A DYNAMIC STUDY OF THE BLACK HOLE X-RAY BINARY NOVA MUSCAE 1991*

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ABSTRACT

We present a dynamical study of the Galactic black hole binary system Nova Muscae 1991 (GS/GRS 1124–683). We utilize 72 high-resolution Magellan Echelle spectra and 72 strictly simultaneous V-band photometric observations; the simultaneity is a unique and crucial feature of this dynamical study. The data were taken on two consecutive nights and cover the full 10.4 hr orbital cycle. The radial velocities of the secondary star are determined by cross-correlating the object spectra with the best-match template spectrum obtained using the same instrument configuration. Based on our independent analysis of five orders of the echellette spectrum, the semi-amplitude of the radial velocity of the secondary is measured to be \( K_2 = 406.8 \pm 2.7 \) km \( s^{-1} \), which is consistent with previous work, while the uncertainty is reduced by a factor of 3. The corresponding mass function is \( f(M) = 3.02 \pm 0.06 \) \( M_\odot \). We have also obtained an accurate measurement of the rotational broadening of the stellar absorption lines (\( v \sin i = 85.0 \pm 2.6 \) km \( s^{-1} \)), and hence the mass ratio of the system \( q = 0.079 \pm 0.007 \). Finally, we have measured the spectrum of the non-stellar component of emission that veils the spectrum of the secondary. In a future paper, we will use our veiling-corrected spectrum of the secondary and accurate values of \( K_2 \) and \( q \) to model multi-color light curves and determine the systemic inclination and the mass of the black hole.

Key words: binaries: general – black hole physics – stars: black holes – X-rays: binaries

Supporting material: data behind figure

1. INTRODUCTION

Mass is the fundamental parameter for a black hole. According to the no-hair theorem (e.g., Israel 1967; Hawking 1971), mass and spin together provide a complete description of an astrophysical black hole. An accurate measurement of mass is a prerequisite for measuring black hole spin via the continuum-measurement of mass is a prerequisite for measuring black hole spin via the continuum-

We utilize 72 high-resolution Magellan Telescopes located at Las Campanas Observatory, Chile.

* This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.
measuring the mass function:

$$f(M) \equiv \frac{PK^2_i}{2\pi G} = \frac{M \sin^3 i}{(1 + q)^2},$$

where $K_i$ is the semi-amplitude of the velocity curve of the secondary, $i$ is the orbital inclination angle of the binary, and $q$ is the ratio of the companion star mass $M_2$ to that of the compact primary $M$. Three dynamical studies performed in quiescence found a value for the mass function (the minimum mass of the compact primary) of $\approx 3M_\odot$ (Remillard et al. 1992; Orosz et al. 1996; Casares et al. 1997), which is widely considered to be the maximum stable mass of a neutron star (Kalogera & Baym 1996).

Orosz et al. (1994) obtained a quite uncertain estimate of the mass ratio $q \equiv M_2/M$ by measuring the radial velocity of the H$\alpha$ emission line. Casares et al. (1997) made a conventional and direct measurement of the mass ratio by measuring the rotational broadening of the photospheric absorption lines of the secondary; they obtained a result that is consistent with that of Orosz et al. (1994).

The inclination angle $i$ is usually estimated by modeling the ellipsoidal modulation of the light curves of the secondary star after a system has returned to its quiescent state. This modeling is complicated in the case of the short-period systems because the stellar component of light is significantly contaminated by the emission from the accretion disk; this so-called “disk veiling,” can be quite significant ($\gtrsim 50\%$ in the V-band) and variable in “active” quiescent states (Cantrell et al. 2010). Orosz et al. (1996) estimated a disk contribution at $\approx 5000$ Å that could be as high as 50%. Meantime, using different data, Casares et al. (1997) estimated a disk contribution at H$\alpha$ $\lambda 6563$ of 15%, suggesting that disk veiling may be less significant at longer wavelengths. Based on this notion, Gelino et al. (2001) modeled near-infrared ($J$ and $K$) light curves of NovaMus assuming that the disk contribution could be ignored in these bands, and they thereby estimated the systemic inclination to be $i = 54^\circ \pm 17.5^\circ$; their estimate of black hole mass (which also depends on the mass ratio $q$) is $M = 6.95 \pm 0.6 M_\odot$.

These estimates of $i$ and $M$ are quite uncertain because they rest on the assumption that the effects of veiling are negligible in the near-infrared, while there is considerable evidence that it may not be (e.g., Reynolds et al. 2007, 2008; Kreidberg et al. 2012). In this paper, we obtain the first detailed and secure measurement of the spectrum of the non-stellar component of light that veils the stellar spectrum. While this achievement is in part due to the quality and quantity of our data, it is based primarily on the strict simultaneity of our spectroscopic and photometric observations. The simultaneity is crucial because of the aperiodic variability of the non-stellar component. Our two other principal results are a greatly refined measurement of the K-velocity and the first robust measurement of the mass ratio $q$, which differs significantly from the earlier estimates mentioned above.

This paper is structured as follows. Observations and data reduction are described in Section 2. We derive the mass function via a radial velocity analysis in Section 3. The mass ratio is determined via rotational broadening in Section 4. The disk veiling is also measured in this section. The light curve of NovaMus is presented in Section 5. Finally, we discuss our results in Section 6. The light curve modeling and the determination of the inclination and black hole mass will be presented in a subsequent paper.

2. OBSERVATION AND DATA REDUCTION

2.1. Magellan Echellette (MagE) Spectroscopy

The spectroscopic data were obtained using the MagE spectrograph (Marshall et al. 2008) mounted on the 6.5-m Magellan/Clay Telescope at the Las Campanas Observatory (LCO) in Chile. All the data were taken on the nights of 2009 April 25–26 UT. A total of 72 spectra were obtained, each with an integration time of 600 s. During the same two nights, and with the same setup, we obtained spectra of 38 stars, principally K dwarfs, that serve as radial velocity templates. The seeing was similar on both nights, with a typical value of $\approx 0^\prime.7$ and a range of $0^\prime.5$–1.3. Each MagE spectrum consists of 15 orders (corresponding to sequence numbers #6–20). The full wavelength coverage of the instrument is 3100–11000 Å, with order #20 at the blue end (central wavelength 3125 Å) and order #6 at the red end (central wavelength 9700 Å). The spatial scale is $\approx 0^\prime.3$/pixel. The spectral dispersion increases from 0.2 Å per pixel for order #20 to 0.7 Å per pixel for order #6, while the velocity dispersion is 22 km s$^{-1}$ per pixel for all orders. For our chosen 0.85 slit, the spectral resolution is $\approx 1$ Å at 5000 Å, corresponding to $\approx 60$ km s$^{-1}$.

The MagE data were reduced using the pipeline developed by Carnegie Observatories,11 which performs bias correction, flat-fielding, and wavelength calibration. The bias was corrected using the overscan region of the detectors. Three sets of flats were utilized in the calibration: (1) order definition flats taken with the Xe-flash lamps; (2) blue flats to define the flat field at the blue end of a spectrum (also taken with the Xe-Flash lamps); and (3) red flats to define the flat field at the red end of a spectrum and to correct the fringing, which were taken with the Qf lamps. The wavelength calibration was performed using arc spectra obtained with Thorium–Argon lamps. The rms residual of the wavelength solution is $< 0.05$ Å for orders #8–18 and <0.1 Å for the remaining orders. The performance of wavelength calibration was examined using sky emission lines; the relative wavelength offset is negligible.

The mean MagE spectrum of NovaMus in the observer’s rest-frame is shown in Figure 1, which covers spectra that span orders #9–14 ($\approx 4300$–7000 Å). The spectrum in each order was normalized by a fifth-order polynomial. In the analysis that follows, we mainly use the data in these orders because of their good signal-to-noise ratio (S/N) and general lack of sky emission lines and telluric absorption features (relative to redder orders). The most prominent features in the spectrum are the broad, double-peaked Balmer lines H$\alpha$ $\lambda 6563$, H$\beta$ $\lambda 4861$ and H$\gamma$ $\lambda 4341$, which are the canonical signatures of a black hole accretion disk. Also present are broad disk lines of He, notably He I $\lambda 5875$. Other features such as Na D $\lambda \lambda 5890$–5896, diffuse interstellar bands (DIBs) at $\lambda \lambda 5780$, $\lambda 6280$, and telluric features redward of $\lambda 6850$ are also evident.

2.2. Optical Photometry

Photometric data were obtained during the same observing run using the du Pont 2.5 m telescope, which is also located at LCO. Seventy-two V-band images were acquired; by design, each 10 min exposure was strictly simultaneous (time

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11 See http://code.obs.carnegiescience.edu/mage-pipeline.
The typical seeing was ≈0″.7 (with a range of 0″.6–1″.1). We used the 2048 × 2048 Tek#5 CCD, which provided a field of view of 8′.85 × 8′.85 at 0″.259 per pixel. Bias correction and flat-fielding were performed with standard IRAF tasks (zerocombine, flatcombine, and ccdproc). The centroid of the optical counterpart was determined using the CIAO routine wavdetect (Freeman et al. 2002), and the quality of the centroiding was confirmed visually. Aperture photometry was performed using the IDL procedure aper. The radius of the aperture was fixed to eight pixels (2″1), which is the largest aperture that securely excludes significant contamination of NovaMus by a faint field star. Choosing a smaller aperture (e.g., ~5 pixels) would provide very similar results. We first produced a light curve of NovaMus relative to nearby field stars and then derived an absolute calibration relative to a pair of nearby (24″ and 41″) standard stars. Our estimate of the uncertainty in the zero-point is 0.05 mag.

3. RADIAL VELOCITY ANALYSIS

The radial velocity $K_2$ of the secondary star was determined by sequentially cross-correlating the 72 object spectra with the spectrum of a template star. This was done in turn for individual echellette orders, rather than using a single merged spectrum. The best quality results were obtained for order #12 (covering ~4700–5500 Å), as expected since strong stellar absorption features are present in this order (e.g., the Mg features at ~5200 Å region), and it is relatively free of contaminating telluric and interstellar features.

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**Figure 1.** Mean MagellanMagE spectrum of NovaMus in the observer’s rest frame, covering MagE orders #9–14 (4000–7000 Å). Broad and double-peaked Balmer lines (Hα, Hβ, Hγ, and Hδ) are prominent in the spectrum. He i λ5875 emission is also evident. The weak, broad emission features redward of Hγ and Hδ are likely to be He i λλ4471 and 6678, respectively. The Na D λλ5890–5896 doublet, DIB features at λ5780 and 6280 (which also has a strong telluric component), as well as the telluric feature at 6860 are also labeled. The NovaMus spectrum covering the full MagE wavelength range (~3000–10000 Å) is available in the online journal in electronic form.

(The data used to create this figure are available.)

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12 The only exception is the first image whose exposure time was only 60 s.
Figure 2. Average TDR value of the cross-correlation between the spectrum of each template star and NovaMus for order #12, plotted against the B − V color of the star. The template star with the highest average TDR value is HD 170493, with B − V = 1.11, which corresponds to a spectral type of K5 with $T_{\text{eff}} \approx 4400$ K, based on the scale of B − V color vs. $T_{\text{eff}}$ vs. Spectral type, which is shown at the top of the figure.

3.1. Choosing the Best Template Spectrum

The cross-correlation analysis was performed using the software package fxcor as implemented in the IRAF package. The task fxcor returns the parameter $K$ defined by Tony & Davis (1979; TDR hereafter) provides an estimate of S/N: the higher the TDR value, the better the quality of the cross-correlation. From among our dozens of template spectra, we chose the one that gives the highest TDR value, while focusing on the NovaMus data for order #12. Specifically, we: (1) selected a K-type template spectrum that gives relatively high values of TDR and cross-correlated it against the 72 spectra of NovaMus; (2) we velocity-shifted all the NovaMus spectra to the rest frame of the template star and summed them; (3) we then cross-correlated this summed spectrum against all of our template spectra in turn and selected the template spectrum that yielded the maximum TDR value.

The results of this analysis are summarized in Figure 2, which shows how TDR varies among the template stars, which we have ordered by their B − V color given in the SIMBAD database; we regard the photometric color as a more accurate measure of the effective temperature than the spectral type (that is given in the same database). The star at the peak of this ordered distribution and having the maximum TDR is HD 170493 with B − V = 1.11, corresponds to an effective temperature $T_{\text{eff}} \approx 4400$ K (Allen’s Astrophysical Quantities, 4th edn.; Cox 2002). We therefore choose HD 170493 as the master template for our cross-correlation analysis. Potential systematic effects related to this choice of template are discussed in Section 6.1.

3.2. Fitting the Radial Velocity Curve

With HD 170493 as the template, we first cross-correlated each of the 72 spectra for order #12. For both the object and template spectra, we masked out the region around the H/β emission line, and also ~100 Å at both ends of each order because the S/N in these regions is poor. We furthermore required that the TDR value for a correlation exceed 2.5 (similar to the criterion in Orosz et al. 1996). All 72 spectra for order #12 delivered reliable measurements of radial velocity, as illustrated in the middle-right panel of Figure 3. We fitted the radial velocity curve with the following model,

$$V(t) = \gamma + K_2 \cos \left( 2\pi \frac{t - T_0}{P} \right).$$

where $\gamma$ is the systemic velocity of the in-helioentric frame, $t$ is the observation time in Heliocentric Julian Days, and $T_0$ is the time of maximum radial velocity; the radial velocity we used for the template star HD 170493 is $\gamma_0 = -55.07 \pm 0.07$ km s$^{-1}$. We initially fixed the orbital period to the spectroscopic value given by Orosz et al. (1996), $P = 0.43260249(9)$ days. Then, using our value of $T_0$ and the one in Orosz et al. we obtained a refined value of the orbital period: $P = 0.43260249(9)$ days. This period and other best-fit parameters are listed in Table 1.

As a check on our value for the $K$-velocity, we performed an independent analysis using the xcor procedure in the molly package developed by T. Marsh in place of fxcor in IRAF. We again analyzed only the data for order #12 and used the same template spectrum (HD 170493) as before. Both the object and template spectra were rebinned to the same velocity dispersion using the vbin procedure, and were normalized using a fifth-order polynomial, as required by the xcor procedure. Fitting a Gaussian to the profile of the cross-correlation function using the molly procedure mgfit, we obtained values for both the $K$-velocity and its uncertainty ($K_2 = 402.9 \pm 1.3$ km s$^{-1}$) that are consistent with those obtained using the IRAF routines.

In order to obtain a more precise value of $K_2$, we analyzed data for orders #10 and #11 (which lie to the red of order #12) and orders #13 and #14, again masking out ~100 Å at both ends of each order; the wavelength ranges of the orders are given in Table 1. As before, we masked out disk emission lines (mainly Balmer lines), and we also masked out a number of strong telluric and interstellar features, which are listed in Table 1. As was the case for order #12 discussed above, all 72 object spectra for order #10 yielded reliable measurements of radial velocity (i.e., TDR > 2.5); the radial velocity curve for this order is shown in Figure 3. For the other three orders, some object spectra were rejected because: (1) the TDR value for the correlation was $\leq 2.5$; (2) the fit to the cross-correlation peak did not converge; or (3) the value obtained for the radial velocity lies more than $\geq 3\sigma$ away from the fitted curve. The velocity data for each order individually were fitted to the same model used for order #12 (Equation (2)). For each of the five orders, Table 1 lists the best-fit parameters, values of reduced $\chi^2$ and the number of useful spectra. Using precisely the velocity uncertainties returned by fxcor, we obtain good fits for all five orders, with $\chi^2$/ν values that are close to unity. We note that there are small differences among the best-fit parameters at the level of $\sim 3$–4σ level.

Table 2 provides a summary of the orbital parameters. The error-weighted mean of $K_2$ among the five orders is 406.8 ± 2.2 km s$^{-1}$. After including our estimate of the systematic error

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13 We assume that the reddening of these template star can be ignored due to their proximity to the Sun (≤100 pc).

14 See http://deneb.astro.warwick.ac.uk/phsaap/software/molly/html/INDEX.html.

15 Only five data points in all five orders lie $\geq 3$–4σ away from the fitted curve; removing these radial velocity points does not significantly change the fitted values of the parameters.
Figure 3. Radial velocities of NovaMus relative to the spectral template HD 170493, in MagE orders #9–14. The best-fit radial velocity curves and residuals for each order are shown.
Average 406.8 ± 2.2 14.2 ± 2.1 46.90278 ± 0.00042

Note. The quoted uncertainties are at the 1σ level of confidence.

The best-fit parameters for order #9 were not included in calculating the average parameter values; for this order, the wavelength ranges 6820–7020 Å and 7150–7200 Å were masked to avoid strong telluric absorption features and sky emission lines.

### Table 2

| Parameter | Value |
|-----------|-------|
| Orbital period $P$ (days) | 0.43260249 ± 0.00000009 |
| $K_2$ velocity (km s$^{-1}$) | 406.8 ± 2.7 |
| $\gamma$ velocity (km s$^{-1}$) | 14.2 ± 6.3 |
| $T_{\text{orb}}$ spectroscopic (HD-2454900) | 46.90278 ± 0.00062 |
| Mass function $f(M)$ ($M_\odot$) | 3.02 ± 0.06 |
| $\nu$ sin $i$ (km s$^{-1}$) | 85.0 ± 2.6 |
| Mass ratio $q$ | 0.079 ± 0.007 |

Note. The quoted uncertainties are at the 1σ level of confidence and include an allowance for systematic error; see Section 6.1.

(see Section 6.1), we obtain for the radial velocity semi-amplitude $K_2 = 406.8 ± 2.7$ km s$^{-1}$. Using this value of $K_2$, the orbital period $P$ (Table 2) and Equation (1), we derive a precise value for the mass function of $f(M) = 3.02 ± 0.06 M_\odot$, thereby confirming the black hole nature of the compact object.

In addition to orders #10–14, and because the residual spectrum of order #12 line and the DIB at λ6280, the only clear spectral feature in NovaMus contains contributions from both the secondary (numerous rotationally broadened absorption features) and the accretion disk (broad disk emission lines like Hα). The best-match template spectrum will have virtually the same set of absorption features as NovaMus; however, the features in the object spectrum will be shallower because they are diluted by the disk continuum emission. In obtaining the best match of a given template spectrum to the object spectrum, one repetitively performs a pair of operations. First, one broadens the narrow-line template spectrum, and then multiplies the spectrum by the factor $f_{\text{star}}(0 \leq f_{\text{star}} \leq 1)$, which represents the fraction of the light contributed by the secondary. Finally, one subtracts the trial template spectrum from the spectrum of NovaMus and determines quantitatively (see below) the template spectrum that is freest of photospheric absorption features. The results of such an analysis for two orders are shown in Figure 4. The residual spectrum for order #10 (upper panel) only shows the broad Hα disk line and the DIB at λ6280. The only clear spectral feature in the residual spectrum of order #12 (Figure 4; lower panel) is the Fe II multiplet 42 at λ4924, λ5018, and λ5169 (Moore 1972), a feature that is also present in the spectra of A0620–00 (Marsh et al. 1994) and the neutron-star transient EXO 0748–676 (Ratti et al. 2012).

In practice, we use the spectrum of our velocity-template star HD 170493 and the phase-averaged spectra of NovaMus for each order to increase the S/N. Before averaging the spectra for a given order, we shifted the individual spectra to the rest frame of HD 170493 using the data in Table 1. We first broadened the template spectrum using a grid of trial values from 5 to 300 km s$^{-1}$ in steps of 5 km s$^{-1}$. We also artificially smeared the template spectrum using the appropriate phase and integration time in order to simulate the velocity smearing during an observation of NovaMus. A $\chi^2$ test was performed on the residual spectrum to determine a minimum and the corresponding approximate value of $v \sin i$. Now, starting with this

4. ROTATIONAL VELOCITY AND DISK VEILING MEASUREMENTS

4.1. Rotational Broadening and Mass Ratio

As the next step toward measuring the mass of the black hole, we obtain a precise estimate of the mass ratio $q$. For a short-period, mass-exchange binary like NovaMus, one can quite confidently assume that the system is tidally locked and that the secondary fills its Roche lobe (Wade & Horne 1988). In this case, $q$ can be simply determined by measuring the rotational broadening of the stellar photospheric lines. Specifically, one measures the radial component of the rotational velocity of the secondary star, $v \sin i$, and uses the following equation (Wade & Horne 1988),

\[
\frac{v \sin i}{K_2} = 0.462 q^{1/3} (1 + q)^{2/3}. \tag{3}
\]

In measuring $v \sin i$ we use the method of optimal subtraction. Figure 4 illustrates the principle of the method using the data for orders #10 and #12. Before doing the optimal subtraction, we first normalized both the object and template spectra using a 5th-order polynomial. The spectra of NovaMus contains contributions from both the secondary (numerous rotationally broadened absorption features) and the accretion disk (broad disk emission lines like Hα). The best-match template spectrum will have virtually the same set of absorption features as NovaMus; however, the features in the object spectrum will be shallower because they are diluted by the disk continuum emission. In obtaining the best match of a given template spectrum to the object spectrum, one repetitively performs a pair of operations. First, one broadens the narrow-line template spectrum, and then multiplies the spectrum by the factor $f_{\text{star}}(0 \leq f_{\text{star}} \leq 1)$, which represents the fraction of the light contributed by the secondary. Finally, one subtracts the trial template spectrum from the spectrum of NovaMus and determines quantitatively (see below) the template spectrum that is freest of photospheric absorption features. The results of such an analysis for two orders are shown in Figure 4. The residual spectrum for order #10 (upper panel) only shows the broad Hα disk line and the DIB at λ6280. The only clear spectral feature in the residual spectrum of order #12 (Figure 4; lower panel) is the Fe II multiplet 42 at λ4924, λ5018, and λ5169 (Moore 1972), a feature that is also present in the spectra of A0620–00 (Marsh et al. 1994) and the neutron-star transient EXO 0748–676 (Ratti et al. 2012).

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approximate value, we repeated the procedure with a trial grid extending from 60 to 120 km s\(^{-1}\) in steps of 1 km s\(^{-1}\). Making use of the \texttt{rbroad} and \texttt{optsub} tasks in the \textsc{molly}, curves of \(v \sin i\) versus \(\chi^2\) were generated (see Figure 5) and fitted with a third-order polynomial; our adopted value of \(v \sin i\) corresponds to the minimum of the fitted curve. All the emission lines, interstellar features, and telluric features are masked out during the optimal subtraction.

The effect of limb darkening needs to be properly considered in the optimal subtraction. Since this effect varies with wavelength, we calculated a linear limb darkening coefficient for each order of the MagE spectra based on the data given by Claret et al. (2012). We retrieved from their table the limb darkening coefficients for the \textit{UBVRI} bands. For the effective temperature of the companion star, we adopted the value \(T_{\text{eff}} = 4400\) K. The star’s surface gravity \(\log g\) (in cm s\(^{-1}\)) is securely in the range 4.0–4.5, and for each band we adopted the average of the tabulated values of the limb darkening coefficient for \(\log g = 4.0\) and \(\log g = 4.5\). Finally we linearly interpolated between the \textit{UBVRI} bands using the central wavelength of each order, thereby obtaining the values we adopt for the limb darkening coefficients (see the third column in Table 3), which range from 0.71 (Order #9) to 0.91 (Order #14).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Results of applying the optimal subtraction procedure for order #10 (upper panel) and order #12 (lower panel). Each panel contains the average normalized spectrum of NovaMus, the normalized spectrum of the template star HD 170493, and the residual spectrum after optimal subtraction. The H\(\alpha\) emission line and strong DIB feature are labeled for order #10. The upper panel also contains the averaged H\(\alpha\) emission line in the observer’s frame, which shows the characteristic double-peaked profile. The Fe II multiplet 42 features in the residual spectrum of order #12 are labeled in the lower panel. All the spectra are smoothed with a 5 pixel boxcar for the purpose of presentation.}
\end{figure}
As a check on the robustness of our measured values of \( v \sin i \) we adopted an uncertainty for systematic uncertainty, related to the choice of template spectrum and the limb darkening coefficient (see Section 6.1), our final adopted value is \( v \sin i = 85.0 \pm 2.6 \text{ km s}^{-1} \). Using this value and our \( K \)-velocity for the secondary (\( K_2 = 406.8 \pm 27.3 \text{ km s}^{-1} \); Section 3.2), and Equation (3), we obtain for the mass ratio the value \( q = 0.079 \pm 0.007 \). Using this mass ratio and the value of the mass function given in Section 3.2, the masses of the black hole and secondary star are \( M = 3.52 \pm 0.07 \text{ (sin}^3 i \text{) M}_\odot \) and \( M_2 = 0.28 \pm 0.03 \text{ (sin}^3 i \text{) M}_\odot \), respectively.

### 4.2. Disk Veiling

The disk veiling factor \( f_{\text{disk}} \), i.e., the fraction of the total light that is non-stellar, is also determined by the optimal subtraction method. For each order, we first broaden the HD 170493 template spectrum using the values of \( v \sin i \) determined in Section 4.1, and then optimally subtract it from the spectrum of NovaMus. The procedure gives the fraction of light due to the secondary star, \( f_{\text{star}} \), for the template spectrum that corresponds to the minimum value of \( \chi^2 \). The disk veiling factor is then simply \( f_{\text{disk}} = 1 - f_{\text{star}} \). As in determining \( v \sin i \) we computed \( f_{\text{disk}} \) using for each order the averaged, rest-frame spectrum of NovaMus. The values we adopt for the disk veiling factor for the six orders are indicated in Figure 6 by dotted lines and are listed in the last column of Table 3.

As a check on the robustness of our measured values of \( f_{\text{disk}} \), we repeated the optimal subtraction procedure for each spectrum individually, using only those spectra that produced...
A reliable measurement of radial velocity (see Section 3). A histogram of $f_{\text{disk}}$ for each order is shown in Figure 6; the dashed line in each panel represents the weighted mean value of the disk veiling factor. These alternative measurements of $f_{\text{disk}}$ are consistent within $\sim 1\sigma$ (for all orders) with the values determined as described above using the phase-averaged spectra. We note that for five of the six orders $f_{\text{disk}}$ is greater than 0.5, i.e., the disk is brighter than the secondary star.

Figure 6 indicates that the disk veiling factor generally decreases with increasing wavelength, i.e., the disk veiling is less significant for redder wavebands. However, this does not necessarily mean that disk veiling can be ignored, even in the $J$ and $K$ bands, as claimed by Gelino et al. (2001) and others. We utilize a simplistic spectral energy distribution (SED) model and an extrapolation to illustrate this point (see Figure 7). Our crude SED by no means represents an accurate model of the disk emission. For the stellar component, we assumed blackbody emission at 4400 K (red line in Figure 7; see Section 3 and Figure 2), and we then computed the relative disk flux in each order (filled blue squares) based on our measurements of $f_{\text{disk}}$. We fitted these estimates of disk flux using a power-law model to represent the SED of the disk component and then extrapolated the power law into the near-infrared (dashed blue line).

At shorter wavelengths, the disk component does indeed decrease rapidly with increasing wavelength so that the stellar component becomes dominant as one approaches the $R$ band. However, at longer wavelengths the blackbody component begins to fall rapidly, and disk veiling reaches a minimum
at around 1 μm and then begins to increase. For our data and this crude model, we estimate that \( f_{\text{disk}} \) for the \( I, J, H, K \) bands is in the range of 40%–60% (see the black dotted lines in Figure 7), which is consistent with the estimates of Reynolds et al. (2008) for NovaMus of 40%–50% in the near-infrared. We note that \( f_{\text{disk}} \) in the near-infrared could be lower than our estimate if the disk component of emission has a thermal spectrum that falls below the extrapolated power-law spectrum, which we assume. However, we conclude that it is not warranted to assume that the effects of veiling are negligible in the near-infrared.

5. LIGHT CURVE

Our calibrated and phase-folded V-band light curve, which was obtained in exposures that obtained simultaneously with the spectroscopic exposures (see Section 2.2), is shown in Figure 8. Zero photometric phase, which is equivalent to 0.75
spectroscopic phase, corresponds to the inferior conjunction of the secondary. Two versions of the light curve are shown, unbinned and binned into 20 phase bins, each with 3–4 data points per bin.

During our observations, NovaMus was \( \sim 0.5 \) magnitude brighter on average in the \( V \) band than it was in earlier photometric monitoring campaigns (e.g., during 1992–1995, as reported by Orosz et al. 1996). Our \( V \) band light curve shows substantial aperiodic flickering (see Section 6.2). Nevertheless, the phase-binned light curve exhibits the characteristic signatures of ellipsoidal modulation, with two minima at phases \( \sim 0.0 \) and \( \sim 0.5 \) and two maxima at phases \( \sim 0.25 \) and \( \sim 0.75 \). The two maxima do not have equal amplitude as one would expect for an ideal ellipsoidal modulation, which could be caused by a hot spot in the accretion disk. Such unequal maxima have frequently been observed in the light curves of other black hole binaries in quiescence, e.g., A0620–00 (McClintock & Remillard 1986; Cantrell et al. 2010).

6. DISCUSSION

6.1. Assessment of Systematic Uncertainties

We identify sources of systematic error, and obtain estimates of their magnitude, first for the orbital parameters \( K_2 \) and \( T_0 \) and the systemic velocity \( \gamma \), and then for the rotational velocity \( v \sin i \).

6.1.1. Orbital Parameters and Systemic Velocity

We first consider the uncertainty associated with the choice of template spectrum. While we chose the spectrum of HD 107493 because it gave the maximum TDR (Section 3.1), obviously this spectrum is not identical to that of the Roche-lobe-filling companion star. Focusing on the high-quality data for order #12, we repeated our analysis for six other template spectra with TDR values >60 (see Figure 2); the results are summarized in Table 4. The spread in the values of \( K_2 \) is <0.8 km s\(^{-1}\), which is significantly smaller than the statistical uncertainty. As our estimate of the systematic error in \( K_2 \) associated with the choice of the template, we take the standard deviation of the seven values of \( K_2 \), which is 0.3 km s\(^{-1}\). In like manner, we obtain estimates of systematic error of 4.2 km s\(^{-1}\) for \( \gamma \), and of 0.00013 days for \( T_0 \).

A second source of systematic uncertainty is the effect of the different widths of the photospheric lines for NovaMus which are rotationally broadened, and for the slowly rotating template star, which are narrow. To assess this effect, we broadened the lines of our chosen template (HD 107493) to 85 km s\(^{-1}\) (Section 4.1) and repeated the radial velocity analysis. The change in \( K_2 \) is 0.5 km s\(^{-1}\) (Table 4), which we adopt as our estimate of systematic error; we obtain similar estimates of systematic error for \( \gamma \) and \( T_0 \) of 0.8 km s\(^{-1}\) and 0.00020 days, respectively.

For each of the three parameters in question, we obtain our final estimate of error, which is given in Table 2, by linearly adding the larger of the two systematic errors discussed above onto the statistical error obtained in Section 3.2 (given in Table 1).

6.1.2. Rotational Velocity

We identify two sources of systematic uncertainty for \( v \sin i \), namely, the value adopted for the limb darkening coefficient and the choice of template spectrum. Again, using the data for order #12, we considered an uncertainty of \( \pm 0.1 \) in our adopted value of 0.845 (Table 3) and find that this corresponds to an uncertainty of \( \pm 1.5 \) km s\(^{-1}\) (see Table 5). We then compared values of \( v \sin i \) derived using once again the six template spectra with TDR values >60. For each template spectrum, we used the appropriate limb darkening coefficient (Claret et al. 2012) based on the \( B-V \) color and corresponding effective temperature of the star. The standard deviation for the six values of \( v \sin i \) is 1.2 km s\(^{-1}\). Using these two estimates of systematic error as a guide, we allow for systematic error by simply doubling the statistical error bar obtained in Section 4.1 (1.3 km s\(^{-1}\)). Our final adopted value of \( v \sin i \) given in Table 2, is therefore 85.0 \( \pm 2.6 \) km s\(^{-1}\).

| Templates (Order #12) | \( B-V \) | Template \( \gamma \) | TDR | \( K_2 \) | \( \gamma \) | \( T_{\gamma-2454000} \) | No. of Object Spectra | \( \chi^2/\nu \) |
|-----------------------|----------|---------------------|-----|--------|--------|-------------------|---------------------|----------|
| HD 147776             | 0.95     | 7.4 ± 0.1           | 60.8| 402.0 ± 2.7 | 17.1 ± 2.0 | 46.90339 ± 0.00044 | 72                  | 0.83     |
| HD 130992             | 1.02     | −57.1 ± 0.1         | 64.1| 401.9 ± 2.7 | 10.9 ± 2.0 | 46.90333 ± 0.00044 | 72                  | 0.79     |
| HD 31560              | 1.09     | 6.4 ± 0.1           | 74.3| 401.6 ± 2.7 | 11.4 ± 2.0 | 46.90332 ± 0.00044 | 72                  | 0.81     |
| HD 170493             | 1.11     | −55.1 ± 0.1         | 78.4| 401.2 ± 2.6 | 9.7 ± 1.9  | 46.90327 ± 0.00044 | 72                  | 0.87     |
| HD 170493 (broadened) | 1.11     | −55.1 ± 0.1         | 76.7| 401.7 ± 3.0 | 10.5 ± 2.2 | 46.90347 ± 0.00050 | 72                  | 0.60     |
| HD 131977             | 1.11     | 26.8 ± 0.1          | 65.9| 401.6 ± 2.7 | 10.9 ± 2.0 | 46.90326 ± 0.00045 | 72                  | 0.79     |
| HD 156026             | 1.16     | 0.1 ± 0.1           | 61.6| 401.9 ± 2.8 | 4.6 ± 2.0  | 46.90344 ± 0.00046 | 72                  | 0.87     |
| HD 120467             | 1.26     | −37.8 ± 0.1         | 63.1| 401.9 ± 2.8 | 5.5 ± 2.1  | 46.90365 ± 0.00047 | 72                  | 0.79     |

| Template              | \( B-V \) | \( u \) (limb darkening) | \( v \sin i \) (km s\(^{-1}\)) |
|-----------------------|----------|--------------------------|----------------------------------|
| HD 170493             | 1.11     | 0.845                    | 82.8 ± 3.5                      |
| HD 170493             | 1.11     | 0.745                    | 81.7 ± 3.6                      |
| HD 170493             | 1.11     | 0.945                    | 84.3 ± 3.7                      |
| HD 147776             | 0.95     | 0.823                    | 82.9 ± 4.6                      |
| HD 130992             | 1.02     | 0.842                    | 82.3 ± 4.5                      |
| HD 31560              | 1.09     | 0.845                    | 82.4 ± 4.2                      |
| HD 131977             | 1.11     | 0.845                    | 82.3 ± 4.0                      |
| HD 156026             | 1.16     | 0.835                    | 83.8 ± 4.3                      |
| HD 120467             | 1.26     | 0.796                    | 85.5 ± 5.2                      |

Note. The quoted uncertainties are at the 1\( \sigma \) level of confidence.
6.2. Comparison to Previous Work

We have obtained precise measurements of the mass function $f(M)$ and mass ratio $q$ for NovaMus using multi-order echellette spectral data obtained with Magellan/MagE. Compared to the data analyzed in previous work (e.g., Orosz et al. 1996 and Casares et al. 1997), our spectra have higher spectral resolution (by a factor of $\approx 3-5$) and provide more complete phase coverage. We also observed many more template stars (38), all of them during the same observing run, which has enabled us to choose a template spectrum that is an exceptionally close match to the spectrum of NovaMus. Analyzing data independently for several orders is also a feature of our work. All of these beneficial factors have contributed to quality of our work.

Our value for the radial velocity amplitude ($K_2 = 406.8 \pm 2.7$ km s$^{-1}$) is very close to that obtained by Orosz et al. (1996; $K_2 = 406 \pm 7$ km s$^{-1}$), while the uncertainty has been reduced significantly. Meanwhile, our $K_2$ value is barely consistent with that of Casares et al. (1997; $K_2 = 420.8 \pm 6.3$ km s$^{-1}$), differing by $\approx 2\sigma$. We have substantially increased the precision of the orbital period (by a factor of $>30$) by extending the baseline of observations from those made earlier (Remillard et al. 1992; Orosz et al. 1996) out to our observations in 2009.

Our mass ratio ($q = 0.079 \pm 0.007$) agrees with the approximate value ($0.0476 < q < 0.0833$) found by Antokhina & Cherepashchuk (1993), which was obtained by modeling an $I$-band light curve. It is significantly smaller than the less reliable estimate of $q = 0.133 \pm 0.019$ obtained by Orosz et al. (1997; see Section 1). Casares et al. (1997), who used the same direct method of measurement we used, likewise obtained a mass ratio greater than ours, $q = 0.13 \pm 0.04$. (Their estimate of the rotational broadening is $v \sin i = 106 \pm 13$ km s$^{-1}$ compared to our value of $v \sin i = 85.0 \pm 2.6$ km s$^{-1}$.) The relative virtues of our measurement is our better spectral resolution ($\approx 60$ km s$^{-1}$ at $\sim 5000$ Å) and our ample selection of template spectra, which allowed us to closely match the spectrum of the donor star; Casares et al. had applied a single template spectrum of a K0V star.

An important feature of our work is the simultaneity of the spectroscopic and photometric observations, which allows one to accurately correct for the effects of disk veiling, despite the aperiodic variability of the non-stellar component of light. Unfortunately, during our observation NovaMus was in an “active” quiescent state (Cantrell et al. 2008), and the light curve is strongly affected by aperiodic flickering and does not provide a useful constraint on the inclination angle. Nevertheless, our simultaneous observations provide very secure measurements of the disk veiling factor at six wavelengths. In a subsequent paper, we will use these data in conjunction with light curves available in the literature, which were obtained in the “passive” quiescent state (Cantrell et al. 2008) to constrain the inclination angle and black hole mass.

6.3. The Li $\lambda$ 6708 Feature

The Li $\lambda$ 6708 absorption line was previously detected in the spectra of NovaMus (Martín et al. 1996). This feature also appears in the spectra of other similar black hole soft X-ray transients like A0620–00 (Marsh et al. 1994) and GS 2000+25 (Filippenko et al. 1995). This feature is potentially relevant in exploring the Li production mechanism around a black hole (Martín et al. 1994). Meanwhile, the variation of the line intensity with orbital phase may reveal effects of irradiation on the formation of the Li feature (Martín et al. 1996).

We find that the Li $\lambda$ 6708 line is marginally detected in the phase-averaged spectrum of NovaMus and also in the residual spectrum after optimal subtraction (Figure 9). We find an
equivalent width of EW(Li) = 210 ± 60 mÅ, after correcting for the disk veiling in order #9, for the NovaMus spectrum averaged over the full orbital phase. Following Martín et al. (1996), we investigated the variation of the EW(Li) with orbital phase (see the inset plot of Figure 9). At zero photometric phase ($\phi > 0.75$ or $\phi < 0.25$), we obtained EW (Li) = 550 ± 90 mÅ, which is slightly higher than the value in Martín et al. (1996; 420 ± 60 mÅ). The Li $\lambda 6708$ feature is not detected at photometric phase 0.5 ($0.25 < \phi < 0.75$), which agrees with the findings in Martín et al. (1996). We note that our EW(Li) for NovaMus is slightly higher (within 1σ) than the value reported for A0620–00 of EW = 160 ± 30 mÅ by Marsh et al. (1994).

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Facility: Magellan:Clay, (Magellan Echellette Spectrograph), du Pont

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