A MULTIWAVELENGTH, MULTIEPOCH STUDY OF THE SOFT X-RAY TRANSIENT PROTOTYPE, V616 MONOCEROTIS (A0620—00)

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ABSTRACT

We have obtained optical and infrared photometry of the soft X-ray transient prototype V616 Mon (A0620—00). From this photometry, we find a spectral type of K4 for the secondary star in the system, which is consistent with spectroscopic observations. We present \(J, H,\) and \(K\)-band light curves modeled with WD98, the newest version of the Wilson-Devinney light-curve modeling code, and the ELC code.

By combining detailed, independently run models for ellipsoidal variations due to a spotted, non-spherical secondary star and the observed ultraviolet to infrared spectral energy distribution of the system, we show that the most likely value for the orbital inclination is \(40.75 \pm 3\degree\). This inclination angle implies a primary black hole mass of \(11.0 \pm 1.9 M_\odot\).

Key words: binaries: close — stars: black holes — stars: individual (V616 Monocerotis) — stars: low-mass, brown dwarfs — stars: variables: general

1. INTRODUCTION

Soft X-ray transients (SXTs) are a family of low-mass X-ray binaries that display infrequent but large and abrupt X-ray and optical outbursts that are believed to be the result of a sudden, dramatic increase in the mass accretion rate onto the compact object. In most cases the compact object is a black hole, and the companion star is a low-mass K- or M-type dwarf (see Charles 2001 for a recent review). During their long periods of quiescence, SXTs are very faint at X-ray and optical wavelengths; however, in this state, the secondary stars can dominate the system luminosity and allow us to derive the SXT parameters.

The SXT prototype, V616 Mon (= A0620—00) \((\alpha_{2000} = 06^h 22^m 44^s, \delta_{2000} = -00^\circ 20' 45'\)\), was discovered by the Ariel 5 satellite on 1975 August 3 (Elvis et al. 1975), while the optical counterpart to the X-ray source was identified by Boley & Wolfson (1975). By studying the optical spectrum of the system, Oke (1977) found that one component of the light came from a K5–K7 dwarf and another from a suspected accretion disk. Since V616 Mon has faded from outburst, it has been studied by McClintock & Remillard (1986), Haswell et al. (1993, hereafter HHRSA), Marsh, Robinson, & Wood (1994, hereafter MRW), Shahbaz, Naylor, & Charles (1994, hereafter SNC), and Froning & Robinson (2001, hereafter FR, and references therein). These authors have found an orbital period of 7.75 hr, a secondary star spectral type of K3 V–K4 V, and a secondary star radial velocity semiamplitude of \(433 \pm 3 \text{ km s}^{-1}\).

V616 Mon therefore has an implied optical mass function, which is the minimum mass of the compact primary object, of \(2.72 \pm 0.06 M_\odot\) (MRW).

McClintock & Remillard (2000) report the X-ray luminosity of V616 Mon in quiescence is \(L_X \approx 6 \times 10^{39} \text{ erg s}^{-1}\), and it exhibits a very low accretion rate \((\dot{M}_d \approx 10^{-10} M_\odot \text{ yr}^{-1})\). Therefore, the current quiescent light curves should be primarily governed by the light from the secondary star. Since the secondary star fills its Roche lobe, the amount of surface area seen by an observer on Earth changes as the star orbits the compact object. This changing line-of-sight surface area corresponds to a changing apparent brightness, giving rise to the so-called ellipsoidal variations. The amplitude of these variations is determined by the orbital inclination angle and mass ratio of the system. By combining the orbital inclination angle with the observed mass function, the SXT system parameters can be determined. In an effort to quell the debate over the inclination angle of the SXT prototype, we have obtained new optical and multiepoch infrared photometry of V616 Mon. We have used two different light-curve modeling programs to interpret the infrared ellipsoidal variations observed over a 22.5 month interval. We have previously used a similar technique to model GU Mus (Gelino, Harrison, & McNamara 2001, hereafter Paper I), an SXT that closely resembles V616 Mon.

Most previous attempts to derive the orbital parameters for V616 Mon have used optical data. If one is searching for the purest ellipsoidal variations, one should observe at a wavelength at which the secondary star provides the majority of the systemic luminosity. In the optical, the accretion disk and hot spot can contaminate, if not dominate, the system luminosity. Even in quiescence, there could be a modest amount of dilution of the optical light curve by the accretion disk, hot spot, and/or a modest amount of weak and variable accretion (Shahbaz, Naylor, & Charles 1997). On the other hand, in the infrared the late-type secondary stars can dominate the quiescent binary’s luminosity. This reduces the uncertainties in modeling the
system. For V616 Mon, MRW find that the K star contributes 83% ± 4% in the blue and 94% ± 3% of the continuum flux near H$_\alpha$. This percentage should be even higher at longer wavelengths. Therefore, observations in the infrared will reveal more genuine ellipsoidal variations than observations in the optical regime.

SNC and FR both observed V616 Mon in the infrared. SNC obtained a K-band light curve, while FR obtained H-band light curves, as well as much more sparsely sampled J- and K-band curves. Neither study could accurately determine the amount of contamination present from other sources of light in the system. Because of this, the orbital inclination angle determined from FR spanned nearly the entire range of published results (38° ≤ i ≤ 75°). To determine whether contamination is present, multiwavelength observations are needed.

Currently, the best way to obtain the orbital inclination angle in noneclipsing binary systems is to model the ellipsoidal light curves. Previously published inclination angles for V616 Mon range from 31° (lower limit from SNC) all the way to 75° (upper limit from FR). These angles correspond to primary masses of 28.8 to 3.3 M$_\odot$, respectively. The large range in derived inclination angles (and masses) appears to be due in part to the changing shape of the observed light curves over time. In 1986 December and 1987 January, HRHSA saw evidence for a “grazing eclipse of the Roche lobe-filling star by the accretion disk,” but when MRW observed the SXT in 1991 December and 1992 January, this feature was no longer present. If the eclipse were real, it would indeed suggest a high orbital inclination angle. However, no other published data on V616 Mon have shown evidence for such events. The most recently published data set on V616 Mon was taken by FR in 1995 and 1996. The data showed that as the H-band light-curve shape exhibited slight changes over the 1 yr baseline of their observations, the mean H magnitude remained constant.

We have undertaken a program to attempt to determine more precise orbital inclination angles and primary masses for five SXTs. We have observed these SXTs in the infrared and have already presented results on GU Mus (Paper I). We now present our results for the prototype SXT, V616 Mon, based on a 2 yr baseline of multiwavelength optical and infrared observations. We model these data with both WD98, as done in Paper I, and independently with the ELC code (Orosz & Hauschildt 2000). In § 2, we describe our observations and data reduction process. In § 3, we present our infrared photometric light curves and discuss the possibility of long- and short-term variability. Section 4 describes our choices for the relevant input parameters for WD98 and ELC. We present the resulting models at J, H, and K, and discuss the possible scenarios to explain the changing shape of the long-term light curves. Finally, in § 5 we discuss the implications of the models and compare our results with those previously published.

2. OBSERVATIONS AND DATA REDUCTION

We obtained infrared photometry of V616 Mon on three separate epochs over a 22.5 month interval. We first observed the SXT prototype using GRIM II$^4$ on the Astrophysical Research Consortium 3.5 m telescope at Apache Point Observatory on 1999 February 25. We then used IRIM$^5$ on the 2.1 m telescope at the Kitt Peak National Observatory on 2000 February 12 and 16 and had our third and final observing run on the same telescope using SQIID$^6$ on 2000 December 8, 9, and 11.

On 1999 February 25, V616 Mon was observed from 0343 to 0741 UT with the camera at the f/5 plate scale (0.473 pixel$^{-1}$). With an orbital period of about 7.75 hr, this first observing session covered just over half of an orbital period. Photometric data were obtained in the GRIM II J ($\lambda_c = 1.265$ μm) filter. Our observing sequence consisted of two 15 s images at one position, a beam switch, and two additional 15 s images. All the data were linearized with an IRAF linearization task written by A. Watson (1996, private communication). After averaging the two images at one position, we subtracted them from the average of the two images at the other position. These sky- and bias-subtracted images were then flat-fielded with a sky flat, using the usual IRAF packages.

V616 Mon was observed again on 2000 February 12 from 0416 to 0641 UT and on February 16 from 0145 to 0806 UT with the camera at the f/15 focus (1:09 pixel$^{-1}$). This second observing run effectively covered one orbital period. Data were obtained in the IRIM J ($\lambda_c = 1.24$ μm), H ($\lambda_c = 1.65$ μm), and K' ($\lambda_c = 2.16$ μm) filters. Our observing sequence was the same as that for the GRIM II data. We began with the K' filter, refocused and switched to the H filter, and repeated the procedure for the J filter before returning to the K' filter and refocusing again. Each individual J image consisted of one frame of 30 s, the corresponding H images consisted of six co-added frames of 8 s each, while each K' image consisted of 10 co-added frames of 4 s each. We processed the images as above, this time linearizing the data using the IRLINCOR package in IRAF with the coefficients supplied in the IRIM User’s Manual.

We observed V616 Mon for the final time on 2000 December 8 from 0459 to 1229 UT, on December 9 from 0436 to 1234 UT, and on December 11 from 0642 to 1218 UT, all with the camera at the f/15 focus (0.69 pixel$^{-1}$). This final observing run covered 2.72 orbits. Data were obtained in the SQIID J ($\lambda_c = 1.267$ μm), H ($\lambda_c = 1.672$ μm), and K ($\lambda_c = 2.224$ μm) filters. This time, we observed with an ABBA sequence. SQIID stands for “simultaneous quad infrared imaging device” and takes images in four filters simultaneously. Due to this, the number of co-adds and exposure times for each filter had to be identical. Each individual image consisted of 8 co-added frames of 7 s each. We chose this exposure time to stay safely below the nonlinear regime of the chip since detailed linearization curves do not yet exist for this newly commissioned instrument. Dome flats were taken because of the long readout time per exposure. We again processed the images as above with IRAF.

For each of the three data sets, we performed aperture photometry on V616 Mon and the same five nearby field stars. Using the IRAF PHOT package, a differential light curve in each wavelength regime was generated with each point being the average of four beam-switched images. For the GRIM II and SQIID data sets, our differential photometric results show that over the course of our observations, the comparison stars did not vary more than expected from photon statistics. Unfortunately, while the

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$^4$ See http://www.apo.nmsu.edu/Instruments/GRIM2/.

$^5$ See http://www.noao.edu/kpno/manuals/irim/.

$^6$ See http://www.noao.edu/kpno/sqid/sqjidmanual.html.
signal to noise ratio (S/N) of the IRIM data set was high (~1% relative photometry), these data showed considerable scatter due to very good seeing, which resulted in the undersampling of the point-spread function (PSF).

Optical observations of V616 Mon were taken with the Cassegrain Focus CCD Imager on the 0.9 m telescope at Cerro Tololo Inter-American Observatory on 2001 March 15 at 0050 UT. Data were obtained in the $B$, $V$, $R$, and $I$ bandpasses for the purpose of determining the quiescent optical colors of the system. The 180 s exposures (300 s for the $B$ band) were zero corrected and flat fielded before aperture photometry was performed. Standards were also observed to transform these data to the system of Landolt. The observed optical and infrared colors of V616 Mon can be found in Table 1, along with previously published optical and infrared colors for this system.

3. LONG- AND SHORT-TERM VARIABILITY OF THE LIGHT CURVE

Since the 1975 outburst of V616 Mon, several variations of light-curve shape have been observed. A few years after the system’s transition into its quiescent state, McClintock & Remillard (1986) obtained “$B + V$” and $I$-band light curves. In both of these light curves, the deeper minimum coincided with the inferior conjunction of the secondary star. When HRHSA observed the system in 1986 and 1987, the deeper minimum instead corresponded to the inferior conjunction of the primary object. In 1990, Bartolini et al. (1991) obtained a light curve with minima consistent with HRHSA’s, but their brightest maximum was observed to be shifted by 0.5 in phase. Similar changes were found by Leibowitz, Hemar, & Orio (1998) when they studied the $R$-band light curve of V616 Mon over a 7 yr period. They found that not only did the shape of the light curve change over time, but also the mean brightness of the system seemed to vary on a timescale of hundreds of days with a peak-to-peak amplitude of 0.3 mag. More recently, FR saw evidence for a slightly changing $H$-band light-curve shape over a 1 yr baseline of observations. However, they did not see any sharp dips or asymmetry reversals between the two light-curve maxima. In addition, the mean $H$-band magnitude remained fairly constant over the course of their observations.

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**TABLE 1**

| Reference | $V$  | $B - V$ | $V - R$ | $V - I$ | $J$  | $J - H$ | $J - K$ | Year* |
|-----------|-----|--------|--------|--------|-----|--------|--------|------|
| 1         | 18.35 | 1.35  | ...    | ...    | ... | ...    | ...    | 1976 |
| 2         | 18.2 ± 0.1 | 1.25 | ...    | ...    | ... | ...    | ...    | 1978 |
| 3         | 18.22 ± 0.03 | 1.08 | 15.44 ± 0.01 | 0.89 | ...    | ...    | 1986/1987 |
| 4         | ... | ...    | ...    | 15.6 ± 0.1 | 0.76 | ...    | ...    | 1990 |
| 5         | 18.20 ± 0.05 | ... | ...    | ...    | ... | ...    | ...    | 1992 |
| 6         | 18.25 ± 0.08 | ... | ...    | ...    | ... | ...    | ...    | 1995/1996 |
| 7         | 18.37 ± 0.05 | ... | ...    | ...    | ... | ...    | ...    | 1998 |
| K4 V ($A_V = 1.21$ mag) | 18.27 ± 0.04 | 1.21 ± 0.04 | 1.57 ± 0.04 | 15.40 ± 0.04 | 0.85 ± 0.04 | 2000/2001 |
| K4 III ($A_V = 1.21$ mag) | 18.27 ± 0.04 | 1.21 ± 0.04 | 1.57 ± 0.04 | 15.40 ± 0.04 | 0.85 ± 0.04 | 2000/2001 |

* Year the data were taken.

**REFERENCES.**—(1) Oke 1977; (2) Murdin et al. 1980; (3) HRHSA; (4) SNC; (5) McClintock & Remillard 2000; (6) FR; (7) this paper.
...magnitudes of the light curves.

25. There are no obvious long-term variations in the shapes or mean ...1999 February 12 and 16. The filled squares in the ...data set (filled triangles) was high (~1% photometry), these data showed considerable scatter due to very good seeing, which resulted in the undersampling of the PSF. In any case, both the shape and brightness of the observed light curves are consistent over the period of observations. Nonetheless, the evidence for long-term changes in the shape of the quiescent light curves of V616 Mon is interesting, and we will return to this subject in the next section.

4. MODELING THE INFRARED LIGHT CURVES OF V616 Mon

We adopt as our light curves the binned $J$-, $H$-, and $K$-band light curves from 2000 December (Fig. 2). To find the inclination of the binary, we conducted two more or less independent analyses of these data, which we describe below.

4.1. Basic Models and Assumptions

4.1.1. Assumed Secondary Star Parameters

For multiwavelength light-curve modeling, the most important input parameters are based on the temperature of the secondary star. In 1977, Oke detected a cool spectrum from the source and attributed it to a K5 V–K7 V star. HRHSA's analysis of V616 Mon favored a spectral type of K3–K4. Shahbaz, Bandyopadhyay, & Charles (1999) compared their observed $K$-band spectrum of V616 Mon with the spectra of comparison stars of spectral types K0 V, K3 V, K5 V, and K7 V and by using $\chi^2$ tests determined a best-fit spectral type of K3 V for the secondary star. Here, we examine multiwavelength photometry to estimate the secondary star's spectral type.

Table 1 presents the postoutburst infrared and optical colors of V616 Mon. The mean colors are consistent with those of a K4 V star reddened by $A_V = 1.21$ mag (Wu et al. 1976; Seaton 1979; $E(B-V) = 0.39$). In Figure 4 we compare the dereddened observed spectral energy distribution (SED) of V616 Mon to that of a K4 V star (Bessell & Brett 1988; Cousins 1976; Johnson 1966; Mikami & Heck 1982). Except at $B$ and $J$, the two sets of data (normalized at $H$) are consistent within the errors. Based on the photometry, there is evidence for excess light at $B$ (22%) and a possible small excess at $J$. This $B$-band excess is consistent with that found by MRW and helps us to constrain the amount of contamination by the accretion disk and/or hot spot. Based on the mean observed colors of V616 Mon and its resulting spectral energy distribution, we adopt a spectral type of K4 for the secondary star. We adopt as the corresponding temperature a value of $T_{\text{eff}} = 4600$ K (Johnson 1966).

Given that the photometry and optical–infrared spectroscopy agree, the simplest assumption is that the K4 secondary star dominates the $VRIJHK$ luminosity of the system. We can, however, envision scenarios (some of which are highly tuned) in which a K-type SED might be mimicked by accretion processes. Without accurate models for the spectra of quiescent SXRT accretion disks, we cannot further speculate on the exact level of contamination associated...
with these processes and therefore assume that nearly all the infrared light in the system comes from the secondary star.

The secondary stars in systems such as SX?Ts can have masses and radii that do not correspond to accepted values for main-sequence stars. In addition, some of these stars have been found to have parameters consistent with those of evolved stars (e.g., Paper I). Mass estimates range from those of a zero-age main-sequence star to those of a less massive subgiant (Iben, Tutukov, & Fedorova 1997; Wilson 1999, private communication). See Paper I for a discussion of the parameters such as limb darkening, gravity darkening, and bolometric albedo. The most important wavelength-independent input values to WD98 are listed in Table 2, and the wavelength-dependent parameters, in Table 3 (units are shown where appropriate). Since any realistic hot spot or disk contamination for this system will have a minimal heating effect on the secondary star (HRHSA; FR), we have used normal, nonirradiated, limb-darkening coefficients in our models. In addition, we adopt the gravity-darkening exponent found by Claret (2000) for a K4 star ($T_\text{eff} = 4600$ K): $\beta = 0.40$ (Table 2).

We did not use the optimizer program supplied with WD98. It proved to be much more convenient to simply compute large grids of models and use a simple program to compute $\chi^2$ values of the fits. The mass ratio was usually fixed at its spectroscopic value. To quantify the sensitivity of the models to the variations of the input parameters, we ran models with inputs covering a wide range of parameter space as in Paper I. We found that the best-fit orbital inclination angle did not change significantly as we varied the temperature of the secondary star by one spectral type. Varying $q$ from 0.057 to 0.077 (the 1 $\sigma$ error bars from MRW) also had no effect on our final orbital inclination angle.

### 4.1.3. ELC Model Setup

The second code we used was the ELC program, which is fully described in Orosz & Hauschildt (2000). In its black-body mode ELC is essentially the same as modes 2, 4, 5, and 6 of WD98. ELC has at least two features with no direct

| Parameter | Value |
|-----------|-------|
| Orbital period (days) | 0.323016 |
| Ephemeris (HJD phase 0.0) | 2,450,000.025 |
| Semimajor axis ($R_\odot$) | 4.6 |
| Orbital eccentricity | 0.0 |
| Temperature of K4 V secondary (K) | 4600 |
| Mass ratio ($M_2/M_1$) | 0.067 |
| Atmosphere model | Kurucz |
| Limb-darkening law | Square-root law |
| Secondary star gravity-darkening exponent | $\beta = 0.40$ |
| Secondary star bolometric albedo | 0.676 |

* From Leibowitz et al. 1998; corresponds to phase 0.0 for light curves presented in this paper and to phase 0.5 from their paper.

| Secondary Star Parameter | J | H | K |
|--------------------------|---|---|---|
| Monochromatic luminosity ($L_\odot$) | 0.223 | 0.281 | 0.296 |
| Square-root limb-darkening coefficient $x_j$ | 0.110 | $-0.063$ | $-0.166$ |
| Square-root limb-darkening coefficient $y_j$ | 0.531 | 0.652 | 0.724 |

* From Nordlund & Vaz 1990.
analog in WD98. The first is the (optional) inclusion of a flared accretion disk around "star 2." The second is the way in which model atmosphere intensities are included in the model. WD98 tabulates the ratios of solar-metallicity model atmosphere intensities to blackbody intensities for surface normals (i.e., a viewing angle of \( \mu = 1 \)). The intensities for other viewing angles are computed using the specified limb-darkening law (a single limb-darkening law is used for the entire star). ELC tabulates model solar-metallicity atmosphere-specific intensities (Hauschildt, Allard, & Baron 1999a; Hauschildt et al. 1999b) as a function of three parameters, namely, the effective temperature, the surface gravity, and the viewing angle, \( \mu \). Hence no parameterized limb-darkening law is needed. For stars with large surface gravities (\( \log g > 3.5 \)) the systematic differences between ELC and WD98 are quite small (less than \( \approx 1\% \)). However, for cool giants, the differences in the light curves can be dramatic (Orosz & Hauschildt 2000).

ELC currently has four different optimizer routines with various levels of sophistication. They are the "grid search" method, a Levengerg-Marquardt routine adapted from Bevington (1969), a routine that uses the downhill simplex method (essentially the "amoeba" routine from Press et al. 1992), and a genetic algorithm based on the PIKAIA routine given in Charbonneau (1995). The genetic routine proved to be by far the most useful routine here. The three basic free parameters of the model are the mass ratio, the inclination, and the orbital separation. The binary observables that were modeled were the three infrared light curves, a simulated velocity curve with \( K_2 = 433 \pm 3 \) km s\(^{-1}\) (MRW), and MRW’s value of the mean rotational velocity of the secondary star (\( 83 \pm 5 \) km s\(^{-1}\)). The optimization routines attempt to find a parameter set so that the total \( \chi^2 \) is minimized (\( \chi^2_{\text{total}} = \chi^2_{\text{light}} + \chi^2_{\text{velocity}} + \chi^2_{\text{rotation}} \)).

4.2. Simple Ellipsoidal Models of the Secondary Star

We first ran models assuming the secondary star was the sole source of light. Aside from limb- and gravity-darkening effects, the secondary star was assumed to have a uniform surface brightness. The WD98 models were run for a range of inclination angles, using the input parameters listed in Tables 2 and 3. The best fit was determined based on \( \chi^2 \) tests. In Figure 5, we present our 2000 December V616 Mon J-, H-, and K-band observations and the corresponding WD98 model (solid line) for the best-fit value of the orbital inclination angle \( i = 40^\circ \).

Three iterations of the ELC grid search program were used to fit the data, and the results are shown as the dashed line in Figure 5. The fitted parameters are \( i = 40.03^\circ \), \( q = 0.0604 \), and \( a = 4.543 \) R\(_{\odot} \). The WD98 and ELC models are nearly indistinguishable.

It is clear that the infrared variations we observed are not purely ellipsoidal. All three light curves reveal a small difference between the two maxima, as well as a small deviation (~3% at K) between phases 0.0 and 0.25. There are several possible explanations that could account for this light-curve shape, and we discuss them in the following sections.

4.3. Possible "Contamination" Scenarios

Two main effects could result in a phase-dependent deviation from ellipsoidal variations. These possibilities are direct light from a hot spot on the edge of the accretion disk and spots on the secondary star, either cool (dark) or hot (bright) spots. The long-term changing shape of the light curves discussed in §3 may be explained if the level of heating or the positions of these spots varies over time. We will consider each of these possibilities in turn.

4.3.1. Migrating Accretion Disk Hot Spot

In 1991, MRW "imaged" V616 Mon through Doppler tomography and found evidence for a hot spot on the accretion disk. The hot spot is presumably formed when the accretion stream from the secondary star impacts the accretion disk. The accretion stream has a predicted path; therefore, for the hot spot to migrate around the edge of the disk the disk size must change. There have been suggestions that the accretion disk in V616 Mon has changed in size over the past two and a half decades. For example, based on the change in the peak separation of observed H2 lines between 1991 and 1993 and its corresponding change in the disk velocity (\( \Delta V = 100 \) km s\(^{-1}\)), Orosz et al. (1994) suggested that the accretion disk had contracted. Thus, the accretion disk may indeed change in size, causing the hot spot to migrate. The hot spot could introduce a phase-dependent source of light if the accretion disk was optically thick. If the spot were more or less on the disk rim, then its viewing angle would change considerably over the orbit, giving rise to a phase-dependent modulation.

We investigated several spotted-disk models by using ELC and its genetic code. There are several extra parameters needed to describe the disk. They are the inner and outer radii, the opening angle of the outer edge, the temperature at the inner edge, and the power-law exponent, which describes the temperature profile. In addition, four parameters are needed for a spot. They are the azimuth angle, the angular size of the spot, its radial extent, and its "temperature factor." About 30,000 models using a wide range of input parameters were computed and fitted using the genetic code. In the end we found what FR had found, namely, that one can find models with a wide range of inclinations that give nearly equally good fits. In our case
the inclinations ranged from about 40° to 60°, with a change in the total χ² of less than 1. Fortunately, with the use of multicolor photometry and the observed spectral energy distribution, we are able to exclude a large number of these models. These models generally predict that on the order of 50% of the light in the infrared should come from the accretion disk. The “disk fraction” in the optical is predicted to be even larger. The ultraviolet to infrared SED of V616 Mon (Fig. 4) limits the excess light from the accretion disk and hot spot to 22% at B and to ≤3% at all other visible and near-infrared wavelengths. Although we cannot rule out up to a ≈3% level of diluting infrared light from the accretion disk and/or hot spot, we can certainly rule out the large dilutions predicted by the spotted-disk models. Based on these arguments, we do not believe that direct light from the hot spot is the cause of the excess in the ellipsoidal variations.

4.3.2. Starspots

Starspots are believed to be common features on many late-type stars. Their colors will not be drastically different from a K4 V star, and therefore do not significantly alter the observed SED. Spots on late-type stars typically vary on timescales of months to a few years (Bouvier & Bertout 1989; Vogt 1975). McClintock & Remillard (1990) state that changes in the brightness of the star by up to 0.2 mag are possible from spots alone. The variation in the V magnitude reported since the SXT returned to quiescence has spanned about 0.17 mag (see Table 1). SNC found that for spots about 750 K below the effective temperature of the star the variability of V616 Mon in its quiescent state by introducing dark spots on the surface of the K star with temperatures 10%–40% lower than the mean stellar temperature. They successfully modeled the B-band light curves obtained by McClintock & Remillard (1986) and Bartolini et al. (1991), even though the light curves were completely different in appearance. They implemented one spot on the hemisphere facing the compact object to explain the light curve of McClintock & Remillard (1986) and two spots on the opposite hemisphere to explain the light curve of Bartolini et al. (1991). Khruzina & Cherepashchuk (1995) conclude that the spotted model is a “natural explanation of brightness’s inequality in the quadratures of both curves and temporal variations of the curves’ ratio, as well as that of the shape and depth of both minima.” The starspots they used reached a few tenths of the stellar radius and had temperatures 10%–40% lower than the mean effective stellar temperature. Finally, Bildsten & Rutledge (2000) suggested that the observed X-ray luminosity of V616 Mon could be attributed to coronal activity on the secondary star. Presumably such coronal activity would have associated spots.

Using these dark spot scenarios, we ran WD98 models with a single cool spot on the surface of the secondary star. The geometry of the WD98 model places 0° longitude at the line of star centers, measured counterclockwise as viewed from the “north” (+z) pole. The angular radius of the spot corresponds to the angle subtended by the spot radius at the center of the star. With i = 40°, we varied the latitude of the spot from 45° to 135° (45° on either side of the equator), the longitude of the spot from 90° to 162° (on the leading side of the star), the radius of the spot from 60° (44% coverage) to 9° (2% coverage), and the temperature of the spot from 4100 to 3000 K. The best-fit χ² value came from the model of a 3600 K spot centered directly on the equator and at longitude 135°, with a radius of 18° (4% coverage). The model is plotted as a solid line in Figure 6. Of course, this same model could be generated by several spots or groups of spots that have the same average parameters as those of the model presented here.

An alternative source of phase-dependent contamination is to have parts of the star brighter than they would otherwise be, either due to stellar activity (i.e., similar to the faculae on the Sun) or possibly due to heating of the star by a disk hot spot. With i = 40°, we varied the hot spot temperature from 4646 to 4800 K, the spot latitude from 45° to 135° (45° on either side of the equator), the spot longitude from 240° to 342° (on the trailing side of the star), and the spot coverage from 100% (spot radius = 90°) to 30% (spot radius = 50°) of one hemisphere of the star. The best-fit model was again determined from χ² tests. While several models had very low χ² values, the model with the lowest value had a 4715 K spot that covered 100% of the hemisphere centered directly on the equator at longitude 315°.

Models with smaller spots (≥60% coverage) and temperatures varying from 4646 to 4738 K gave slightly higher χ² values. For example, a 4681 K spot centered at the same longitude and latitude and that covered 64% of the hemisphere had a χ² value that was 0.02 higher than that of the best-fit model.

We also used ELC and its genetic code to explore spotted-star models. The spot parameters are used in the

![Figure 6](image-url)
same way as in WD98. Several populations were evolved, allowing for either a hot or a cool spot. Roughly 120,000 models and fits were computed. In general, compact hot spots (with typical angular radii of 10°) on the trailing face of the star or larger cool spots (with radii of up to 90°) near the leading face of the star provided good fits. The cool spot model with the best $\chi^2$ is shown as the dashed line in Figure 6. This model has $i = 40°.88$, $q = 0.0654$, and $a = 4.157 R_\odot$. The 3495 K cool spot is centered at latitude $172°.4$ and longitude $0°.1$ and has angular radius $86°.8$. The hot spot model with the best $\chi^2$ has $i = 41°.56$, $q = 0.0628$, and $a = 4.404 R_\odot$ with a 9050 K spot at latitude $83°.4$, longitude $171°.1$, and angular radius $7°.9$.

Could these hot spots be “intrinsic” to the star, or could the star be externally heated? The best-fit WD98 model has the entire trailing hemisphere of the star slightly hotter than the leading hemisphere. This type of temperature distribution may be explained by external heating of the secondary star. One major problem for the external heating scenario, however, is that there is little evidence for a luminous hot spot on the accretion disk that could act as the source of heating. McClintock & Remillard (2000) report a low UV flux. A blackbody of 12,000 K fits the dereddened UV points from McClintock & Remillard (2000) fairly well and explains the 22% contamination at $B$. When the blackbody is added to the flux for the K4 V (Fig. 4, open triangles), it nicely accounts for the differences between the K4 V SED and the observed SED of V616 Mon. Based on the total flux of the blackbody and the distance to V616 Mon, the radius of the blackbody area is 0.05 $R_\odot$. This amounts to roughly 2.5% of the radius of the accretion disk if the disk fills half its predicted Roche lobe. If this blackbody is used to represent the hot spot on the disk, these results suggest that the hot spot temperature is about 12,000 K, consistent with hot spot temperatures found for cataclysmic variable disks (Hoard & Szkody 1996). We also attempted to fit the observed UV data with a 9000 K blackbody, as found in McClintock, Horne, & Remillard (1995); however, the 12,000 K blackbody better explained the data. Is this hot spot luminous enough to heat the star the amount required to explain the observed light curves? According to Brett & Smith (1993), if the irradiated atmosphere is assumed to adopt the structure of a hotter star with an effective temperature $T_{\text{eff}}$, then $\sigma T_{\text{eff}}^4 = \sigma T_{\text{eff}}^4 + w F_{\text{inc}}$, where $F_{\text{inc}}$ is the flux incident on the star being heated. To determine the most favorable case for a heating scenario, the value of $w$ is taken to be 1 here (the normal value is approximately 0.5). To raise the temperature of the star from 4600 to 4715 K, a flux of $2.63 \times 10^8$ ergs s$^{-1}$ cm$^{-2}$ is needed. A 12,000 K hot spot with a $B$ magnitude equal to 22% of the dereddened $B$-band flux cannot be more than 0.86 $R_\odot$ (0.25$L_{\odot}$) away from the secondary star to heat it by 115 K. To heat the star by 81 K, the accretion disk hot spot cannot be more than 1.211 $R_\odot$ (0.35$L_{\odot}$) away from the secondary star. These solutions require a disk radius of 0.65 to 0.75$L_{\odot}$, while the system probably needs a much smaller disk to allow the accretion stream to travel around it to the “back side” before impacting the disk. Unless the phasing of Leibowitz et al. (1998) is off by 180°, the heating model seems unlikely.

The best-fit ELC hot spot model places a small 9050 K spot near the equator on the end of the star opposite the L1 point. Since it is unlikely that such a spot could be a result of external heating, we explore the possibility of faculae on the secondary star. Solar faculae are found around groups of sunspots and are normally visible near the limb of a star. The lifetime of an average solar faculae is about 15 days, while that of a large faculae that dominates solar variations can last almost three months (Chapman & McGuire 1977). Since individual starspots can exist for much longer timescales than their solar counterparts, it may be possible for stellar faculae also to exhibit much longer lifetimes. However, even though it may be possible for faculae to remain stable over the baseline of our observations, they do not appear to be able to account for a spot that has a temperature almost twice that of the effective temperature of the star. Chapman & McGuire (1977) find that in general the facular contrast has a $\lambda^{-1}$ dependence. “White light” faculae on the Sun are associated with bright regions, but in the infrared they appear darker than the quiet photosphere (Foukal, Little, & Mooney 1989). It does not appear as though faculae on the secondary star in V616 Mon could have parameters consistent with the ELC hot spot.

4.4. Adopted Model and its Uncertainties

Given the plausibility of the physical nature of the dark spots and their ability to reproduce light curves of vastly differing shapes through migration, we suggest that cool spots on the surface of the secondary star are the cause of the phase-dependent deviations in the ellipsoidal variations seen in the J-, H-, and K-band light curves. From the SED shown in Figure 4, we adopt a model that has no light from an accretion disk.

The best-fitting inclination from the WD98 models is $i = 40°$ and that from the ELC models is $i = 41°.5$. Based on errors in the amount of infrared diluting light in the system and the ability of the $\chi^2$ tests to distinguish between model fits to the observed data, the uncertainty in the WD98 value is about 1°. The ELC code and its genetic routine provide an easy way to estimate the uncertainties on the fitted parameters, especially the inclination. We simply plotted the $\chi^2$ values as a function of the inclination and looked to
see how the value of $\chi^2$ changes near the minimum. Figure 7 shows the “lower envelope” of the $\chi^2$ values as a function of the inclination, which is basically the smallest $\chi^2$ value within each 0.1 bin. The $\chi^2$ values were scaled to give $\chi^2_{\text{min}} = 1$ at the minimum. Although not all bins are filled, it appears that the formal statistical uncertainty in the inclination is rather small, on the order of 2° or so. We estimate that the systematic error caused by contamination of disk light at the few percent level is on the order of 1°. We adopt as our final inclination $i = 40.75 \pm 3^\circ$.

Our derived orbital inclination angle is inconsistent with HRHSA’s, but agrees with SNC’s inclination, determined from their K-band light curve of V616 Mon. We do not see any evidence for an accretion disk hot spot affecting the infrared light curves, and thus our results differ from those of FR.

5. DISCUSSION

With the excellent match of the observed photometry with a K4 V SED, we find that the optical and infrared contamination from a constant source of light in the system is ≤3%, with an exception at B. Combining Hubble Space Telescope UV observations (assuming a 12,000 K blackbody for the hot spot on the accretion disk), we can explain the observed SED from the ultraviolet to the infrared. We first ran models for an uncontaminated K4 V star and found a best-fit orbital inclination of 40°. This model could not fit the unequal maxima of the infrared light curves, as a purely ellipsoidal model exhibits equal maxima. To determine the phase-dependent nature of the ellipsoidal deviations in the V616 Mon light curves, we have considered three possibilities. We ruled out models for a migrating hot spot on the accretion disk, based on the low level of optical and infrared diluting light in the system. However, models with either cool spots or hot spots on the surface of the star fit the data nearly as well, although the heated spot model was slightly better. However, each model has its own problems.

There are several main problems with the heated-face models. First, the heated part of the star is the trailing hemisphere. This means that the hot spot needed to heat it would have to be on the side of the accretion disk opposite to the side normally expected. Second, the heating mechanism must be uncomfortably close to the secondary star to heat it and explain the data. There does not appear to be sufficient luminosity in the system to heat the star from the suggested distance of a hot spot on the accretion disk (0.5R$_{\text{L1}}$). This scenario might work if the phasing were off by 180° (but this possibility seems unlikely).

Contrary to the heated models, the dark spot models seemed to be physically viable, but even these models had their own peculiarities. The best-fit WD98 dark spot models placed the spot directly on or very close to the equator. Also, the model had one spot on the leading face of the secondary star. Thus this model may require a special scenario; however, it is likely that this same model could be generated by multiple spots that have the same average parameters. Nonetheless, this model is consistent with both the long-term, as well as current, observations of V616 Mon. Spots are presumed to be a natural occurrence on the surfaces of late-type stars. Any such spots, however, must be nearly unchanged on multiyear timescales. Dark spots have also been used to explain the changing light curves of Cen X-4 (McClintock & Remillard 1990), as well as those of other binary systems. Detailed long-term monitoring of V616 Mon and other SXTs should prove extremely useful in determining the behavior of spots (if present) on long timescales.

With the orbital inclination angle determined as $i = 40.75 \pm 3^\circ$, we can estimate the mass of the primary and other interesting parameters. The other observed quantities needed for this exercise are the (projected) radial velocity and the rotational velocity of the secondary star ($K_2 = 433 \pm 3 \text{ km s}^{-1}$ and $\sin i = 83 \pm 5 \text{ km s}^{-1}$; MRW), and the orbital period ($P = 0.323016$ days; McClintock & Remillard 1986). The ELC code was used to numerically find the relationship between $K_2$, $\sin i$, and the mass ratio $q$, and a simple Monte Carlo code was used to compute the uncertainties on the binary system parameters, assuming the quoted uncertainties on all the input values above are 1σ. We find a black hole mass of $11.0 \pm 1.9 M_\odot$ and a mass of $0.68 \pm 0.18 M_\odot$ for the secondary star. Note that this mass is consistent with that of a “normal” K4 V (Gray 1992).

The distance to the source depends on its luminosity and extinction. We used the synthetic photometry computed from the NEXTGEN models to compute the expected absolute $J$, $H$, and $K$ magnitudes of the star from its temperature, radius, and surface gravity. For this exercise we adopt a 1σ error on the effective temperature of 200 K, which is roughly one subclass in K (Gray 1992). We used the color excess of $E(B-V) = 0.39 \pm 0.02$ given by Wu et al. (1976) and the extinction law of Cardelli, Clayton, & Mathis (1989) to find the extinctions in the three bands, assuming $A_V = 3.1E(B-V)$. Using our infrared photometry (Table 1) and the quoted 1σ errors, we used another simple Monte Carlo procedure to compute the absolute magnitude, the distance modulus, and their uncertainties in each of the $J$, $H$, and $K$ filters. The results are summarized in Table 4. Our adopted value of the distance is the simple average of the distances derived for the three filters: $d = 1164 \pm 114$ pc. This distance is consistent with that found by SNC (660 pc ≤ $d$ ≤ 1450 pc, with the most probable value at 1050 pc).

To understand the outbursts of SXTs, we need to be able to model them with refined input parameters. As discussed in Paper I, the orbital inclination angle can play an important role in the appearance of an SXT outburst. Esin et al.

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8 See ftp://calvin.physast.uga.edu/pub/NextGen/Colors/.

| Table 4: Derived Parameters for V616 Mon |
|-----------------------------------------|
| Parameter | Value |
| Black hole mass, $M_1$ ($M_\odot$) | 11.0 ± 1.9 |
| Secondary mass, $M_2$ ($M_\odot$) | 0.68 ± 0.18 |
| Total mass, $M_{\text{tot}}$ ($M_\odot$) | 11.70 ± 2.05 |
| Orbital separation, $a$ (R$_\odot$) | 4.47 ± 0.27 |
| Secondary star radius, $R_2$ (R$_\odot$) | 0.80 ± 0.07 |
| Secondary star gravity (log $g$ cgs) | 4.46 ± 0.04 |
| Absolute magnitude, $J$ | 4.77 ± 0.23 |
| Absolute magnitude, $H$ | 4.17 ± 0.20 |
| Absolute magnitude, $K$ | 4.11 ± 0.20 |
| Distance modulus, $J$ (mag) | 10.29 ± 0.23 |
| Distance modulus, $H$ (mag) | 10.40 ± 0.21 |
| Distance modulus, $K$ (mag) | 10.30 ± 0.21 |
| Adopted distance (pc) | 1164 ± 114 |
(2000) used a black hole mass of $4.5 \, M_\odot$, an orbital inclination angle of $i = 65^\circ$, and a distance of 1.4 kpc as inputs to their advection-dominated accretion flow models. While the distance they used was close to the one we find here, the black hole mass and inclination angle are not. Any new models that are constructed to explain the outburst of V616 Mon should take into account our results for the mass of the black hole, the orbital inclination angle, and the distance.

We assumed that the accretion disk contributes essentially no light in the infrared. Based on this assumption, we adopted a value of the inclination of $i = 40^\circ:75$. As the SED in Figure 4 shows, there are good reasons to think that this assumption is valid. Given how critical this assumption is (i.e., a disk contamination of 50% would drive the inclination up to around 60$^\circ$), it would be extremely worthwhile to test it in as many ways as possible. Shahbaz et al. (1999) obtained a $K$-band spectrum of the source with modest resolution (47 Å FWHM) and signal-to-noise ratio ($\approx 30$) and concluded that the $2 \sigma$ upper limit on the accretion disk contamination is $\leq 27\%$ in the $K$-band. FR, however, criticized this result on the grounds that template stars with inappropriate surface gravities were used and that an inappropriate spectral feature [the $2.29 \, \mu m \, ^{12}\text{CO}$ (2, 0) bandhead] was used. It should be relatively easy to obtain a much better infrared spectrum by using the latest generation of infrared spectrographs available on the 8 to 10 m-class telescopes. One could observe a wider variety of templates and also use the increasingly detailed spectral models for cool stars (for example the NEXTGEN models discussed in Leggett et al. 2001) to derive a more definite upper limit on the disk contamination in the infrared.

The shape of the X-ray outburst light curves of V616 Mon and GU Mus are very similar (as can be seen in Fig. 1 of King, Harrison, & McNamara 1996) with one main difference, the time of their secondary maxima. The light curve of V616 Mon began the rise to its second X-ray maximum about 40 days after its initial outburst, while the light curve of GU Mus shows this rise beginning about 60 days afterward. Both secondary maxima lasted for about 30 days. Based on the orbital period and radial velocity of the secondary star, the GU Mus system ($P = 10.38$ hr; $K_2 = 406 \pm 7$ km s$^{-1}$) is larger than the V616 Mon system ($P = 7.75$ hr; $K_2 = 433 \pm 3$ km s$^{-1}$). V616 Mon has a larger primary mass ($M_{1,\text{Mon}} = 11.0$, $M_{1,\text{Mus}} = 6.95$), and we see it at more of a face-on angle ($i_{\text{Mus}} = 40^\circ:75$, $i_{\text{Mus}} = 54^\circ$) than GU Mus. Could the larger size of the system account for the increase in time between X-ray outburst maxima, or could it be related to the mass of the black hole? Close study of more SXTs is needed before this question can be answered with any certainty.

In Paper I, based on the comparison of optical and infrared colors, we determined a spectral type of K4 for the secondary star in the GU Mus system. The colors were intermediate to those of a K4 dwarf and giant. As discussed above, we also determine a spectral type of K4 for V616 Mon. In this case, however, the colors are consistent with those of a K4 dwarf. By Kepler's third law, the ratio of the secondary stars' Roche lobe radii is simply related to the ratio of the orbital periods: $R_{\text{Mus}} / R_{\text{Mon}} = (P_{\text{Mon}} / P_{\text{Mus}})^{2/3} = 0.82$. A K4 V star nominally has a radius of 0.70 $R_\odot$ on the zero-age main-sequence (Gray 1992). Such a star would nearly fill the Roche lobe in V616 Mon ($R_2 = 0.80 \pm 0.07 R_\odot$), whereas it would fill only $\approx 80\%$ of the Roche lobe in GU Mus. Surprisingly, accurate multiwavelength photometry appears to be somewhat sensitive to these small radial differences.

The nature of the mass distribution of stellar-mass black holes has been in question for many years now. Based on observational evidence for seven stellar black holes with low-mass companions, Bailyn et al. (1998) attempted to constrain this distribution. Using Bayesian statistics, they suggested that six of the seven systems had black hole masses clustered around $7 \, M_\odot$. The other system, V404 Cyg, was thought to be drawn from a different distribution. Models of the evolution and supernova explosions of massive stars should be able to predict the mass distribution of stellar-mass black holes. However, because of their findings Bailyn et al. (1998) suggested considering a new underlying mechanism for the origin of the black hole mass distribution in low-mass X-ray binaries.

The mass we found for GU Mus in Paper I ($M_1 = 6.95 \pm 0.6 \, M_\odot$) is consistent with, but more precise, than the mass adopted by Bailyn et al. (1998). In the case of V616 Mon, Bailyn et al. (1998) adopted a wide range of inclinations reported in the literature ($31 \leq i \leq 70^\circ:5$). As a result, the allowed range of the mass of the black hole was rather large. The more precise mass we determine for V616 Mon is well above the cluster of masses near $7 \, M_\odot$ and falls nicely in the mass range plotted in their Figure 1 for V404 Cyg. Although the orbital period and evolutionary status of the secondary star in V404 Cyg are significantly different from V616 Mon, their similar black hole masses may say something about the amount of postsupernova mass transfer that has taken place in both these systems. The sample size of SXTs with measured mass functions has doubled since the analysis of Bailyn et al. (1998) was done, so it would be worthwhile to revisit the issue of the distribution of stellar black hole masses. Indeed, the four most recently determined SXT optical mass functions are all rather large: $6.0 \pm 0.36 \, M_\odot$ for XTE J1118+480 (McClintock et al. 2001), $6.86 \pm 0.71 \, M_\odot$ for XTE J1550-564 (Orosz et al. 2001), $9.5 \pm 3 \, M_\odot$ for GRS 1915+105 (Greiner 2001), and $7.4 \pm 1.1 \, M_\odot$ for XTE J1859+226 (Filippenko & Chornock 2001). It is likely that some of these systems have black hole masses that are also well above the cluster of masses near $7 \, M_\odot$. In addition, better measurements for more of the known systems can be used to reduce the uncertainties in the mass distribution.

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REFERENCES

Bailyn, C. D., Jain, R. K., Coppi, P., & Orosz, J. A. 1998, ApJ, 499, 367
Bartolini, C., Guarnieri, A., Piccioni, A., Solmi, L., & Teodorani, M. 1991, in IAU Colloq. 129, Structure and Emission Properties of Accretion Discs, ed. C. Bertout, S. Colin-Souffrin, J. P. Lasota, & J. Tran Tranh Van (Paris: Ed. Frontières), 373
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Bevington, P. R. 1969, Data Reduction and Error Analysis for the Physical Sciences (New York: McGraw Hill)
Bildsten, L., & Rutledge, R. E. 2000, ApJ, 541, 908
Bouvier, J., & Bertout, C. 1989, A&A, 211, 99
Brett, J. M., & Smith, R. C. 1993, MNRAS, 264, 641
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chapman, G., & McGuire, T. 1977, ApJ, 217, 657
Charbonneau, P. 1995, ApJS, 101, 309
Charles, P. A. 2001, in Black Holes in Binaries and Galactic Nuclei, ed. L. Kaper, E. P. J. van den Heuvel, & P. A. Woudt (Berlin: Springer), 27
Cousins, A. W. 1976, MmRAS, 81, 25
Elvis, M., Griffiths, C. G., Turner, M. J. L., & Page, C. G. 1975, IAU Circ. 2814
Esin, A. A., Kuulkers, E., McClintock, J. E., & Narayan, R. 2000, ApJ, 532, 1069
Filippenko, A. V., & Chornock, R. 2001, IAU Circ. 7644
Foukal, P., Little, R., & Mooney, J. 1989, ApJ, 336, L33
Froning, C. S., & Robinson, E. L. 2001, AJ, 121, 2212 (FR)
Gelino, D. M., Harrison, T. E., & McNamara, B. J. 2001, AJ, 122, 971 (Paper I)
Gray, D. F. 1992, The Observations and Analysis of Stellar Photospheres (New York: Cambridge Univ. Press)
Greiner, J., et al. 2001, Nature, submitted
Haswell, C. A., Robinson, E. L., Horne, K., Stiening, R. F., & Abbott, T. M. C. 1993, ApJ, 411, 802 (HRHSA)
Hauschildt, P. H., Allard, F., & Baron, E. 1999a, ApJ, 512, 377
Hauschildt, P. H., Allard, F., Ferguson, J., Baron, E., & Alexander, D. R. 1999b, ApJ, 525, 871
Hoard, D. W., & Szkody, P. 1996, ApJ, 470, 1052
Iben, I., Tutukov, A. V., & Fedorova, A. V. 1997, ApJ, 486, 955
Johnson, H. L. 1966, ARA&A, 4, 193
Khruzina, T. S., & Cherepashchuk, A. M. 1995, Astron. Rep., 39, 178
King, N. L., Harrison, T. E., & McNamara, B. J. 1996, AJ, 111, 1675
Leggett, S. K., Allard, F., Geballe, T. R., Hauschildt, P. H., & Schweitzer, A. 2001, ApJ, 548, 908
Leibowitz, E. M., Hemar, S., & Ori, M. 1998, MNRAS, 300, 463
Marsh, T. R., Robinson, E. L., & Wood, J. H. 1994, MNRAS, 266, 137 (MRW)
McClintock, J. E., Garcia, M. R., Caldwell, N., Falco, E. E., Garnavich, P. M., & Zhao, P. 2001, ApJ, 551, L147
McClintock, J. E., Horne, K., & Remillard, R. A. 1995, ApJ, 442, 358
McClintock, J. E., & Remillard, R. A. 1986, ApJ, 308, 110
———. 2000, ApJ, 531, 956
Mikami, T., & Heck, A. 1982, PASJ, 34, 529
Murdin, P., Allen, D. A., Morton, D. C., Whalen, J. A. J., & Thomas, R. M. 1980, MNRAS, 192, 709
Nordlund, A., & Vaz, L. P. R. 1990, A&A, 228, 231
Oke, J. B. 1977, ApJ, 217, 181
Orosz, J. A., Bilyn, C. D., Remillard, R. A., McClintock, J. E., & Foltz, C. B. 1994, ApJ, 436, 848
Orosz, J. Á., & Hauschildt, P. H. 2000, A&A, 364, 265
Orosz, J. A., van der Klis, M., McClintock, J. E., Jain, R. K., Bailyn, C. D., & Remillard, R. A. 2001, Astron. Telegram, 70, 1
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in FORTRAN: The Art of Scientific Computing (2nd ed.; Cambridge: Cambridge Univ. Press)
Seaton, M. J. 1979, MNRAS, 187, 73P
Shahbaz, T., Naylor, T., & Charles, P. A. 1999, A&A, 346, 82
Shahbaz, T., Naylor, T., & Charles, P. A. 1994, MNRAS, 268, 756 (SNC)
———. 1997, MNRAS, 285, 607
Vogt, S. S. 1975, ApJ, 199, 418
Wilson, R. E. 1998, in Reference Manual to the Wilson-Devinney Program, Computing Binary Star Observables, Version 1998 (Gainesville, FL: Univ. Florida)
Wu, C.-C., Aalders, J. W. G., van Duinen, R. J., Kester, D., & Wesselius, P. R. 1976, A&A, 50, 445