THE STRUCTURE OF THE ACCRETION DISK IN THE ACCRETION DISK CORONA X-RAY BINARY 4U 1822–371 AT OPTICAL AND ULTRAVIOLET WAVELENGTHS

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ABSTRACT

The eclipsing low-mass X-ray binary 4U 1822–371 is the prototypical accretion disk corona (ADC) system. We have obtained new time-resolved UV spectroscopy of 4U 1822–371 with the Advanced Camera for Surveys/Solar Blind Channel on the Hubble Space Telescope and new V- and J-band photometry with the 1.3 m SMARTS telescope at Cerro Tololo Inter-American Observatory. We use the new data to construct its UV/optical spectral energy distribution and its orbital light curve in the UV, V, and J bands. We derive an improved ephemeris for the optical eclipses and confirm that the orbital period is changing rapidly, indicating extremely high rates of mass flow in the system, and we show that the accretion disk in the system has a strong wind with projected velocities up to 4000 km s\(^{-1}\). We show that the disk has a vertically extended, optically thick component at optical wavelengths. This component extends almost to the edge of the disk and has a height equal to \(\sim 0.5\) of the disk radius. As it has a low brightness temperature, we identify it as the optically thick base of a disk wind, not as the optical counterpart of the ADC. Like previous models of 4U 1822–371, ours needs a tall obscuring wall near the edge of the accretion disk, but we interpret the wall as a layer of cooler material at the base of the disk wind, not as a tall, luminous disk rim.

Key words: binaries: eclipsing – pulsars: individual (4U 1822–371) – X-rays: binaries

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1. INTRODUCTION

4U 1822–371 is a low-mass X-ray binary (LMXB) with an orbital period of \(P_{\text{orb}} = 5.57\) hr (Mason et al. 1980). The compact star in the system is an X-ray pulsar with spin period \(P_{\text{pulse}} = 0.593\) s (Jonker & van der Klis 2001) and is, therefore, a neutron star. The UV/optical spectrum of 4U 1822–371 is rich with emission and absorption lines (Charles et al. 1980; Mason & Cordova 1982a; Mason et al. 1982; Harlaftis et al. 1997; Cowley et al. 1982, 2003; Jonker et al. 2003; Hutchings et al. 2005). Doppler tomography of the He \(\text{ii}\) \(λ4686\) and O \(\text{vi}\) \(λ3811\) emission lines confirms expectations that there is an accretion disk around the neutron star fed by a stream of gas from the secondary star (Casares et al. 2003).

4U 1822–371 is one of the rare eclipsing LMXBs (Mason et al. 1980; White et al. 1981). Many analyses of the eclipse have been published (White et al. 1981; White & Holt 1982; Mason & Cordova 1982a, 1982b; Hellier & Mason 1989; Baptista et al. 2002; Cowley et al. 2003) and, although the detailed results of the various analyses often differ greatly, there is substantial agreement on several points. The eclipse is a transit of the secondary star across the accretion disk and, since the eclipse is very broad at optical wavelengths, the accretion disk is large, although exactly how large is uncertain. Mason & Cordova (1982b) find \(r_{\text{disk}}/a = 0.28\) to 0.38 and Hellier & Mason (1989) find \(r_{\text{disk}}/a = 0.58 \pm 0.08\), where \(r_{\text{disk}}\) is the radius of the disk and \(a\) is the separation of the stars. The X-ray eclipse is also broad. Its flux at minimum is at about 50% of the un eclipsed flux level, and it has no sharp features, showing that the X-ray emission comes from a partially eclipsed extended cloud around the neutron star—an accretion disk corona (ADC; White et al. 1981; Mason & Cordova 1982a). The corona extends to \(\sim 0.5r_{\text{disk}}\) in the plane of the disk and is vertically extended. Estimates of the ratio of its height to its radius in the plane of the disk range from 0.3 to 1 (White & Holt 1982; Mason & Cordova 1982a; Hellier & Mason 1989). The orbital inclination lies in the range \(78° < i < 84°\).

The ratio of the X-ray luminosity of 4U 1822–371 to its optical luminosity, \(L_X/L_{\text{opt}}\), lies between \(\sim 15\) and \(\sim 65\), much less than that for typical LMXBs, indicating that the ADC is optically thick and blocks most of the X-ray emission from the inner disk and neutron star (Griffiths et al. 1978; Mason et al. 1980). Fits to the X-ray spectrum using realistic Comptonization models yield electron temperatures near \(T_e \approx 5 \times 10^7\) K and electron scattering optical depths in the range \(\tau_e \approx 13\)–26 depending on the geometry of the ADC and the Comptonization model (Parmar et al. 2000; Iaria et al. 2001). The mean unabsorbed apparent luminosity of 4U 1822–371 in the 0.1–100 keV energy range is \(L_{\text{X}} \approx 1.16 \times 10^{36}\) erg s\(^{-1}\) for a distance of 2.5 kpc (Iaria et al. 2001). As most of the X-ray flux escapes roughly perpendicularly to the orbital plane and is beamed away from the Earth, the true luminosity is much greater than the apparent luminosity. If one corrects for the ADC obscuration by simply multiplying \(L_X\) by a factor to raise \(L_X/L_{\text{opt}}\) to the typical value for LMXBs (\(\sim 500\)), the true X-ray luminosity is \(\sim 10^{37}\) erg s\(^{-1}\). Even this should be taken as a lower limit because the disk is observed edge-on, reducing \(L_{\text{opt}}\). A true luminosity near the Eddington luminosity is not impossible.

All solutions for the X-ray eclipse have invoked a vertically extended wall of optically thick material whose height varies with angle around the neutron star (White et al. 1981). The wall generally has been identified as a vertically extended disk rim, and, indeed, Hellier & Mason (1989) showed the wall must be near the edge of the disk. The rim invoked by Hellier & Mason (1989) has \(0.08 < h_{\text{rim}}/r_{\text{disk}} < 0.22\), while the maximum height of the rim invoked by White & Holt (1982) approached \(h_{\text{rim}}/r_{\text{disk}} \approx 0.5\). Iaria et al. (2001) also needed a thick belt of absorbing material around the ADC to match the observed X-ray spectral energy distribution (SED). Placing the belt at the edge of the disk, they found the angle subtended by the absorbing
We have obtained new *Hubble Space Telescope* (HST) objective-prism ultraviolet spectroscopy and V and J photometry of 4U 1822–371, from which we construct its SED and its orbital light curves in the UV, V, and J bands (Section 2). In Section 3, we derive an improved ephemeris for the optical eclipses and confirm that the orbital period is changing rapidly, indicating extremely high rates of mass flow in the system. In Section 4, we show that the accretion disk has a strong wind with projected velocities up to 4000 km s\(^{-1}\). The core of this paper is Section 5, in which we model the orbital light curves with our light-curve synthesis program. We show that much of the disk is vertically extended and optically thick at UV/optical wavelengths. This vertical structure extends almost to the edge of the disk and has a height equal to \(\sim 0.5\) of the disk radius. As this structure has a brightness temperature near \(3 \times 10^4\) K, we identify it as the optically thick base of the disk wind, not as the optical counterpart of the ADC. We, too, need a tall obscuring wall near the edge of the accretion disk, but we interpret the wall as a layer of cooler material at the base of the disk wind, not as a tall disk rim. Our results are summarized in Section 6.

### 2. OBSERVATIONS AND DATA REDUCTION

We observed 4U 1822–371 with the ANDICAM optical/IR photometer on the SMARTS 1.3 m telescope at Cerro Tololo Inter-American Observatory (CTIO) using Johnson V and CTIO/CIT J filters (DePoy et al. 2003). We obtained one or two observations per night over two observing seasons, the first season from 2005 June 30 to September 15, the second from 2006 March 29 to October 20. The data were reduced to instrumental magnitudes with IRAF\(^4\) and the instrumental magnitudes were converted to absolute fluxes using the photometric standard stars PG1657+078 for the V band and Two Micron All Sky Survey (2MASS) J18254777–3706131 for the J band (Landolt 1992), both of which were observed on three photometric nights in 2007 June.

We also obtained a time series of objective prism ultraviolet spectrograms of 4U 1822–371 with the HST using the Advanced Camera for Surveys/Solar Blind Channel (ACS/SBC) and the PR130L prism (Pavlovsky et al. 2006). We obtained 300 spectrograms in two visits between HJD 2453828.7 and HJD 2453830.9 (2006 April), each visit lasting five HST orbits. The spectrograms were integrated for 45 s and separated by a 40 s dead time, with occasional long exposures of 350 s when data were transferred from the ACS internal buffer memory to the HST solid state data recorder. The spectrograms cover the wavelength range from 1222 Å to 2002 Å, but we used only the wavelengths from 1222 to 1900 Å because there is a significant red leak in the SBC at wavelengths greater than 1900 Å. The spectral resolution is \(R = \Delta \lambda / \Delta \lambda \approx 150\) near 1300 Å, but decreases to \(R \approx 100\) near the C\(\text{iv}\) doublet and to \(R \approx 40\) near 1900 Å. The UV data were reduced with the *aXe* package in STSDAS (Kuemmel et al. 2004).

The time-averaged mean UV spectrum of 4U 1822–371 is shown in Figure 1. The prominent emission lines are N\(\text{v}\) at 1240 Å, a blend of O\(\text{iv}\), O\(\text{v}\), and Si\(\text{iv}\) near 1370 Å, the C\(\text{iv}\) doublet at 1548 Å/1550 Å, and He\(\text{ii}\) at 1640 Å. There are also ISM absorption blends of Si\(\text{ii}/\text{C}\)\(\text{i}\) and O\(\text{iii}/\text{Si}\)\(\text{iii}\) near 1260 Å and 1300 Å respectively. There is a significant red leak in the SBC at wavelengths longer than \(~1900\) Å.

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\(^4\) IRAF is distributed by NOAO, which is operated by the Association of Universities for Research in Astronomy, Inc., under the cooperative agreement with the National Science Foundation.
Table 1

Times of $T_{\text{min}}$ and $O-C$ Values as Calculated Using a Quadratic Least-Squares Fit to the Ephemeris

| Eclipse Time (HJD) | Error in $T_{\text{min}}$ | Ref. | $O - C$ |
|-------------------|--------------------------|------|---------|
| 2444044.8450      | 0.0060                   | 1    | -0.0207 |
| 2444090.1140      | 0.0080                   | 1    | -0.0128 |
| 2444101.0280      | 0.0080                   | 1    | -0.0079 |
| 2444105.6650      | 0.0060                   | 1    | -0.0131 |
| 2444106.5970      | 0.0060                   | 1    | -0.0095 |
| 2444137.9350      | 0.0100                   | 1    | -0.0062 |
| 2444411.1320      | 0.0080                   | 2    | -0.0007 |
| 2444412.0580      | 0.0080                   | 2    | -0.0031 |
| 2444664.8120      | 0.0080                   | 3    | -0.0152 |
| 2444783.8940      | 0.0060                   | 2    | -0.0048 |
| 2445579.5650      | 0.0050                   | 4    | -0.0019 |
| 2445580.7250      | 0.0050                   | 4    | -0.0025 |
| 2445615.3115      | 0.0020                   | 4    | -0.0002 |
| 2445937.7110      | 0.0021                   | 4    | 0.0004  |
| 2446234.5787      | 0.0018                   | 4    | 0.0010  |
| 2447296.4798      | 0.0010                   | 4    | 0.0040  |
| 2447379.3410      | 0.0010                   | 4    | 0.0022  |
| 2447999.7674      | 0.0039                   | 5    | 0.0011  |
| 2449163.0960      | 0.0028                   | 6    | -0.0020 |
| 2449164.0237      | 0.0028                   | 6    | -0.0027 |
| 2449164.2542      | 0.0028                   | 6    | -0.0043 |
| 2449165.1852      | 0.0028                   | 6    | -0.0018 |
| 2449166.1190      | 0.0028                   | 6    | 0.0036  |
| 2450250.5308      | 0.0008                   | 7    | -0.0003 |
| 2450250.7626      | 0.0008                   | 7    | -0.0006 |
| 2450252.6196      | 0.0008                   | 7    | -0.0004 |
| 2451208.5446      | 0.0035                   | 5    | -0.0060 |
| 2451373.7094      | 0.0008                   | 7    | -0.0007 |
| 2451756.4577      | 0.0012                   | 7    | -0.0016 |
| 2451782.4542      | 0.0012                   | 7    | -0.0015 |
| 2452089.7602      | 0.0008                   | 7    | -0.0001 |
| 2453618.6767      | 0.0050                   | 8    | -0.0023 |
| 2453828.9720      | 0.0010                   | 8    | 0.0010  |
| 2453830.8299      | 0.0010                   | 8    | 0.0020  |
| 2453932.7201      | 0.0040                   | 8    | -0.0042 |

References. (1) Mason et al. 1980; (2) Mason et al. 1982; (3) Cowley et al. 1982; (4) Hellier & Mason 1989; (5) Cowley et al. 2003; (6) Harlaftis et al. 1997; (7) Baptista et al. 2002; (8) This paper.

3. THE UV/OPTICAL EPHEMERIS AND ORBITAL LIGHT CURVES

Because the V and J light curves are sparsely sampled, it was not possible to extract times of minima for individual eclipses. Instead we measured a single mean time of minimum for each season by folding the V-band data on the orbital period from Parmar et al. (2000) to form seasonal mean orbital light curves. The times of minimum light extracted from the mean light curves are $T_{\text{min}} = \text{HJD} 2453618.677 \pm 0.005$ for the 2005 data and $T_{\text{min}} = \text{HJD} 2453932.720 \pm 0.004$ for the 2006 data. To form UV light curves, the flux in each UV spectrogram was integrated from 1222 Å to 1900 Å and then divided by $\Delta \lambda = 678$ Å. We folded the light curves on the Parmar et al. (2000) period and extracted two times of minimum light, one for each $\text{HST}$ visit: $T_{\text{min}} = \text{HJD} 2453828.972 \pm 0.001$ and $T_{\text{min}} = \text{HJD} 2453830.830 \pm 0.001$.

The four new eclipse times plus all of the previously published optical eclipse times are listed in Table 1. A fit to the eclipse times yielded the ephemeris

$$T_{\text{min}} = \text{HJD} 2445615.31166(74) + 0.232108641(80)E + 2.46(21) \times 10^{-11}E^2,$$

(1)

where $E$ is the eclipse number. The $O-C$ diagram for this ephemeris is shown in Figure 2. The quadratic term in the optical ephemeris is consistent with the low-significance quadratic term derived by Baptista et al. (2002) and agrees with the quadratic term in the X-ray ephemeris, $(2.06 \pm 23) \times 10^{-11}$, to within the measurement errors (Parmar et al. 2000). The $T_{\text{min}}$ of our new optical ephemeris lags the $T_{\text{min}}$ from the X-ray ephemeris of Parmar et al. (2000) by 100 \pm 65 s. Although the lag is only marginally statistically significant, it cannot be dismissed because the X-ray and optical/UV flux emanate from different regions and could be eclipsed at slightly different times. Recently, T. Burderi et al. (2009, private communication) derived a new X-ray ephemeris for 4U 1822–371. Using this new ephemeris, the lag is 122 seconds.

The rate of change of the orbital period is $\dot{P} = 2.12 \times 10^{-10}$ and the timescale for a change in the orbital period is $P/\dot{P} = (3.0 \pm 0.3) \times 10^6$ yr. One must generally be cautious about interpreting timescales for orbital period changes as evolutionary timescales because mass-transfer binaries often show short-term systematic advances and delays in times of eclipse that can mimic rapid period changes. The X-ray binary EXO 0748–676 shows this behavior (Wolff et al. 2009), and there are many examples among cataclysmic variables (see Warner 1995). However, the eclipse times for 4U 1822–371 span 27 years, and the accumulated phase shift is $\Delta \phi = \Delta T_{\text{min}}/P \approx 0.17$, an order of magnitude larger than the random phase shifts observed in EXO 0748–676 and cataclysmic variables. It appears safe, therefore, to identify the value of $P/\dot{P}$ measured from the ephemeris as the timescale for orbital evolution.

On dimensional grounds, one has $m/m_\odot \approx |P/\dot{P}|$. If mass and angular momentum are conserved, for example, then $m_{\text{NS}}/m_\odot = [3(1 - q)/q]P/\dot{P}$ (Warner 1995), where $m_{\text{NS}}$ is the mass of the neutron star, $q = m_2/m_{\text{NS}}$, and $m_2$ is the mass of the secondary star. For $q = 0.3$ and $m_{\text{NS}} = 1.35 M_\odot$, we find $m_{\text{NS}} = 6.4 \times 10^{-8} M_\odot$ yr$^{-1}$. This is an extremely high rate of accretion, corresponding to $\approx 4$ times the Eddington luminosity. In this, we agree with the analysis of Heinz & Nowak (2001). We do not agree that the flow of mass and angular momentum can be characterized by a single parameter. Specifically, the angular momentum per unit mass can vary enormously in various parts of the flow and depends on the detailed properties of the
Figure 3. UV light curve of 4U 1822−371 from 2006. The fluxes were extracted from the HST spectrograms and folded on the orbital period of 4U 1822−371 (Equation (1)) to produce one light curve for each of the HST visits. The internal errors on the fluxes are ~0.5%, giving error bars smaller than the points used to plot the data.

Figure 4. V-band light curves of 4U 1822−371 in 2005 and 2006. The data have been folded on the orbital period given by the UV/optical ephemeris (Equation (1)). The error bars correspond to the internal measurement errors.

Figure 5. J-band light curves of 4U 1822−371 in 2005 and 2006. The data have been folded on the orbital period given by the UV/optical ephemeris (Equation (1)). The error bars correspond to the internal measurement errors.

flow. Absent a precise description for the flow of mass and angular momentum, it is not possible to infer accurate rates of mass transfer and mass loss from the evolutionary timescale, nor even a ratio of the two rates. Few cataclysmic variables have rates of mass transfer greater than $3 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}$ (Warner 1995), so we suspect that the rate of mass transfer in 4U 1822−371 is at least a factor of 2 smaller than the value for conservative mass transfer. Yet, a mass transfer rate of $3 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}$ is still extremely high and much of the transferred mass cannot be accreting onto the neutron star, but leaves the system altogether.

Figure 3 shows the UV light curves of 4U 1822−371 from the two HST visits folded on the orbital period given by Equation (1); and Figures 4 and 5 show the two seasons of $V$- and $J$-band photometry also folded on the orbital period. The folded UV light curves and the $V$-band light curve from 2006 have been averaged into 200 equal-width phase bins. The $J$-band light curves from both 2005 and 2006 and the $V$-band light curve from 2005 have fewer observations, and have not been binned. We define the internal error of a data point to be the standard deviation that includes photon counting noise and calibration errors. The internal errors of the UV fluxes are small, typically only 0.5%; the internal errors of $V$- and $J$-band data were typically 4%–5% but occasionally somewhat larger. The error bars in the figures correspond to these internal errors.

The light curve of 4U 1822−371 shows large-amplitude non-repeating variability (“flickering”) and, because of this variability, individual orbital light curves can differ substantially from the mean orbital light curve (Baptista et al. 2002). Let us define the external error of a data point as the standard deviation introduced by the non-repeating variability. We estimated the external error of the UV fluxes by comparing the light curves of 4U 1822−371 from the two HST visits. After folding all the UV data together to form a single (noisy) light curve, we divided the light curve into four phase sections (0.11–0.23, 0.33–0.52, 0.62–0.9, and 0.9–1.11) and fit a polynomial to each section. The standard deviation of the data points about the fitted polynomial
of all three ASM bandpasses. The vertical dashes mark the times of eclipse minima at UV/optical wavelengths measured by Cowley et al. (2003), Baptista et al. (2002; 4 eclipses), Casares et al. (2003), and by us with HST and SMARTS.

Figure 6. X-ray light curve of 4U 1822–371 between 1996 January 5 and 2008 March 5 from the all-sky monitor on RXTE. Each point is the monthly average of all three ASM bandpasses. The vertical dashes mark the times of eclipse minima.

The shape of the V- and J-band light curves changed systematically between 2005 and 2006. While the 2006 light curves are roughly symmetrical about phase 0.0, the 2005 light curves are asymmetric, having a large hump near phase 0.2. The asymmetric light curves from 2005 are similar to the optical light curves shown in Mason et al. (1980), Harlaftis et al. (1997), and Baptista et al. (2002). The more symmetric light curves from 2006 are similar to our UV light curves—also obtained in 2006—and to the optical light curves shown in Cowley et al. (2003).

Figure 6 shows the X-ray light curve of 4U 1822–371 between 1996 January 5 and 2008 March 5 from the all-sky monitor (ASM) on the Rossi X-ray Timing Explorer (RXTE). Each point in the figure is the monthly average count rate summed over the three ASM passbands. The dates on which optical eclipses were observed are marked in the figure. The X-ray light curve shows a low-amplitude variability superimposed on a slow decrease in flux. The pronounced changes in the optical/UV light curves from year to year were not accompanied by large changes in the X-ray light curve.

4. THE UV SPECTRUM, UV/OPTICAL SPECTRAL ENERGY DISTRIBUTIONS, AND EVIDENCE FOR A STRONG HIGH-VELOCITY WIND

Although the direction to 4U 1822–371 is within 11° of the direction to the galactic center, 4U 1822–371 is close to Baade's window and its reddening is low. Mason & Cordova (1982a) find a color excess $E(B-V) = 0.1$ with $3\sigma$ upper and lower bounds of 0.29 and 0.01 based on the depth of the 2200 Å interstellar absorption feature. According to Iaria et al. (2001) the photoelectric absorption at soft X-ray energies corresponds to a neutral hydrogen column density of $N_{\text{H}} \approx (1.05 \pm 0.45) \times 10^{21}$ cm$^{-2}$. Adopting $A_V = N_{\text{H}}/(2.12 \pm 0.09) \times 10^{21}$ mag cm$^{-2}$ (Güver & Özel 2009) and $R_V = 3.1$, we find $A_V = 0.48 \pm 0.2$ mag and $E(B-V) = 0.15 \pm 0.1$ mag in agreement with Mason & Cordova (1982a).

Figure 7 shows de-reddened UV and V- and J-band fluxes calculated for $E(B-V) = 0.15$ and the extinction law of Cardelli et al. (1989) for $R_V = 3.1$. The top (green) line and triangles in the figure show the mean fluxes over orbital phases 0.75–0.85 and 0.15–0.25, during which the system is uneclipsed and contribution from the irradiated face of the secondary star is minimized. The next (orange) line and squares show the fluxes during eclipse. The third (blue) line and crosses are the green minus orange fluxes, giving the flux from that part of the system that is eclipsed. The bottom (red) line and open circles show the mean fluxes at phases 0.25–0.75 minus the uneclipsed (green) fluxes, which should be dominated by the flux from the irradiated face of the secondary. The solid line shows $f_\lambda \propto \lambda^{-7/3}$ and the dashed line $f_\lambda \propto \lambda^{-4}$.

(A color version of this figure is available in the online journal.)

5 Results provided by the ASM/RXTE teams at MIT and at the RXTE SOF and GOF at NASA’s GSFC. http://xte.mit.edu.
to a blackbody $\lambda^{-2}$ slope in the $H$ and $K$ bands. While it is tempting to identify the $\lambda^{-7/3}$ SEDs with the theoretical SED for an optically thick, steady-state $\alpha$-model accretion disk, this identification is probably not correct. It is difficult to make an $\alpha$-model disk produce the same SED at mid-eclipse, when all but the outer parts of the disk are obscured, as it produces when it is not eclipsed and the entire disk is visible. Moreover, as we will show in the following section, most of the disk is hidden by optically thick vertically extended structures and is invisible at UV/optical wavelengths, so the theoretical SED of a simple $\alpha$-model disk is not relevant.

The bottom (red) line and open circles in Figure 7 show the mean fluxes at phases 0.25–0.75 minus the uneclipsed (green) fluxes. This red SED isolates the flux in the large hump in the light curve at orbital phases opposite the eclipse. The flux contributed by the irradiated face of the secondary star is maximized at these phases. The flux from the irradiated secondary should be roughly a multi-temperature blackbody distribution. The red SED appears to be flattening near $\log \lambda = 3.1$, suggesting that the flux-weighted temperature of the heated face is $\sim 25,000$ K.

With the exception of the $Nv$ line, the flux in the UV emission lines is neither reduced during eclipse nor enhanced at other orbital phases. This shows clearly in the spectrum of the eclipsed parts of the system (the blue spectrum), which is nearly devoid of emission lines. The emission lines must, then, arise from optically thin material far above and below the disk. After accounting for the extra width introduced by the poor spectral resolution of the UV spectrogram, we find the full width at zero intensity of the $CIV$ emission line to be $\sim 45$ Å. We compare this to its width in the $HST$ Faint Object Spectrograph spectra from which the data presented by Puchnarewicz et al. (1995) were derived. In these spectrograms, the width is near 40 Å. These widths correspond to projected velocities up to $\pm 4400$ km $s^{-1}$. Thus, the lines come from a high-velocity wind. Neither the strength nor the width of the $CIV$ line depends on orbital phase.

Since the material in the wind must be continuously replenished by outflowing gas closer to the disk, there must be a base to the wind. We do not observe $CIV$ emission from the base of the wind, so either the base does not produce $CIV$ emission or it is hidden by vertically extended optically thick material further out in the disk. The $Nv$ line is an exception. Its strength decreases by $\sim 50\%$ during eclipse and arises nearer the orbital plane.

5. LIGHT-CURVE ANALYSIS AND A MODEL FOR 4U 1822−371

5.1. Preliminaries

5.1.1. The Light-curve Synthesis Program

We modeled the UV/optical light curves of 4U 1822−371 using a light-curve synthesis program\(^6\) we wrote to model X-ray binaries (e.g. UW Cor Bor, Mason et al. 2008) and related objects (e.g. SS Cygni, Bittner et al. 2007). The program assumes that the orbits of the stars are circular, the secondary star fills its Roche Lobe, and the primary star is a point source surrounded by an accretion disk. The accretion disk can have a complicated geometry. It can be non-circular, non-axisymmetric, and vertically extended; and it can have a rim, an interior torus, and bright or dark spots. The flux from the secondary star has a realistic spectrum using Kurucz stellar atmospheres (Kurucz 1996), but the remaining parts of the system emit like a blackbody. The program includes heating by irradiation. Because the geometry and temperature distributions in the model can be complex and asymmetric, the program resorts to ray tracing to calculate both irradiation and the orbital light curve. The program outputs synthetic light curves for Johnson/Cousins filter bandpasses and for square bandpasses over user-specified wavelength ranges. If provided with an observed light curve, our code calculates the $\chi^2$ for the fit of the synthetic light curve to the observed light curve. A calling program allows the user to find the model parameters that minimize $\chi^2$ either by a grid search through parameter space or by a simplex algorithm.

5.1.2. The Masses and Dimensions of 4U1822−371

The arrival times of the X-ray pulses from the neutron star yield accurate values for the projected semi-major axis of the neutron star orbit $a_{NS} \sin i = (3.015 \pm 0.015) \times 10^{10}$ cm and the mass function $f(m_2) = m_2 q_i^2 (1 + q_i)^{-2} \sin^2 i = 0.0203 \pm 0.0003 M_{\odot}$, where $a_{NS}$ is the radius of the neutron star’s orbit and $i$ is the orbital inclination (Jonker & van der Klis 2001). The orbital eccentricity is not measurably different from zero.

It appears to us that the masses of the two stars in 4U 1822−371 have not yet been determined with certainty. The mass function can be recast to the form $m_{NS} \sin^3 i = (0.0203 \pm 0.0003) q_i^{-3} (1 + q_i)^{-1} M_{\odot}$. The eclipse solution limits the orbital inclination to a narrow range near $82^\circ$, so $m_{NS} \approx 0.209 q_i^{-3} (1 + q_i)^{-1} M_{\odot}$. There have been several attempts to determine the mass ratio from the radial velocity curve of the secondary star. The spectrum of the heated face of the secondary star has $Hei$ absorption lines and a narrow emission line from N $\lambda$4640, which is excited by the Bowen fluorescence mechanism (Harlaftis et al. 1997; Casares et al. 2003). The radial velocity curve of the $Hei$ absorption has been measured, and its amplitude is $K_{Hei} \approx 230$ km s$^{-1}$ (Harlaftis et al. 1997; Cowley et al. 2003; Casares et al. 2003). It is, however, unclear how to interpret $K_{Hei}$ because the absorption lines arise on only one face of the secondary and because the line profiles are probably distorted by helium emission lines from the accretion disk. The radial velocity curve also suffers from a phase shift of $\sim 0.1 P_{orb}$ with respect to the pulsar ephemeris, further complicating its interpretation (Jonker et al. 2003; Casares et al. 2003).

The radial velocity curve of the N $\lambda$4640 emission line also has been measured and has an amplitude $K_{N \lambda 4640} = 280 \pm 3$ km s$^{-1}$ (Casares et al. 2003; Muñoz-Darias et al. 2008). We agree with Casares et al. (2003) that this is a firm lower limit to the amplitude of the secondary’s radial velocity curve, which translates to lower limits on the masses: $m_{NS} \geq 1.14 M_{\odot}$ and $m_2 \geq 0.36 M_{\odot}$. Correcting from $K_{N \lambda 4640}$ to the true amplitude $K_2$ of secondary star’s radial curve requires a model for the distribution of the N $\lambda$4640 emission across the face of the secondary star. Muñoz-Darias et al. (2005, 2008) have developed such a model and used it to deduce $1.52 M_{\odot} < m_{NS} < 1.85 M_{\odot}$. In their model, the N $\lambda$4640 line is emitted uniformly over the face of the irradiated secondary except where shadowed by a simple thin disk with a raised, optically thick rim. We will show that a more complex model is required for the disk in 4U 1822−371. The $K$-correction derived from the thin-disk model is likely be only qualitatively correct.

As the masses of most neutron stars in binary X-ray pulsars fall in a narrow range near $1.35 M_{\odot}$ (Thorsett & Chakrabarty

\(^6\) A full description of the program is available at http://pisces.as.utexas.edu/robinson/XRbinary.pdf.
in the fitted parameters, but the overall results were qualitatively models to the light curves yielded small quantitative differences accretion disk is optically thick and its inner edge is near the in a steady state. These considerations suggest strongly that the − \in \text{the X-ray luminosity of 4U 1822–371, the disk rim is a significant contributor, often the dominant contributor to the UV/optical flux. This is shown most clearly in Figure 9 of Hellier & Mason (1989). Many of the differences between our results and earlier results flow from the different handling of the disk rim flux.}

5.2. The Disk Is Large, Its Center Obscured

We first establish that the accretion disk is large and its center obscured at UV/optical wavelengths. The left panel in Figure 8 shows the eclipse portion of the binned UV light curve normalized to 1.0 just outside eclipse. The eclipse is wide, lasting $\Delta \phi \approx 0.20$ in phase. The panel also shows two synthetic light curves, both calculated for a disk that is geometrically flat, has a nearly flat temperature distribution ($T \propto r^{-0.1}$), and is eclipsed at an orbital inclination $i = 81^\circ$. One light curve was calculated for $r_{\text{disk}}/a = 0.30$, the other for $r_{\text{disk}}/a = 0.45$, and both have been normalized to match the flux at mid-eclipse to emphasize the effect of disk width on the light curve. Disks with $r_{\text{disk}}/a \gtrsim 0.40$ are needed to fit the observed eclipse.

The dashed line in the right panel of Figure 8 is the synthetic light curve for a geometrically thin, optically thick, steady-state $\alpha$-model disk with a $T \propto r^{-3/4}$ temperature distribution. The radius of the disk is $r_{\text{disk}}/a = 0.4$, its temperature is 20,000 K at the outer edge, and the orbital inclination is $77^\circ$. The bright central regions of this model disk produce an eclipse light curve with a deep, narrow central strip in striking disagreement with the observed eclipse. The solid line in the panel is the synthetic light curve for a disk model with similar geometry but with a flatter temperature distribution to reduce the brightness of its central regions ($T \propto r^{-0.1}$ and $i = 78.5^\circ$). This model matches the general shape of the observed eclipse and, indeed, the fit is formally excellent. We do not conclude that the disk actually has a flat temperature distribution as we consider a flat distribution physically unrealistic. We do conclude that the flat temperature distribution is mimicking the true appearance of the disk, a disk that appears not to have bright central regions. As argued in the previous section, the central regions of the disk must be hot and bright, so the central regions of the disk must be obscured by disk structures extending above and below the orbital plane.

We now consider two broad groups of models for obscuring the central disk. The first group includes models similar to standard thin-disk models. In these models, the edge of the disk is tall enough to hide the center of the disk either because the disk has a large flare or because the disk is flat but has a vertically extended rim. In the second group of models, the obscuration is produced by vertically extended structures interior to the disk edge.

5.3. Obscuration by a Tall Disk Rim?

The top panel of Figure 9 shows the observed UV eclipse light curve and a synthetic light curve produced by a geometrically thin disk with a vertically extended rim. The orbital inclination of the model is $81^\circ$, the disk radius is $r_{\text{disk}}/a = 0.44$, and the rim height is $h_{\text{rim}}/a = 0.056$, or $h_{\text{rim}}/r_{\text{disk}} \approx 0.13$. This rim is quite tall, raising concerns about the physical validity of the model; but the tall rim does produce a light curve that fits the observed light curve fairly well. Nevertheless, this model is fatally flawed. It has a combination of rim height and orbital inclination that leaves most of the central disk unobserved.
Therefore, to avoid an eclipse that is too narrow and deep, the model must have a flat temperature distribution, thus failing to avoid the very problem it was contrived to solve. Worse, the neutron star is visible, disagreeing with X-ray observations. This is a generic and robust result for thin-disk tall-rim models. We have explored the parameter space for these models extensively, varying the orbital inclination, the disk radius and temperature, the rim height and temperature, and the irradiation of the inner surface of the rim by the inner disk and neutron star. Models that fit the observed light curve with an acceptable \( \chi^2 \) always have a flat temperature distribution, and the neutron star is usually visible.

Flared disks—disks whose thickness increase with radius—automatically have thick rims that can hide the inner disk and neutron star. In our computer code, the height of a flared disk above the orbital plane is given by

\[
H = H_{\text{edge}} \left( \frac{a - a_{\text{min}}}{a_{\text{max}} - a_{\text{min}}} \right)^{H_{\text{pow}}},
\]

where \( a_{\text{min}} \) and \( a_{\text{max}} \) are the radii of the inner and outer edges of the disk, and \( H_{\text{edge}} \) is the thickness of the disk at its outer edge. If \( H_{\text{pow}} > 1 \), the disk has a concave flare. The middle panel of Figure 9 shows a synthetic light curve for a flared disk. The model disk has \( H_{\text{edge}}/a = 0.060, a_{\text{min}}/a = 0.01, a_{\text{max}}/a = 0.43, \) and \( H_{\text{pow}} = 2.0 \). The synthetic light curve fits the observed light curve at all orbital phases, not just the eclipse. The model disk has enough free parameters to produce an excellent fit to the observed light curve. But the inner disk and the neutron star still remain visible and the model fails. Thus, we reject this entire group of models.

5.4. Torus Plus Variable-height Rim

The previous discussion leads us to consider vertically extended disk structures closer to the neutron star. Inspired by the presence of the ADC at X-ray wavelengths, we give the disk vertical extension by adding an opaque torus (a donut with the neutron star centered in the hole of the donut). Our code allows the torus to have an elliptical cross section and specifies its geometry by three parameters: the distance from the center of the cross section of the torus to the neutron star, which we call its radius or \( a_n \), the maximum height of the torus above and below the orbital plane, and the width of the torus between its inner and outer walls as measured in the orbital plane. The toroidal structure should not be taken too literally. Because 4U 1822—371 has a high orbital inclination, we observe the torus from the side and, like a donut viewed from the side, we observe only the outer wall of the torus. The observations give little information about
The torus is poorly constrained. The SED of 4U 1822–371 is not a blackbody distribution, which precludes assignment of a meaningful color temperature. The large uncertainty on the distance and reddening to 4U 1822–371 preclude measurement of an accurate brightness temperature, but the brightness temperature of the outer wall of the torus must be surprisingly low. Fits to the UV eclipse show that the outer wall extends to ~0.35a in the orbital plane (~80% of the disk radius) and the maximum height of the torus is ~0.2a (~50% of the disk radius), giving the torus a projected surface area of roughly 0.28a^2 ~ 4 × 10^{23} cm^2. About half the projected area is eclipsed. A_ecl ~ 2 × 10^{21} cm^2, and the de-extincted eclipsed flux is \( f_{\text{ecl}} = 3.1 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \) at 1600 Å (the blue line in Figure 7). The brightness temperature of the eclipsed surface of the torus can be calculated from \( B_\lambda = f_{\text{ecl}}D^2/A_{\text{ecl}} \), where \( D \) is the distance to 4U 1822–371. For \( D = 5000 \) pc, the monochromatic brightness temperature at 1600 Å is \( T_\lambda \approx 26,000 \) K. Although this temperature cannot be trusted to within a factor of 2 or so, it is ~10^3 times lower than temperatures typically associated with coronae. Thus, the brightness temperature of the torus—least the outer wall of the torus—is not consistent with an ADC. The temperature is, however, high enough that the torus dominates the UV/optical flux from 4U 1822–371. This justifies our earlier claim that the flux from unirradiated surfaces of the secondary star and the outer surface of the disk rim can be ignored.

This torus-like structure is far too tall to agree with the thickness of an \( \alpha \)-model disk for any reasonable choice of parameters. Its temperature is far too low for it to be part of the ADC. What, then, is this vertical structure? Since we have already found a high velocity disk wind and have shown that there is much mass loss from the disk, we suggest that the vertical structure is simply the optically thick base of the disk wind.

The torus by itself does not produce a synthetic light curve that fits the observed eclipse light curve adequately, but the addition of either an opaque vertically extended rim or a flared disk yields an excellent fit. The best-fit synthetic light curve for a flared disk is shown in Figure 10. The model from which the light curve was calculated has an orbital inclination of 83.5, a concave flared disk with radius \( r_{\text{disk}}/a = 0.43 \) and an edge height \( H_{\text{edge}}/r_{\text{disk}} = 0.07 \). The disk is covered by an opaque torus with midpoint at \( a_0 = 0.53 r_{\text{disk}} \), maximum height of 0.56\( r_{\text{disk}} \), and width of 0.5\( r_{\text{disk}} \), so that the inner wall of the torus extends to 0.26\( r_{\text{disk}} \) and the outer wall out to 0.81\( r_{\text{disk}} \). The torus blocks flux from the neutron star and from the disk out to 0.81\( r_{\text{disk}} \), and the edge of the flared disk blocks flux from most of the rest of the disk.

### 5.5. A Model for the Entire Orbital Light Curve

We now model the entire orbital light curve using the eclipse model from Section 5.4 as a starting point. The salient feature
of the non-eclipse part of the orbital light curve is the large-amplitude, roughly sinusoidal hump. The phase of the hump might lead one to suspect that the hump is caused primarily by the varying visibility of the irradiated face of the secondary star, but our attempts to model the hump with just the irradiated secondary star yielded poor fits. The hump’s precise phase, its shape, and the variations of its shape from year to year cannot be produced by the irradiated secondary alone.

The model producing the synthetic light curve shown in Figure 10 had a torus and a disk with a dark, vertically extended edge. We now allow the height of the edge to vary with azimuth around the neutron star. As its height varies, the rim blocks more or less of the flux from the torus, helping to produce the hump. In the previous section, we introduced the vertically extended edge by invoking a concave flared disk, but a flat disk with a vertically extended rim would have worked just as well. In the current context, it is more convenient to model the edge with a flat disk and extended rim, allowing the rim height to vary with azimuth.

We also include flux from the heated secondary in the model and allow fits to the light curve to determine how much flux the secondary contributes. The secondary is heated in part by the torus and disk but mostly by X-ray flux. While we include X-ray flux in the model, it is not a physically meaningful quantity since the amount of flux needed depends sensitively on the geometry of the X-ray-emitting regions, on the radiative transfer of the flux through the ADC and torus, and on the reprocessing and redistribution of the flux in the secondary star. As we have little information about any of these factors, we regard the X-ray heating of the secondary star as merely a convenient parameter to specify the irradiative temperature of the secondary star. With the addition of a variable-flux parameter, we achieve successful fits to the entire orbital light curve and no further complications were needed.

While the foregoing discussion has been necessarily lengthy, the resulting model is actually rather simple. The parameters describing the geometry of the model are as follows:

1. the orbital inclination, which also fixes the mass ratio and the mass of the secondary star through the mass function;
2. the outer radius of the disk;
3. the height, width, and radius of the disk torus; and
4. the height of the disk rim as a function of azimuth around the neutron star.

We assume that the secondary star and the disk rim have low temperatures and do not contribute significant flux except where heated by irradiation. Fits to the light curve show that the inner regions of the disk are hidden by the torus and the outer regions are hidden by the disk rim, so the disk is not visible and its temperature is irrelevant. Thus, the only temperature that needs to be specified is the monochromatic brightness temperature of the torus. Finally, the amount of X-ray energy irradiating the disk rim and the secondary star must be specified. There are also a few nuisance parameters such as the zero point in orbital phase, a scale factor on the flux, and various albedos that must be specified but are irrelevant to the model.

We fit the model to the observed UV light curve using a simplex algorithm to find the set of parameters that minimized the $\chi^2$ of the fit. We also examined parameter space extensively with grid searches to test the uniqueness of the fit. Within the context of the model the values of the fitted parameters are unique and robust. The resulting synthetic light curve is superimposed on the observed light curve in the top panel of Figure 11. The rim height as a function of the azimuth angle is shown in Figure 12, where the azimuth angle is defined to be 0° on the side of the disk opposite the secondary star and increases in the direction opposite the direction of orbital motion. We fit only the $V$- and $J$-band light curves obtained in 2006, the same year as the UV light curves were obtained. To fit the light curves, we retained the values of all the parameters determined from the fit to the UV light curve except for those specifying the geometry and temperature of the torus. The fitted synthetic light curves in the $V$- and $J$-bands are shown superimposed on the observed light curves in the bottom two panels of Figure 11. The values of $\chi^2$ for the fits are 163.5 for 195 data points and 13 free parameters in UV, 210.3 for 150 data points and four free parameters in $V$, and 130.7 for 116 data points and four free parameters in $J$, for a total reduced $\chi^2$ of 1.05.

Values for the fitted parameters are given in Table 2. The radius of the disk is $r_{\text{disk}}/a = 0.40 \pm 0.01$, and the disk rim can have a height up to $h_{\text{rim}}/r_{\text{disk}} \approx 0.17$, but the height for much of the disk is near $h_{\text{rim}}/r_{\text{disk}} \approx 0.05$, close to the $\alpha$-model $h/r$ values (Section 5.1). The height of the torus, $0.20a = 0.55r_{\text{disk}}$, is the same in all three passbands, but the position of its outer
Table 2
Parameters of 4U 1822–371 as Determined by Model Light Curves

| Parameter            | Value          |
|----------------------|----------------|
| Period (days)        | 0.223109       |
| Inclination (degrees)| 81.17 ± 0.14  |
| \( M_{\text{NE}} (M_{\odot}) \) (fixed) | 1.35           |
| \( q = M_{\odot}/M_{\text{NE}} \) | 0.2971         |
| \( H_{\text{low}} \) | 1.1            |
| \( r_{\text{disk}} \) | 0.4 ± 0.01     |
| UV Torus             |                |
| Location, \( a_{\text{UV}} \) | 0.165          |
| Torus width\(a\)    | 0.283          |
| Torus edge height\(a\) | 0.201         |
| V Torus              |                |
| Location, \( a_{\text{V}} \) | 0.245          |
| Torus width\(b\)    | 0.282          |
| Torus edge height\(b\) | 0.205         |
| J Torus              |                |
| Location, \( a_{\text{J}} \) | 0.243          |
| Torus width\(c\)    | 0.288          |
| Torus edge height\(c\) | 0.204         |

Note. \( a \) In units of the orbital separation (see Section 5.1.2).

On considering these results, a new issue arises. While we and Hellier & Mason (1989) before us needed to place the opaque wall near the edge of the accretion disk to fit the light curve, neither the X-ray nor the UV/optical light curves require it to be precisely at the disk edge. It could, in fact, be anywhere between the edge of the disk at \( a \sim 0.4\) and the outer wall of the torus in the V and J bands at \( a \sim 0.39\). Although this is not a large change in position, it allows a significant re-interpretation of the wall. We placed the wall at the disk rim—and we suspect others placed it at the disk rim—primarily because there was no other disk structure to which the wall could be attached. With the addition of a disk torus the wall can plausibly be made part of the torus, becoming an opaque belt around the outside of the torus. The wall now becomes part of the disk wind, not a disk rim. This re-interpretation has a considerable advantage. When made part of the disk wind, the wall no longer need be in hydrostatic equilibrium, requiring impossibly high gas pressure or supersonic turbulence for support. It is simply a cooler, darker layer at the base of the disk wind.

6. SUMMARY AND DISCUSSION

Combining our new times of eclipses with the previously published times, we have derived an improved ephemeris for the eclipses in the UV/optical light curves of 4U 1822–371 (Equation (1)). The quadratic term in the ephemeris yields a timescale for a change in orbital period of \( P/P = (3.0 \pm 0.3) \times 10^6 \) yr. The deduced rate of mass transfer is large, probably greater than \( 3 \times 10^{-8} M_{\odot} \) yr\(^{-1}\). Mass cannot be accreting onto the neutron star at this rate without violating the Eddington limit, so much of the transferred mass must be lost from the system.

We have inferred a strong disk wind from the C iv emission line in the UV spectrum. The wind is axially symmetric and has projected outflow velocities up to 4000 km s\(^{-1}\). The flux in the C iv emission lines does not decrease during eclipses. Since regions less than \( \sim 0.5r_{\text{disk}} \) above the disk are at least partially eclipsed, the C iv emission arises from regions yet further above the disk. The outflowing material closer to the disk either does not produce C iv emission or is hidden by other optically thick structures.

Much of this paper was devoted to developing a model for the accretion disk in 4U 1822–371 from fits to the UV/optical orbital light curves. The following properties of the accretion disk appear to be robustly determined. The disk is large; the fitted radius is \( r_{\text{disk}}/a = 0.40 \pm 0.01 \), close to the tidal truncation radius. To avoid an eclipse that is deeper and narrower than the observed eclipse, the neutron star and the central regions of the accretion disk must be obscured. The dual requirements that the models must produce synthetic light curves that fit the observed eclipse and must obscure the neutron star and central disk forces most of the obscuring material to be at intermediate radii in the disk, not at the edge of the disk. We modeled the obscuring material as an optically thick torus. The torus extends more than 3/4 of the way to the edge of the disk at UV wavelengths and nearly all the way to the edge in the V and J bands, and it extends to a height of \( \sim 0.5r_{\text{disk}} \) above the disk at all wavelengths.

The surface brightness of the outer (visible) wall of the torus is only \( \sim 26,000 \) K. While this estimate is highly uncertain, the true brightness temperature is unlikely to be more than a factor of 2–3 higher and is far less than coronal temperatures. We have, therefore, interpreted the torus as the optically thick base of the disk wind, not as the optical counterpart of the X-ray ADC.

We modeled the large hump in the orbital light curve of 4U 1822–371 with a combination of heated face of the secondary star and a variable-height, optically thick wall located at the edge of the disk. All previous models for the orbital light curve have needed a similar wall, but we now suggest that the wall is actually slightly closer to the neutron star than the edge of the disk and is part of the disk wind, not the disk rim. The wall is a cooler, darker layer at the base of the disk wind just above the disk.

Our results thus yield a more complex view of the structure of the disk in 4U 1822–371. The previous X-ray observations have shown that there is a vertically extended, optically thick ADC stretching roughly half way out to the edge of the disk. Our UV/optical observations show that most of the outer disk emits a cooler disk wind. The wind is optically thick close to the accretion disk but becomes optically thin at a height of \( \sim 0.5r_{\text{disk}} \) above the disk. Close to the disk, the wind is yet cooler and darker, forming a relatively dark wall around disk. The disk itself appears to be nearly entirely buried within and obscured by these vertically extended structures.

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