

THE NATURE OF THE SECONDARY STAR IN THE BLACK HOLE X-RAY TRANSIENT V616 MON (=A0620-00)

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ABSTRACT

We have used NIRSPEC on Keck II to obtain K -band spectroscopy of the low-mass X-ray binary V616 Mon (=A0620-00). V616 Mon is the prototypical soft X-ray transient containing a black hole primary. As such it is important to constrain the masses of the binary components. The modeling of the infrared observations of ellipsoidal variations in this system lead to a derived mass of $11.0 M_{\odot}$ for the black hole. The validity of this derivation has been called into question due to the possibility that the secondary star's spectral energy distribution is contaminated by accretion disk emission (acting to dilute the variations). Our new K -band spectrum of V616 Mon reveals a late-type K dwarf secondary star, but one that has very weak ^{12}CO absorption features. Comparison of V616 Mon with SS Cyg leads us to estimate that the accretion disk supplies only a small amount of K -band flux, and the ellipsoidal variations are not seriously contaminated. If true, the derived orbital inclination of V616 Mon is not greatly altered, and the mass of the black hole remains large. A preliminary stellar atmosphere model for the K -band spectrum of V616 Mon reveals that the carbon abundance is approximately 50% of the solar value. We conclude that the secondary star in V616 Mon has either suffered serious contamination from the accretion of supernova ejecta that created the black hole primary or is the stripped remains of a formerly more massive secondary star, one in which the CNO cycle had been active.

Key words: infrared: stars — stars: individual (V616 Monocerotis, SS Cygni) — X-rays: binaries

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1. INTRODUCTION

V616 Mon (=A0620-00) is the prototype for a small family of binaries known as black hole X-ray transients (BHXTs) in which the primary is a black hole and the secondary a relatively low mass star. A sudden increase in the mass transfer rate due to an accretion disk instability has been used to explain the outbursts of these systems (Cannizzo 1993; Menou 2002). After a number of months, the BHXTs return to relative quiescence and are very faint at X-ray and optical wavelengths. During this time, both their broadband spectral energy distributions (SEDs) and moderate-resolution spectra are dominated by a late-type secondary star (cf. Gelino et al. 2001; González Hernández et al. 2004). Because the secondary star is clearly visible, radial velocity observations are possible, allowing the derivation of its orbital and rotational motion. When combined with the orbital period and an estimate for the orbital inclination, it is possible to

put useful limits on the masses of both components in the system. When this is done for V616 Mon, the mass of the black hole primary is $11 M_{\odot}$. As such, V616 Mon ($P_{\text{orb}} = 7.75$ hr) has the largest mass black hole for any X-ray binary whose orbital period is $P_{\text{orb}} \leq 24$ hr (Lee et al. 2002). As discussed by Kalogera (1999), it is difficult to produce a binary with a black hole primary that has such an extreme mass ratio.

In the case of V616 Mon, the leading uncertainty in the derivation of the black hole mass is the orbital inclination angle. Measurement of the orbital inclination in any close binary system depends on some assumptions about the nature of the stellar components. But with estimates for the gravity and effective temperature of the stars in such systems, it is possible to use light-curve modeling software (e.g., the 1998 Wilson-Divinity code; see Kallrath et al. 1998) to fit the orbital inclination if it exhibits eclipses or if one of the components is distorted enough to produce ellipsoidal variations. Since the outbursts of BHXTs are believed to be due to an accretion disk event, the secondary star must be acting as the donor in such systems and can safely be assumed to fill its Roche lobe. Therefore, BHXTs will exhibit ellipsoidal variations if the orbit is inclined to our line of sight and the secondary star emits a significant fraction of the systemic luminosity. As shown by Shahbaz et al. (1994) and Gelino et al. (2001), V616 Mon exhibits such ellipsoidal variations in the near-infrared. Using published parameters for the system derived from earlier radial velocity studies, Gelino et al.

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concluded that the system has an orbital inclination of $41^\circ \pm 3^\circ$. In that work, Gelino et al. found that the existing *BVRJHK* photometry of V616 Mon was consistent with a K4 V secondary star and assumed that the *JHK* ellipsoidal variations were relatively uncontaminated by emission from the accretion disk and/or hot spot. Hynes et al. (2005) have recently cast doubt on the efficacy of such a model by exploring the possibility that the accretion disk severely contaminates the SED and might even mimic a K-type secondary star. They justify this exercise by reference to an existing *K*-band spectrum of this source by Shahbaz et al. (1999) that seemed to lack obvious CO absorption features. Below we present a new, higher resolution and higher signal-to-noise ratio (S/N) infrared spectrum of V616 Mon in which we find a late K-type stellar spectrum, one in which the ^{12}CO features are anonymously weak. We then present preliminary stellar atmosphere models for this object, from which we derive estimates for the ^{12}C abundance, and discuss these results in the context of existing BHXT formation scenarios.

2. OBSERVATIONS

V616 Mon was observed on 2005 February 17 using NIRSPEC⁴ on Keck II in photometric conditions. We used NIRSPEC in low-resolution mode with a $0.38''$ slit. The grating tilt was set so as to cover the wavelength region $2.04 \mu\text{m} \leq \lambda \leq 2.46 \mu\text{m}$, with a dispersion of $4.27 \text{ \AA pixel}^{-1}$. We employed the two-nod script and obtained 12 individual exposures with 4 minute integration times. To correct for telluric absorption we observed bright A0 V stars located close to the program object so as to minimize their relative differences in air mass. We used standard IRAF spectroscopic data reduction routines to produce the final spectra. In the *K*-band the spectra of A0 V stars are nearly featureless, except for the prominent H I Br γ absorption line at $2.16 \mu\text{m}$. To remove the telluric features we divide by the spectrum of this A star. This process artificially enhances the H I emission. To allow for an examination of the profile of the H I Br γ emission line, we have patched over the intrinsic H I absorption feature in the A0 V star before division into our program spectra.

Before we can co-add the 12 spectra we must correct for the radial velocity motion of the secondary star. Gelino et al. (2001) found that the observed ellipsoidal variations of V616 Mon were synchronized to the orbital ephemeris of Leibowitz et al. (1998). We have phased our spectra using that ephemeris. The final *K*-band spectrum of V616 Mon, obtained from the median of the Doppler-corrected spectra, is presented in Figure 1, where we compare it to Infrared Telescope Facility (IRTF) spectra of two K dwarfs (from Harrison et al. 2004). Note that the profiles of the H I Br γ line and that of the He I line at $2.058 \mu\text{m}$ are affected by the Doppler correction, since the origin of the line emission occurs interior to the orbit of the secondary star. All spectra have been smoothed to a dispersion of $20 \text{ \AA pixel}^{-1}$, and the K dwarf spectra have been convolved to a rotation velocity of 83 km s^{-1} to match the observed $v \sin i$ of the secondary star in V616 Mon (Marsh et al. 1994). The S/N of our V616 Mon spectrum is lower than might be expected using NIRSPEC, but the seeing early in the night was very poor, FWHM $\sim 2''$. Fortunately, it improved as the night wore on (see Harrison et al. 2005).

3. THE SECONDARY STAR OF V616 MON

As is clear from Figure 1, the spectrum of V616 Mon appears to be that of a K-type dwarf except for the presence of He I (at

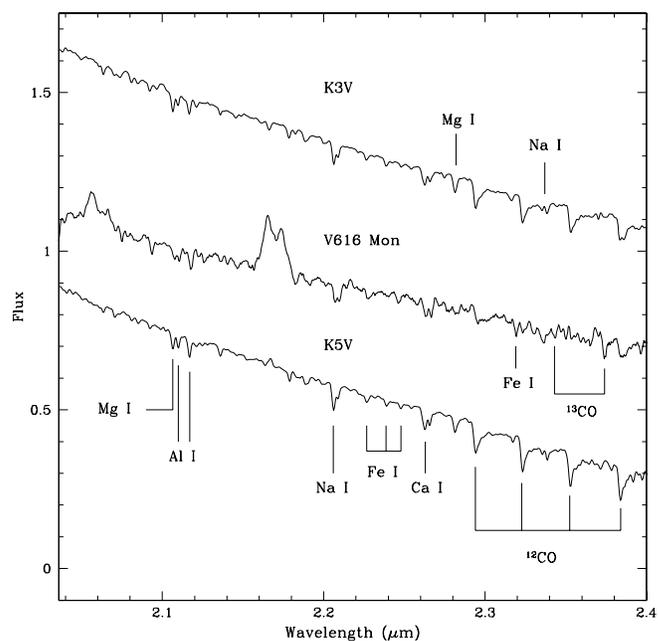


FIG. 1.—NIRSPEC data for V616 Mon (middle line) compared with the IRTF + SPECT data for two K dwarfs. Emission lines from He I at $2.06 \mu\text{m}$ and H I Br γ at $2.16 \mu\text{m}$ are present in the spectrum of V616 Mon. The template spectra have been convolved to match the observed rotation rate of the secondary star in V616 Mon ($v \sin i = 83 \text{ km s}^{-1}$). The strongest absorption features are identified. Close comparison to the template spectra suggests that the secondary star in V616 Mon has a spectral type of K5.

$2.058 \mu\text{m}$) and H I (at $2.166 \mu\text{m}$) emission and the weakness of its CO absorption features. The presence of the H I and He I emission lines indicates continued accretion in the system. The equivalent widths of the H I ($23.0 \pm 1.2 \text{ \AA}$) and He I ($12.0 \pm 1.7 \text{ \AA}$) lines remained constant over the small range in orbital phase covered by our observations ($0.93 \leq \phi \leq 1.00$) except for a brief decline of 30% in both lines at phase 0.98. However, our data only cover 12% of an orbital period for V616 Mon, so nothing can be said on how repeatable this is, whether phase 0.975 is special, or whether similar variations occur at other times. Shahbaz et al. (1999) measured an orbitally averaged equivalent width for H I of $14.6 \pm 1.2 \text{ \AA}$, suggesting either increased accretion activity during our observations or that the observed H I emission is higher near inferior conjunction of the secondary star.

Previous estimates of the spectral type of the secondary star range from K3/4 V (Haswell et al. 1993; Shahbaz et al. 1999) to K5/7 V (Oke 1977). Gelino et al. (2001) assumed a spectral type of K4 V. Careful visual comparison of our new spectrum of V616 Mon to our library of templates suggests a slightly later spectral type of K5 V. This is more clearly shown by comparison of the strengths of Na I and Ca I equivalent widths listed in Table 1, as well as in the trends of other atomic absorption features to have values closer to those of the K5 V template when compared to those of the K3 V. It is important to note that González Hernández et al. (2004) concluded that iron and aluminum were slightly enhanced (as were Li, Ti, and Ni) in the secondary star of V616 Mon. The equivalent widths we measure for iron and aluminum are consistent with those findings. Due to the large rotational velocity of V616 Mon, a number of the lines for which we have tabulated equivalent widths in Table 1 are blends, making it impossible to deconvolve which species is responsible for the measured line strength.

⁴ For more on NIRSPEC, see <http://www2.keck.hawaii.edu/inst/nirspec/nirspec.html>.

TABLE 1
EQUIVALENT WIDTHS

WAVELENGTH (μm)	SPECIES	EQUIVALENT WIDTH (\AA)		
		K3 V	K5 V	V616 Mon
2.0735.....	Fe I	0.86 ± 0.04	0.38 ± 0.03	0.65 ± 0.03
2.0820.....	Si I + Fe I	0.69 ± 0.03	0.57 ± 0.03	1.46 ± 0.07
2.0927.....	Si I	0.49 ± 0.04	0.36 ± 0.02	0.76 ± 0.04
2.1065.....	Mg I	1.05 ± 0.06	1.28 ± 0.06	1.04 ± 0.08
2.1099.....	Al I + Fe I	0.59 ± 0.04	0.63 ± 0.04	0.94 ± 0.07
2.1169.....	Al I + Fe I	0.81 ± 0.03	0.99 ± 0.03	1.30 ± 0.07
2.1214.....	Al I	0.35 ± 0.02	0.19 ± 0.02	0.32 ± 0.04
2.1239.....	Fe I	0.07 ± 0.02	0.19 ± 0.02	0.34 ± 0.05
2.1360.....	Si I	0.35 ± 0.03	0.50 ± 0.04	0.56 ± 0.03
2.1460.....	Fe I + Ca I + Mg I	0.52 ± 0.05	0.70 ± 0.06	1.20 ± 0.06
2.1889.....	Si I + Ti I + Fe I	1.00 ± 0.05	0.76 ± 0.03	1.39 ± 0.07
2.2011.....	Ti I	1.09 ± 0.05	0.41 ± 0.04	0.30 ± 0.06
2.2076.....	Na I	2.49 ± 0.07	3.39 ± 0.09	3.32 ± 0.09
2.2264.....	Fe I	0.48 ± 0.03	0.59 ± 0.03	1.01 ± 0.04
2.2380.....	Fe I	0.58 ± 0.03	0.47 ± 0.03	0.62 ± 0.05
2.2642.....	Ca I	2.94 ± 0.08	3.61 ± 0.10	3.35 ± 0.09
2.2814.....	Mg I	1.54 ± 0.05	1.55 ± 0.05	1.45 ± 0.08
2.3165.....	Fe I	0.77 ± 0.03	0.53 ± 0.03	0.97 ± 0.07

The continuum of V616 Mon does appear to be flatter than either of the templates, having a slope of -1.1 (times λ in μm), versus -1.5 for the templates. The template spectra obtained at the IRTF were reduced using the SPEXTOOL program, which employs a stellar atmosphere model for telluric correction, while our Keck data were reduced assuming a blackbody spectrum for the A star. Thus, some of this difference in spectral slope could result from these different reduction procedures. But spectra of a number of long-period cataclysmic variables (CVs) presented in Harrison et al. (2004) had flatter than expected spectral slopes when the secondary star was the sole source of luminosity in the K band. In each of those cases (e.g., SS Cyg) the CVs in question have detectable infrared emission from their accretion disks (see below). Obviously, the presence of H I and He I emission in the spectrum of V616 Mon shows that accretion is continuing at a low level, and thus, it is likely that the continuum slope of the infrared spectrum is affected.

The most prominent anomalies in the spectrum of V616 Mon are the weakness of the ^{12}CO features and the apparent enhancement of the absorption from ^{13}CO . While the $^{13}\text{CO}_{(2,0)}$ feature at $2.345 \mu\text{m}$ is not well defined, the next overtone, $^{13}\text{CO}_{(3,1)}$ at $2.374 \mu\text{m}$, is quite prominent. As shown in Figure 1, the ^{13}CO features are insignificant in the spectra of normal late-type dwarfs. Thus, we interpret its strength here as an enhancement over its normal abundance. We attempt to derive the abundances of both ^{12}CO and ^{13}CO in § 3.1.

3.1. Derivation of the Isotopic Abundances of Carbon

While the weakness of the ^{12}CO features could be due to deficits of either carbon or oxygen, an enhanced level of ^{13}C would suggest CNO cycle processing, the end result of which is enhanced levels of nitrogen and ^{13}C and reduced levels of ^{12}C , with little change in the global oxygen abundance (Marks & Sama 1998). We have used the atmosphere program SPECTRUM by Gray & Corbally (1994) to produce models for V616 Mon. SPECTRUM comes with an extensive line list (796,782 lines!) for modeling stellar spectra in the $1\text{--}4 \mu\text{m}$ region. Unfortunately, trial spectra using this line list produced a large number of very strong lines that are not seen in the template spectra and

appear to be due to scandium, vanadium, nickel, and other relatively rare atomic species. Thus, we decided to construct our own line list from scratch to model the CO lines, limiting ourselves to the region $2.28\text{--}2.42 \mu\text{m}$. For this purpose we used the CO line list compiled by Goorvitch (1994). In addition, both Na I and Mg I have strong features in this region, so data for the Na I doublet at $2.34 \mu\text{m}$ and three lines from Mg I near $2.38 \mu\text{m}$ were also included in our line list.⁵

We found that in all of our initial trial model spectra calculated by SPECTRUM using Kurucz atmospheres⁶ of the appropriate temperature, the spectral lines/features were weaker than they should be when compared to the template spectra. To fix this, we globally elevated the oscillator strengths [the log (gf) values] of the CO, Na, and Mg lines until we achieved a good match between the model and template spectrum for the K5 V. We then constructed both hotter and cooler models using this line list and compared them to our other template spectra to see whether the spectral features evolved with temperature in the correct fashion. The result of this exercise is shown in Figure 2. The models fit our observed MK template spectra quite well considering the limited line list, except for the match of the $^{12}\text{CO}_{(5,3)}$ feature at $2.383 \mu\text{m}$ to the spectra of the K5 V and K7 V. This CO band head is strongly affected by the Mg I absorption lines noted above. We tested how sensitive the shape of this feature was to the Mg I lines by increasing their oscillator strengths and found that such models were better fits to the K5 and K7 spectra but were worse for the hotter K2 V and K3 V templates (where the Mg I lines are more prominent relative to the $^{12}\text{CO}_{(5,3)}$ feature). It is difficult to ascertain the origin of this discrepancy given that both the hotter and cooler template spectra are well modeled. Perhaps the K5 V and K7 V templates (61 Cyg A and B) have slightly enhanced levels of magnesium.

With confidence that we could reproduce normal K dwarf spectra, we then ran a series of K5 V models ($T_{\text{eff}} = 4500 \text{ K}$) with reduced levels of ^{12}C and enhanced levels of ^{13}C . We constructed

⁵ The data for these five transitions were obtained from the NIST Atomic Spectra Database at http://physics.nist.gov/cgi-bin/AtData/lines_form.

⁶ The model atmospheres were obtained from Kurucz's Web site, <http://kurucz.harvard.edu/grids.html>.

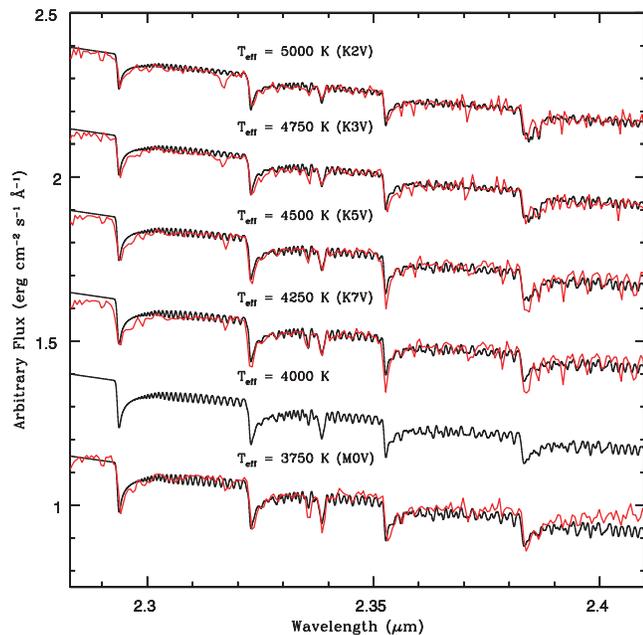


FIG. 2.— Comparison of model spectra (black lines) generated using Kurucz atmospheres and the spectral modeling program SPECTRUM compared to a sequence of MK templates (red lines) covering the range K2 V to M0 V. The model spectra have been smoothed to match the resolution of the SPEX instrument ($5.1 \text{ \AA pixel}^{-1}$).

models that had carbon deficits that ranged from 0.9 to 0.1 solar. We attempted χ^2 tests between the model spectra and the observations, but such tests were inconclusive. This is partly due to several important absorption features in this wavelength range missing from our models but is also due to the low S/N of the data. The models that appear to *visually* fit the observed spectrum of V616 Mon the best, shown in Figure 3, are ones in which the ^{12}C abundance is $\approx 50\%$ of solar. Unfortunately, our spectrum of V616 Mon is quite poor beyond $2.33 \mu\text{m}$, and it is difficult to be confident about the level of enhancement of ^{13}C in our spectrum. A model in which the isotopic ratio is $^{13}\text{C}/^{12}\text{C} = 1$ does a reasonable job of qualitatively fitting the observed features.

4. DISCUSSION

Our new spectrum of V616 Mon resolves some of the earlier issues with the nature of its secondary star. Clearly, the CO features in this object are much weaker than they should be, while most of the atomic features are at more normal strengths for a K5 V. If the weakness is assumed to be due to a deficit of carbon, then its abundance is about one-half the solar value. The weakness of the CO features explains why Shahbaz et al. (1999) were unable to clearly detect them in their low-S/N spectrum. Thus, the suggestion of Hynes et al. (2005) that the K-band luminosity of V616 Mon has a significant nonstellar component can be rejected. This is not to say, however, that there is no contamination. The presence of He I and H I emission indicates continued accretion, as does the flatter than expected continuum.

4.1. Determination of the K-Band Contamination via Comparison with SS Cygni

Both weak CO features and red continua were common in our infrared spectroscopic survey of long-period CVs (Harrison et al. 2004). *In fact, the slope of SS Cyg's K-band spectrum is very similar to that of V616 Mon.* SS Cyg is a dwarf nova with an orbital period of 6.6 hr whose quiescent accretion rate is

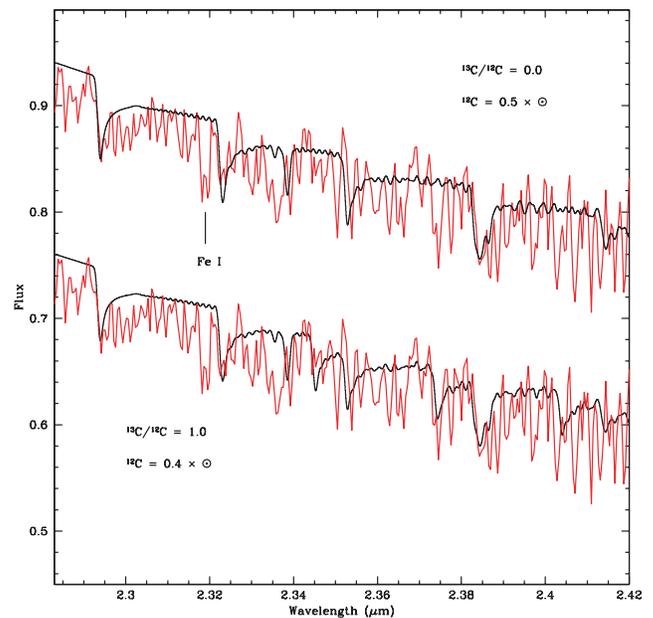


FIG. 3.— Comparison of the spectrum of V616 Mon (red lines) to two model spectra (black lines). The model spectrum on top has 50% of the solar value of ^{12}C and no ^{13}C , while the bottom model has 40% of the solar abundance of ^{12}C and $^{13}\text{C}/^{12}\text{C} = 1.0$. We also identify the location of a strong Fe I feature that can be clearly seen in the template star spectra shown in Figs. 1 and 2.

about $4.8 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$ (Wheatley et al. 2003). This should be compared with an estimated accretion rate for V616 Mon of $\leq 3.0 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$ (McClintock et al. 1983). Along with nearly identical spectra, both secondary stars have similar masses— $0.70 M_{\odot}$ for SS Cyg (Friend et al. 1990) and $0.68 M_{\odot}$ for V616 Mon (Gelino et al. 2001)—and line-of-sight rotation rates of 83 km s^{-1} for V616 Mon (Marsh et al. 1994) and 87 km s^{-1} for SS Cyg (Martinez-Pais et al. 1994). As shown in Figure 4, the *JHKL'* light curves of SS Cyg exhibit ellipsoidal variations of similar amplitude to those observed for V616 Mon (see Fig. 3 in Gelino et al. 2001). The orbital inclinations of the two binaries are also quite similar. Thus, one can make the case that the quiescent accretion rate in V616 Mon might not be too different from that for SS Cyg. The question is by how much does this accretion luminosity actually dilute the ellipsoidal variations of these two objects?

The key to estimating the contamination level requires observations at longer wavelengths, where the flatter continuum component can become dominant over the rapidly falling Rayleigh-Jeans tail of the secondary star. Unfortunately, such data do not yet exist for V616 Mon. If we continue with the analogy with SS Cyg, an object that does have mid-infrared photometry, we can derive both the spectrum and contamination level of its accretion disk emission. In Figure 5 is the *UBVRIJHKL'M* SED of SS Cyg in quiescence from Dubus et al. (2004). In addition, Dubus et al. have used Keck to obtain $11.7 \mu\text{m}$ observations of SS Cyg. It is clear that there is a mild mid-infrared excess above the SED of an isolated K4 V secondary star. We find that the simplest model for the observed SED of SS Cyg is one in which a minor component due to free-free emission is added to the SED of the cool secondary star. If we use the “nonflaring” $11.7 \mu\text{m}$ flux of SS Cyg, we find that the free-free component accounts for 4% of the K-band flux in SS Cyg. (If we include the flaring flux level, the free-free component is responsible for 13% of the K-band luminosity. The origin of this short-timescale flaring has not been identified.) Thus, the ellipsoidal variations of SS Cyg are not significantly

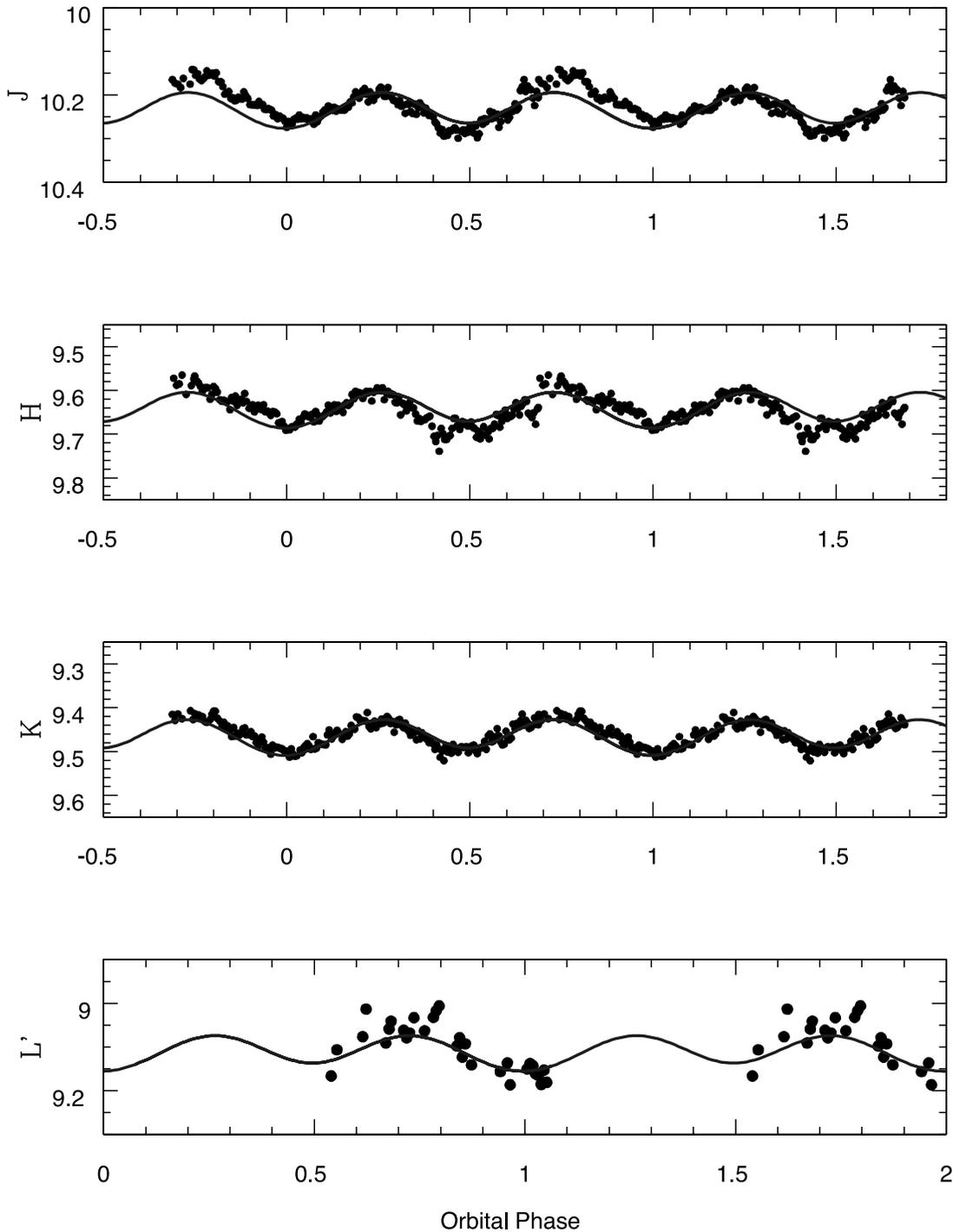


FIG. 4.— $JHKL'$ light curves of SS Cyg obtained using SQUIID on the Kitt Peak National Observatory 2.1 m telescope and NSFCAM on the IRTF. The L' data were obtained at the IRTF in 2004, while the JHK data were obtained in 2003. Obviously, these data were not simultaneous, but a K -band light curve of SS Cyg obtained at the same time as the L' observations revealed ellipsoidal variations of the same amplitude as seen in the SQUIID K -band observations. The solid line is for a model with a K4 V secondary star and an orbital inclination angle of 40° . [See the electronic edition of the *Journal* for a color version of this figure.]

contaminated. Assuming an identical contamination level for V616 Mon and using the model parameters from Gelino et al. (2001), we find that a 4% dilution of the K -band light curve leads to an orbital inclination angle of 44° . This implies a mass for the black hole of $M_1 \geq 9.2 \pm 1.9 M_\odot$. However, it is important to note that the JHK light curves of SS Cyg reveal direct evidence for contamination with significant deviations from the light-curve model and asymmetric minima in both the J and H bands. Such features are not seen in the multipoch data presented by Gelino et al. (2001) but were present in the infrared

light curves published by Froning & Robinson (2001), suggesting some variability in the accretion rate for V616 Mon.

4.2. The Evolutionary History of the Secondary Star in V616 Mon

González Hernández et al. (2004) have discussed the scenarios in which the secondary star could have become polluted by the accretion of supernova (SN) ejecta assuming the currently observed secondary star mass is similar to its initial mass ($M_{2\text{initial}} \leq 1.0 M_\odot$). For their models in which the black hole

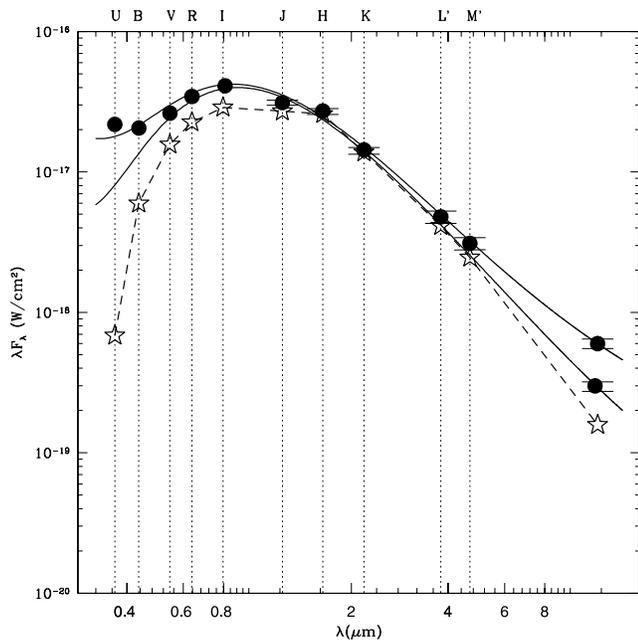


FIG. 5.—SED of SS Cyg (circles) from Dubus et al. (2004) supplemented with our L' photometry from the IRTF (+NSFCAM). The error bars on the infrared data are plotted (the error bars on $UBVRI$ data are $\leq 2\%$ and are not plotted). The SED of a K4 V star, normalized so that it has 96% of the K -band flux of SS Cyg, is represented by the stars. Two blackbody + free-free models are plotted as solid lines. The lower one, fitted to the nonflaring $11.7 \mu\text{m}$ flux of SS Cyg, has 96% of the K -band flux originating in the blackbody component, while the “flaring” flux light curve is normalized so that the blackbody has 87% of the K -band flux.

mass is $M_1 > 11 M_\odot$, they could achieve the Al and Fe abundance enhancements through efficient capture of material enriched by nucleosynthesis in the SN eruption. In those models, however, they did not specifically analyze the carbon abundance but assumed that it would track the enrichment of iron. They did note the possibility that O-, Mg-, and C-enhanced materials might be preferentially ejected in the equatorial plane. Given the observed carbon deficit, the accretion of significant SN ejecta seems less plausible.

In Harrison et al. (2005) we discussed the apparent need for a revision in the evolutionary history of CVs due to our observations of carbon deficits and apparent deficits/enhancements of other species, such as Mg and ^{13}C . In the case of CVs, the secondary stars in the pre-CV binaries were originally proposed to have always been of low mass and be relatively unevolved. However, if higher initial masses are assumed, the observed abundance anomalies could have simply been created through normal evolutionary effects in the secondary star over the lifetime of the binary system. If the initial mass of the secondary star was high enough ($M_{2,\text{initial}} \geq 1.3 M_\odot$) to ignite the CNO cycle, an extended period of mass transfer could have stripped the outer envelope of this object, revealing deeper layers in which the CNO cycle once had been active. Certainly, such a model could also apply to V616 Mon.

The formation and evolution of black hole binaries has been reexamined by Podsiadlowski et al. (2003). They confirm the

results from earlier studies that it is quite difficult to produce short-period binaries containing a black hole and a low-mass secondary star. However, Podsiadlowski et al. found that they could produce substantial numbers of binaries with black hole primaries in models that started with intermediate-mass secondary stars ($2 M_\odot \leq M_{2,\text{initial}} \leq 20 M_\odot$). In addition, for the highest mass secondary stars they found that they could both grow the mass of the black hole and produce a low-mass X-ray binary with a chemically peculiar secondary star, *one that would show evidence for CNO processing*. In such models dramatic increases in the mass of the black hole (of up to $7 M_\odot$) were possible, even though they assumed Eddington-limited accretion. Given our evidence for CNO cycling in the secondary star of V616 Mon, its enhanced abundances of other metals, and the high-mass primary, it seems likely that its secondary began life with a mass substantially larger than what is observed today.

It is critical to determine the level of the nitrogen and ^{13}C enhancements to fully explore the case for CNO cycle-processed material in the secondary star of V616 Mon to derive limits on its initial mass. For CVs, Harrison et al. (2005) noted the strong correspondence between extreme N v/C iv line ratios seen in UV spectra with the observed deficits of carbon seen in infrared spectra. It is interesting to note that the black hole system XTE J1118+480 has an extreme N v/C iv ratio, suggesting that CNO processed material is being transferred to the $\sim 7 M_\odot$ black hole in that system (Haswell et al. 2002). Unfortunately, data of similar quality do not exist for V616 Mon, but our CV analogy suggests that it too should display an extreme N v/C iv ratio. In contrast, the black hole systems GU Mus (Shrader et al. 1993) and J0422+32 (Shrader et al. 1994) appear to have normal N v/C iv line ratios. Thus, we would expect that the secondaries in those systems would have normal CO features and be relatively unevolved. In this way they would be like the secondary stars in the magnetic CVs (“polars”; see Harrison et al. 2005). To explain the dichotomy seen in the secondary stars of magnetic and nonmagnetic CVs, Harrison et al. proposed that there must be two formation channels for those objects. It would be interesting if a similar result were found for close binaries containing black holes. Such a conjecture can be easily tested with further UV and infrared spectroscopy of these systems.

5. CONCLUSIONS

We have obtained a new K -band spectrum of V616 Mon using NIRSPEC on Keck II and find that the secondary star is clearly detected and appears to be a late-type K dwarf with a significant ^{12}C deficit. The weakness of the CO absorption explains the lack of detection of these features in an earlier spectrum, a result that had been used to argue for a significant contamination of the system’s K -band flux. While we do find that there is some contamination of the infrared spectrum in V616 Mon due to continuing accretion, it does not dramatically change previously estimated values for the orbital inclination, and hence the black hole mass for this system remains large. This source warrants further infrared spectroscopy to conclusively determine whether ^{13}C is truly enhanced and UV spectroscopy to investigate the N v/C iv ratio, which is a strong indicator for the transfer of material that has undergone CNO cycle processing.

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