeris for the source indicates that the 7.1 hr orbital period of the system is decreasing with a timescale of 10⁻⁸ yr. Contemporaneous optical observations provide the first ever light curve of V2134 Oph, the optical counterpart of X1658–298. The optical modulation is highly variable from night to night and exhibits a distinct, narrow eclipse feature of about 0.2 mag superposed on a gradual brightness variation with ~0.7–0.8 mag amplitude. Our data indicate that there is no significant offset between the time of mideclipse in the X-ray and optical and that the narrow optical eclipse feature is of the same duration as the X-ray eclipse. This implies an accretion disk structure characterized by enhanced optical emission coincident with the central X-ray–emitting area.

Subject headings: accretion, accretion disks — binaries: close — binaries: eclipsing — stars: individual (V2134 Ophiuchi) — stars: neutron — stars: variables: other — X-rays: stars

1. INTRODUCTION

X1658–298 is a soft X-ray transient discovered in 1976 by Lewin, Hoffmann, & Doty (1976). The detection of type I bursts indicates that the compact object in the system is a neutron star. Observations during a temporary brightening of the source in 1978 showed dips in the X-ray light curve. Detailed analysis of the combined 1976–1978 data set by Cominsky & Wood (1984, 1989) revealed that X1658–298 is one of the rare low-mass X-ray binary systems (LMXBs) that exhibit eclipses of the central X-ray source by the mass-donating star. The dipping activity lasts for about 25% of the 7.1 hr orbital cycle followed by an eclipse of ~15 minutes duration.

The optical counterpart of X1658–298 was identified during the 1978 X-ray outburst with a faint (V = 18.3), blue star (V2134 Oph) by Doxsey et al. (1979). Spectroscopic observations show a typical LMXB spectrum, a blue continuum with emission lines of He II λ4686 and the C III/N III λ4640/4650 blend (Canizares, McClintock, & Grindlay 1979). X1658–298 entered an X-ray off state in 1979, and the counterpart became undetectable with a magnitude limit of V > 23 (Cominsky, Ossmann, & Lewin 1983).

Renewed X-ray activity from X1658–298 was detected by BeppoSAX on April 2–3 1999 (In't Zand et al. 1999), marking the first X-ray detection of the source since 1978. Follow-up observations were quickly scheduled with RXTE under a public Target of Opportunity program and with optical telescopes at Cerro Tololo Inter-American Observatory (CTIO). In this paper we present the first optical light curve of X1658–298 and the results of our RXTE eclipse timing and spectral fitting analysis.

2. OBSERVATIONS

2.1. X-Ray

X1658–298 was observed with the RXTE satellite for a series of four public observations between 1999 April 5 and 15, soon after the recommencement of X-ray activity. The X-ray data we present here were obtained using the RXTE Proportional Counter Array (PCA) instrument with the Standard 2 and E_125us_64M_0.1s configurations, with time resolutions of 16 s and 125 μs, respectively. The PCA consists of five Xe proportional counter units (PCUs), with a combined effective area of about 6500 cm² (Jahoda et al. 1996). For operational reasons, differing numbers of PCUs were utilized in each observation. In Table 1 we list the observation times and the PCUs that were on during each observation. Data extraction was performed using the RXTE standard analysis software, FTOOLS, version 4.2. The “skyle/fskyactiv” models generated by the RXTE PCA team were used for background subtraction and found to be accurate to better than 1 count s⁻¹. Light curves and spectra were analyzed in the 2–20 keV band. Barycentric corrections have been applied to all X-ray timings. Two percent systematic errors were added to the spectral data before fitting to represent the current uncertainties in response matrix generation.

2.2. Optical

CCD V- and I_c-band photometry of V2134 Oph was performed with the CTIO 1.5 m and Yale, AURA, University of Lisbon, and Ohio State University (YALO) telescopes from UT 1999 April 29 to May 3. The image scale at...
the telescopes was 0'24 and 0'30 pixel⁻¹, respectively. The data were overscan corrected, bias corrected, and flat-fielded in the standard manner using IRAF. Photometry was performed by point-spread function fitting with DAOPHOT II (Stetson 1993). The instrumental magnitudes were transformed to the standard system through comparison with previously calibrated local standards (Wachtler & Smale 1998). The intrinsic 1 σ error of the relative photometry is about ±0.02 mag as derived from the rms scatter in the light curve of comparison stars of similar brightness. The standardized magnitudes are accurate to about ±0.10 mag. Exposure times were 300 s for the YALO data and 200–240 s (around the times of eclipse) for the 1.5 m data, depending on the observing conditions.

3. RESULTS

3.1. X-Ray

The X-ray observations were scheduled to occur centered on the expected times of eclipse, as extrapolated from the ephemeris of Cominsky & Wood (1989). As intended, one complete eclipse was observed per observation. We have determined the duration, midpoint, and transition times for each eclipse by modeling each ingress and egress transition with a "step and ramp" model, consistent with the methodology adopted in studies of eclipses from the similar transient LMXB X0748–676 (e.g., Parmar et al. 1986; Corbet et al. 1994). The model assumes a linear transition into and out of eclipse and has four free parameters per transition: the start and end time and the count rates before and after the transition. From these we derive the ingress and egress durations, ΔT_{ing} and ΔT_{egr}, the eclipse duration ΔT_{ecl} (measured from the end of ingress to the beginning of egress), and the eclipse midpoints (midway between the end of ingress and the start of egress). Table 2 contains the measured values of these quantities for each eclipse. We find a spread of ingress/egress times of 6–13 s, with mean values for ΔT_{ing} and ΔT_{egr} of 9.1 ± 3.0 and 9.5 ± 3.3 s, respectively, and a mean eclipse duration of 901.9 ± 0.8 s. The X-ray eclipse transitions of X1658–298 together with the model fits are shown in Figure 1.

These four eclipse centers occur an average of 407.4 s earlier than predicted by the ephemeris of Cominsky & Wood (1989). We have combined our eclipse timings with the eclipse centers (corrected to barycentric dynamical time [TDB]) from the HEAO A-1 and SAS 3 observations of Cominsky & Wood (1984, 1989) to produce the updated ephemeris presented in Table 3. A parabolic ephemeris is required to obtain a good fit to the eclipse timings; the P/P

| Table 1: RXTE Observation Log |   |
|-------------------------------|---|
| Observation | Start/Stop Time (UT) | PCUs On |
| 1 | 1999 Apr 5 20:12–Apr 6 01:18 | 0124 |
| 2 | 1999 Apr 9 19:34–Apr 9 20:13 | 023 |
| 3 | 1999 Apr 13 16:07–Apr 13 16:46 | 02 |
| 4 | 1999 Apr 15 17:58–Apr 15 18:26 | 024 |

| Table 2: X-Ray Eclipse Parameters |   |
|-----------------------------------|---|
| Observation Date | Cycle Number* | Eclipse Centers (JD–2440,000)* | ΔT_{ecl} (s) | ΔT_{ing} (s) | ΔT_{egr} (s) |
| 1976 Oct 7th | 0 | 3059.22595(15) | ... | ... | ... |
| 1978 Mar 7th | 1740 | 3575.1443(15) | ... | ... | ... |
| 1999 Apr 5th | 27707 | 11274.4780792(15) | 902.3 ± 0.2 | 6.4 ± 0.1 | 5.5 ± 0.2 |
| 1999 Apr 9th | 27720 | 11278.3326259(37) | 899.0 ± 0.5 | 8.2 ± 0.5 | 13.2 ± 0.7 |
| 1999 Apr 13th | 27733 | 11282.1817143(37) | 904.4 ± 0.5 | 8.3 ± 0.6 | 11.0 ± 0.8 |
| 1999 Apr 15th | 27740 | 11284.2627259(32) | 902.1 ± 0.4 | 13.4 ± 0.6 | 8.2 ± 0.9 |

* Cycle numbers are relative to the ephemeris presented in Table 3 and differ by 1 from the eclipse numbering used in Cominsky & Wood 1989.
* TDB. Error on final digits given in parentheses.
* Data from Cominsky & Wood 1989.
term implies that the orbital period of the system is decreasing on a timescale of $10^7$ yr. This ephemeris was then used to phase our optical data in the following sections.

We have also performed a spectral analysis of the RXTE PCA data. From each data set, we extracted a spectrum of the persistent (non-eclipse, nondip) emission and an eclipse spectrum. The spectra of the persistent emission each contain $\sim 1300$ s of data and the eclipse spectra $\sim 880$–896 s. In each case the persistent spectrum can be well fitted using a power-law plus high-energy cutoff model, with power-law index $\alpha = 2.1 \pm 0.1$, cutoff $8.6 \pm 0.6$ keV, and a hydrogen column density $N_H$ of $(5.0 \pm 0.6) \times 10^{22}$ cm$^{-2}$. A Comptonized Sunyaev & Titarchuk model also provides reasonable fits to the data, with $kT = 3.9 \pm 0.2$ keV, $\tau = 7.1 \pm 0.3$, and $N_H = (6.1 \pm 0.5) \times 10^{22}$ cm$^{-2}$. The reduced $\chi^2$ values for both models are acceptable, in the range $1.0$–$1.2$. Two-component models (such as a power law plus blackbody) will also fit the data, although an $F$-test does not justify the inclusion of the second component. The mean persistent $2$–$20$ keV flux of the source throughout the observations is $1.05 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$. The eclipse spectra can be consistently fitted with a simple, steeper power law with $\alpha = 3.5 \pm 0.4$ and $N_H = (15 \pm 5) \times 10^{22}$ cm$^{-2}$. Over the $2$–$20$ keV range, the eclipse flux level is measured to be $1.9 \pm 0.7\%$ of the persistent emission.

The durations we measure for the X-ray eclipse transitions are shorter than those determined from the previous activity cycle (mean $A\Delta T_{\text{ing}} = 41 \pm 13$ s, mean $A\Delta T_{\text{eq}} = 19 \pm 13$ s; Cominsky & Wood 1989). However, a broad spread of values for the eclipse transitions from a given source may be common; the similar source X0748–676 shows transition times from $1.5$ to $40$ s (Parmar et al. 1991). Transition times are defined by the atmospheric scale height of the companion, which can be affected by flaring activity or the presence of an X-ray–induced evaporative wind or corona; a more detailed discussion of such effects in X1658–298 will be worthwhile once a larger sample of eclipses is obtained.

Period changes have been previously detected in six other LMXBs and may provide valuable clues about the progression of binary evolution. For conservative mass transfer, the loss of angular momentum leads to an expected timescale for evolution of the orbital period ($\tau = P_{\text{orb}}/P_{\text{orb}}$) of $10^{8}$–$10^{10}$ yr. However, the timescales measured to date have been considerably shorter than this. The periods of X1822–371 and X2127+119 are increasing on timescales of $\tau = 2.9 \times 10^6$ yr and $\tau = 1.1 \times 10^6$ yr, respectively (Helliwell et al. 1990; Homer & Charles 1998), while X1820–303 and Her X-1 show decreasing orbital periodicities with $\tau = 1.9 \times 10^7$ yr (van der Klis et al. 1993 and references therein) and $\tau = 7.6 \times 10^7$ yr (Deeter et al. 1991). Cyg X-3 (possibly not an LMXB) shows an increasing orbital period, with $\tau = 7.3 \times 10^6$ yr, with a possible second period derivative (van der Klis & Bonnet-Bidaud 1989; Kitamoto et al. 1992). Most complex of all, X0748–676 shows a period change behavior initially seen to decrease (Parmar et al. 1991) but later impossible to reconcile with a simple constant period derivative. A sinusoidally varying orbital period (Asai et al. 1992) provided an acceptable fit until the RXTE era, when an unusually large excursion from this pattern was detected that defies straightforward parameterization (Hertz, Wood, & Cominsky 1997). The variation observed in X1658–298 is of a similar magnitude to these cases, despite the fact that (presumably) mass transfer was not occurring during the interval 1978–1999. This may pose a difficulty in explaining the change using models based on angular momentum coupling, irradiation of the secondary, or magnetic cycling (e.g., Parmar et al. 1991; Richman, Applegate, & Patterson 1994; Hertz et al. 1997).

### Table 3

| Parameter | Value  |
|-----------|--------|
| $T_0$ (JD/TDB) | 2443059.22583 ± 0.00013 |
| $P_{\text{orb}}$ (days) | 0.296504869 ± 0.000000079 |
| $P_{\text{orb}}$ (yr$^{-1}$) | $(-7.2 \pm 1.8) \times 10^{-11}$ |
| $P_{\text{orb}}/P_{\text{orb}}$ (yr$^{-1}$) | $(-8.8 \pm 2.3) \times 10^{-8}$ |

*Note:* $T_0 = T_0 + nP_{\text{orb}} + \frac{1}{2}n^2P_{\text{orb}}^2$. A.
period-mass relations for mass transfer systems imply a K0 star instead. Note, however, that the $R$ magnitudes of the comparison stars A and E (A and 1 in our nomenclature) in Filippenko et al. (1999) are systematically 0.6–0.7 mag fainter than those given in Wachter & Smale (1998). If the $R$ magnitude of V2134 Oph is similarly too faint, the resulting $(R-I)_0$ is consistent with the required early K spectral type within the errors. A K0 companion would have $V = 23.6$, in accordance with the observed $V > 23$ limit.

Our 1999 $V$- and $I$-band light curves of V2134 Oph during outburst are shown in Figure 3. Data obtained with the CTIO 1.5 m telescope are indicated with filled circles for $V$ and triangles for $I$, and YALO data are indicated with stars. The observations span almost a full orbital cycle on

---

**Fig. 2.** $50' \times 50'$ $I$-band exposures of the X1658 – 298 field obtained with the CTIO 1.5 m telescope while the source was in quiescence (left, 1997 May 5) and during outburst (right, 1999 May 2). Star A is the star previously assumed to be the counterpart (Wachter & Smale 1998). The actual counterpart (flagged) is 0.8 east and 1.0 north of A.

**Fig. 3.** $V$- and $I$-band light curves of V2134 Oph, the optical counterpart of X1658 – 298, obtained in 1999 May, shortly after renewed X-ray activity was detected from the source. Data obtained with the CTIO 1.5 m telescope are indicated with filled circles ($V$) and triangles ($I$); data obtained with the YALO 1 m telescope are indicated with stars.
each night. Superposed on a gradual brightness variation with \( \sim 0.8 \) mag amplitude, a distinct, narrow eclipse feature of about 0.2 mag is visible on each night. Strong nightly variations in the shape of the light curve are also evident. For the nights with simultaneous \( V \)- and \( I \)-band coverage we rebinned the data to the average time sampling interval using linear interpolation and calculated the \((V-I)\) color index. There is no evidence for any \((V-I)\) color variation across the orbit or for a change in color from night to night. We obtain an average of \((V-I) = 0.645 \pm 0.054\) from the combined color data of the three nights.

4. DISCUSSION

Figure 4 shows the outburst data folded according to our updated X-ray ephemeris (Table 3). Following the usual convention, the time of the X-ray mid-eclipse is defined as phase 0. The deepest point of the optical light curves on each night was chosen as a reference point for the brightness of the system and the data (vertically) shifted accordingly. X-ray dips are observed for X1658 – 298 between the phases of 0.6 and 0.8. No analogous stable optical feature is evident in the folded light curves; however, our data sampling in that phase interval is fairly sparse. The folded \( V \)-band light curve clearly shows a distinct central drop in brightness within \( \sim 0.2 \) mag of the faintest observed magnitude, which is also characterized by reduced scatter compared to other phases of the light curve. The presence of such a narrow central component is evident in the individual light curves of each separate night as well. We determined the optical eclipse center to occur at phase 0.004 \( \pm 0.003 \) by selecting the folded \( V \)-band data within 0.2 mag of the faintest magnitude and calculating the time on either side of which the area within the eclipse profile was equal. The average data-sampling interval in this part of the folded \( V \)-band light curve is about 1 minute. A close-up of the central region is shown in the lower left panel of Figure 4 together with the fit to the 1999 April 5 X-ray eclipse (dotted line). Our data indicate that there is no significant offset between the time of mid-eclipse in the X-ray and optical and that the narrow component of the optical eclipse is of the same duration as the X-ray eclipse (we measure an FWHM of 14 \( \pm 2 \) minutes for this optical feature). This implies a distinct optical emission region associated with the X-ray-emitting area.

The only other LMXBs known to exhibit X-ray eclipses are X0748 – 676, X2129 + 470, X1822 – 371, Her X-1, and X0921 – 630. For systems with inclinations \( 75^\circ \leq i \leq 80^\circ \) (X1658 – 298, X0748 – 676, X1822 – 371, Her X-1), both dips and total eclipses are observed in X-rays. In higher inclination systems (\( i \gtrsim 80^\circ \); X1822 – 371, X2129 + 470), only partial X-ray eclipses are seen; the accretion disk is thought to block the direct line of sight to the central X-ray source, and the observed X-ray flux is due to scattering in an extended accretion disk corona (ADC). The optical/UV eclipse in the ADC source X1822 – 371, one of the most extensively studied systems, is found to be much broader than the X-ray eclipse (Hellier & Mason 1989; Puchnarewicz, Mason, & Cordova 1995) indicating an accretion disk radius of about twice the ADC radius. The optical light curve of X1822 – 371 varies very little from night to night and even over a time span of years. Modeling shows that several emission components such as the X-ray–heated face of the mass donor and the accretion disk rim contribute to produce the overall morphology of the optical light curve (Mason & Cordova 1982). It is therefore difficult to determine the time of ingress and egress of the optical eclipse for a given system solely from the shape of the light curve.

In contrast to X1822 – 371, our X1658 – 298 data clearly display a narrow optical feature of the same duration as the X-ray eclipse. However, the data do not reveal whether this feature merely represents the central core of a wider optical eclipse. Because of the highly variable shape of the light curve outside this narrow component, we cannot ascertain the presence or absence of wider ingress/egress signatures. The standard model calls for successively longer eclipse durations when moving from observations in X-rays to longer wavelengths to account for the eclipse of the cooler outer regions of an extended accretion disk (which would not be visible in X-rays). Our data clearly indicate an accretion disk structure characterized by enhanced optical emission coincident with the central X-ray-emitting area. We would consequently predict equivalent optical structures in all systems in which the X-ray source is believed to be viewed directly. An optical feature on the timescale of the X-ray eclipse has been observed in Her X-1 (Kippenhahn, Schmidt, & Thomas 1980). For X0748 – 676, an inspection of the individual optical light curves displayed in Crampton et al. (1986) and van Paradijs, van der Klis, & Pedersen (1988) also reveals a narrow central eclipse component very similar to that of our X1658 – 298 data. However, in both cases the authors conclude that the optical eclipse is twice as wide as the X-ray eclipse, based on which part of the light curve looks like “clearly an eclipse” and/or consideration of an average light curve that does not exhibit any central structure. While it is difficult to tell with certainty from the
published figures, it appears likely that a reexamination of these X0748 — 676 data would also show this narrow optical component to have the same duration as the X-ray eclipse.

We thank Alistair Walker for assigning us director’s discretionary time for the optical observations of this project.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France and of results provided by the ASM/RXTE team at MIT and NASA/Goddard Space-Flight Center. C. Bailyn is supported by NSF grant AST 97-30774.

REFERENCES

Asai, K., Dotani, T., Nagase, F., Corbet, R. H. D., & Shaham, J. 1992, PASJ, 44, 633
Canizares, C. R., McClintock, J. E., & Grindlay, J. E. 1979, ApJ, 234, 556
Cominsky, L., Ossmann, W., & Lewin, W. H. G. 1983, ApJ, 270, 226
Cominsky, L. R., & Wood, K. S. 1984, ApJ, 283, 765
Corbet, R. H. D., Asai, K., Dotani, T., & Nagase, F. 1994, ApJ, 436, L15
Cowley, A. P., Hutchings, J. B., & Crampton, D. 1988, ApJ, 333, 906
Crampton, D., Cowley, A. P., Stauffer, J., Ianna, P., & Hutchings, J. B. 1986, ApJ, 306, 599
Deeter, J. E., Boynton, P. E., Miyamoto, S., Kitamoto, S., Nagase, F., & Kawai, N. 1991, ApJ, 383, 324
Doxsey, R., Grindlay, J., Griffiths, R., Bradt, H., Johnston, M., Leach, R., Schwartz, D., & Schwarz, J. 1979, ApJ, 228, L67
Filippenko, A. V., Leonard, D. C., Matheson, T., Li, W., Moran, E. C., & Riess, A. G. 1999, PASP, 111, 960
Hellier, C., & Mason, K. O. 1989, MNRAS, 239, 715
Hoffmann, J. A., & Doty, J. 1976, IAU Circ., 2994, 2
Mason, K. O., & Cordova, F. A. 1982, ApJ, 262, 253
Navarro, J. 1996, in Radio Emission from the Stars and the Sun, ASP Conf. Ser. 93, ed. A. R. Taylor & J. M. Paredes (San Francisco: ASP), 159
Parmar, A. N., Smale, A. P., Verbunt, F., & Corbet, R. H. D. 1991, ApJ, 366, 253
Parmar, A. N., White, N. E., Giommi, P., & Gottwald, M. 1986, ApJ, 308, 199
Puchnarewicz, E. M., Mason, K. O., & Cordova, F. A. 1995, Adv. Space Res., 16(3), 65
Richman, H. R., Applegate, J. H., & Patterson, J. 1994, PASP, 106, 1075
Shahbaz, T., Smale, A. P., Naylor, T., Charles, P. A., van Paradijs, J., Hassall, B. J. M., & Callanan, P. 1996, MNRAS, 282, 1437
Stetson, P. B. 1993, DAOPHOT II User’s Manual (Victoria: Dominion Astrophys. Obs.)
van der Klis, M., & van Paradijs, J. 1989, A&A, 214, 203
van der Klis, M., et al. 1993, MNRAS, 260, 686
van Paradijs, J. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 543
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), 91
van Paradijs, J., & Pedersen, H. 1988, A&AS, 76, 185
Wachter, S., & Smale, A. P. 1998, ApJ, 496, L21