A Black Hole in the X-Ray Nova Velorum 1993

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ABSTRACT. We have obtained 17 moderate-resolution (~2.5 Å) optical spectra of the Galactic X-ray Nova Velorum 1993 in quiescence with the Keck II telescope. Cross-correlation with the spectra of late-type dwarfs (especially K7–M0) yields excellent radial velocities for the secondary star. The orbital period (P) is 0.285206 ± 0.0000014 days, and the semiamplitude (K2) is 475.4 ± 5.9 km s⁻¹. We derived the mass function, f(M₁) = PK₁²/2πG = 3.17 ± 0.12 M☉, is close to the conventional absolute limiting mass for a neutron star (~3.0–3.2 M☉)—but if the orbital inclination i ≤ 80° (given the absence of eclipses), then M₁ ≥ 4.2–4.4 M☉ for nominal secondary-star masses of 0.5 M☉ (M0) to 0.65 M☉ (K6). Even if the secondary is quite undermassive (e.g., M₂ = 0.3 M☉), we derive M₁ ≥ 3.9 M☉. The primary star is therefore almost certainly a black hole rather than a neutron star.

Fits to the wings of the double-peaked Hα emission line yield approximate radial velocities for the compact primary. The velocity curve has a semiamplitude (K₁) of 65.3 ± 7.0 km s⁻¹, but with a phase offset by 237° (rather than 180°) from that of the secondary star. Under the assumption that the observed semiamplitude reflects the motion of the primary (despite this offset, which is common), the mass ratio q = M₂/M₁ = K₁/K₂ = 0.137 ± 0.015, and hence for M₂ = 0.5–0.65 M☉ we derive M₁ = 3.64–4.74 M☉. The constraints from q and the mass function yield M₁ = 4.4 M☉ and i ≈ 78° if we use a normal K7–K8 secondary (M₂ ≈ 0.6 M☉). Indeed, consistency cannot be achieved for M₂ ≤ 0.59 M☉ if the maximum inclination estimate (80°) is correct. An adopted mass M₁ ≈ 4.4 M☉ is significantly below the typical value of ~7 M☉ found for black holes in other low-mass X-ray binaries.

Keck observations of MXB 1659−29 (V2134 Oph) in quiescence reveal a probable optical counterpart at R = 23.6 ± 0.4 mag. This object recently went into a new X-ray and optical (R ≈ 18 mag) outburst, after about 21 years of inactivity.

1. INTRODUCTION

An important class of binary systems has been identified in which a low-mass secondary (companion) star orbits a probable black hole; see White, Nagase, & Parmar (1995), van Paradijs & McClintock (1995), and Tanaka & Lewin (1995) for extensive reviews. In all cases they were first observed in outburst as “X-ray novae” (or “soft X-ray transients”). Their X-ray spectra are generally characterized by a prominent, “soft” thermal component (kT ≈ 1 keV) as well as a “hard” power-law tail extending to very high energies (0.1–1 MeV). During outburst, the radiation from these and other low-mass X-ray binaries (LMXBs; the “low mass” refers to the secondary star) is emitted predominantly by the accretion disk surrounding the primary star.

A lower limit to the mass of the primary (M₁) in a given X-ray transient can be measured when it returns to quiescence. At that time, light from the secondary star contributes significantly to (or even dominates) the visible spectrum, and the secondary’s radial-velocity curve can be determined with a series of time-resolved spectra (see Cowley 1992 for a review). The orbital period (P) and semiamplitude (K₂) of the secondary yield the mass function of the primary, f(M₁) = PK₁²/2πG = M₁ sin³ i/(M₁ + M₂)², where i is the inclination of the orbital plane to our line of sight. Clearly, f(M₁) provides an absolute lower limit to the mass of the primary; only if M₂ = 0 and i = 90° is M₁ = f(M₁). It is generally acknowledged that if the primary is dark and has f(M₁) ≥ 3.2 M☉, it is probably a black hole, since the theoretical upper limit to the mass of a normal neutron star is ~3.0–3.2 M☉ (Friedman, Ipser, & Parker 1986; but see Friedman & Ipser 1987, as well as Bahcall, Lynn, & Sel...
The now-quiescent nova is about north-northwest of star A.

The six best examples of LMXBs whose mass function exceeds (or is close to) $\sim 3 \, M_\odot$, along with the derived values of $f(M_1)$ (in units of $M_\odot$) and references, are as follows in chronological order of the mass-function measurement: A0620−00 = V616 Mon (3.18 ± 0.16: McClintock & Remillard 1986; 2.72 ± 0.06: Marsh, Robinson, & Wood 1994; 2.91 ± 0.08: Orosz et al. 1994), GS 1124−68 = Nova Mus 1991 (3.1 ± 0.4: Remillard, McClintock, & Bailyn 1992; 3.01 ± 0.15: Orosz et al. 1996), GS 2023+338 = V404 Cyg (6.26 ± 0.31: Casares, Charles, & Naylor 1992; 6.08 ± 0.06: Casares & Charles 1994), GRO J1655−40 = Nova Sco 1994 (3.16 ± 0.15: Bailyn et al. 1995; 3.24 ± 0.09: Orosz & Bailyn 1997), GS 2000+25 = Nova Vul 1988 (5.02 ± 0.47: Casares, Charles, & Marsh 1995; 4.97 ± 0.10: Filippenko, Matheson, & Barth 1995a, slightly revised to 5.01 ± 0.15 [not ±0.12] by Harlaftis, Horne, & Filippenko 1996), and Nova Oph 1977 (4.0 ± 0.8: Remillard et al. 1996; 4.86 ± 0.13: Filippenko et al. 1997, slightly revised to 4.65 ± 0.21 by Harlaftis et al. 1997). Here we add a seventh object to this list: Nova Vel 1993 = GRS 1009−45, with a derived mass function of 3.17 ± 0.12 $M_\odot$.

Nova Vel 1993 was discovered on 1993 September 12 with the WATCH all-sky monitor aboard Granat (Lapshov, Sazanov, & Sunyaev 1993; Lapshov et al. 1994) and with BATSE on the Compton Gamma-Ray Observatory (Harmon et al. 1993). Its spectrum exhibited an “ultrasoft” hump at low energies ($\lesssim 1$ keV) and a power-law tail out to at least 100 keV (Kaniovsky, Borozdin, & Sunyaev 1993), typical of X-ray binaries in which the compact object is a black hole. Two months later (November 17), Della Valle & Benetti (1993) discovered a blue optical counterpart at $V \approx 14.6$ mag, but reasonable estimates suggest that the magnitude at the time of outburst was $V = 13.8 \pm 0.3$ (Della Valle et al. 1997). Optical photometry conducted by Bailyn & Orosz (1995) about half a year after the primary outburst showed the presence of a secondary outburst and several mini-outbursts, again reminiscent of black hole X-ray novae. Della Valle et al. (1997) suggested an orbital period of about 4 hr, but a more reliable period of 6.86 ± 0.12 hr was obtained by Shahbaz et al. (1996). The spectral type of the secondary star in the binary system was estimated to be late-G/early-K by Shahbaz et al. (1996) and later than G5−K0 by Della Valle et al. (1997).

On 1998 January 25 (UT dates are used throughout this paper), we obtained several $R$-band images of the field of Nova Vel 1993 with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) at the Cassegrain focus of the Keck II telescope. As can be seen in Figure 1, which shows a subset of one image (seeing the nova was in quiescence), the nova was in quiescence by this time, with $R = 21.2 \pm 0.2$ mag. To determine whether Nova Vel 1993 should be considered a good dynamical black hole candidate, we decided to obtain a radial-velocity curve with LRIS. Our group had already obtained excellent results in this way for the black hole candidates GRO J0422+32 (Filippenko, Matheson, & Ho 1995b; Harlaftis et al. 1999), GS 2000+25 (Filippenko et al. 1995a; Harlaftis et al. 1996), and Nova Oph 1977 (Filippenko et al. 1997; Harlaftis et al. 1997), all of which are comparably faint.

2. OBSERVATIONS AND REDUCTIONS

Nova Vel 1993 was observed with LRIS in 1998 during the nights of January 25, February 1, March 5–6, and May 2, as well as in 1999 during the night of January 21. A journal of useful observations is given in Table 1. (The spectra obtained on 1998 May 2, and a few spectra on other nights, were of marginal quality and are not considered here.) Given the object’s far southerly declination ($-45^\circ$), and the restrictive southwest azimuth limit on Keck II ($\leq 185^\circ$), observing was restricted to $\sim 1.5$ hr per night; hence, a number of different observing runs separated by a range of intervals was needed to avoid serious aliasing of the orbital period. Conditions were always clear, and the

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2 We adopt the magnitudes of comparison stars quoted in Table 1 of Della Valle et al. (1997). There appears to be a numbering mismatch, or errors in the photometry, of some stars in Table 1 of Shahbaz et al. (1996): for example, their stars 2, 5, and 7 should have comparable magnitudes, yet they are listed as being very different.
seeing was about 1′.2, reasonably good considering the high air mass (≈ 2.4). Typical exposure times were 1100 s.

The long slit of width 1′′ was oriented at a position angle (P.A.) of 160° for all observations except that of 1998 January 25. This was close to the parallactic angle at the time of observation, thereby reducing differences in the relative amount of light lost at different wavelengths (Filippenko 1982). At such a P.A., the slit went directly through star A, which is much brighter than the quiescent (Filippenko 1982). At such a P.A., the slit went directly through star A, which is much brighter than the quiescent nova (Shahbaz et al. 1996; Della Valle et al. 1997). Also, spectra of some sdF stars (Oke & Gunn 1983) were obtained for flux calibration and removal of telluric absorption lines.

Cosmic rays were eliminated from the two-dimensional spectra through comparison of pairs of consecutive exposures. The two-dimensional spectra were bias-subtracted and flattened in the usual manner. The wavelength scale was determined from polynomial fits to the positions of emission lines in spectra of Hg-Ne lamps obtained with the telescope at (or near) the position of each object. To ensure accurate wavelength calibration, final corrections (≈ 0.0–0.3 Å) to the wavelength solution were obtained from night-sky emission lines in the spectra of the nova.

We used the APALL task in IRAF3 to optimally extract (Horne 1986) one-dimensional, sky-subtracted spectra of Nova Vel 1993. However, to minimize contamination from star A, we extracted only a few rows of the CCD centered on the position of the nova; as shown in Figure 2, these were rows 3–5 from the center of star A, in the left wing of its spatial profile, corresponding to a displacement of 1′′.3–2′′.1. To further remove contamination, we also observed with the same setup, given the estimated classification of the secondary star in Nova Vel 1993 (Shahbaz et al. 1996; Della Valle et al. 1997).

\[ \text{TABLE 1} \]

| HJD*a | UT Date | Exposure (s) | Air Massb | Phasec | \( \dot{v}_2 \) (km s\(^{-1}\)) | \( \dot{v}_1 \) (km s\(^{-1}\)) |
|-------|---------|-------------|-----------|---------|-----------------|-----------------|
| 838.96576 ...... | 1998 Jan 25 | 900 | 2.53 | 0.67402 | -236.7 ± 21.7 | 123.0 ± 62.3 |
| 845.95655 ...... | 1998 Feb 1 | 1200 | 2.46 | 0.18531 | 219.4 ± 18.9 | -36.10 ± 21.7 |
| 845.97085 ...... | 1998 Feb 1 | 1200 | 2.39 | 0.23545 | 52.09 ± 17.1 | -21.29 ± 25.1 |
| 877.85456 ...... | 1998 Mar 5 | 900 | 2.58 | 0.026917 | 448.5 ± 13.4 | -61.26 ± 28.3 |
| 877.86708 ...... | 1998 Mar 5 | 1200 | 2.48 | 0.070815 | 430.6 ± 15.0 | -79.79 ± 19.7 |
| 877.88132 ...... | 1998 Mar 5 | 1200 | 2.41 | 0.12074 | 328.9 ± 8.62 | -34.98 ± 18.8 |
| 877.89554 ...... | 1998 Mar 5 | 1200 | 2.36 | 0.17060 | 248.4 ± 17.5 | -51.49 ± 17.6 |
| 877.90868 ...... | 1998 Mar 5 | 1000 | 2.35 | 0.21667 | 123.3 ± 15.3 | -71.38 ± 21.1 |
| 877.92060 ...... | 1998 Mar 5 | 1000 | 2.35 | 0.25847 | -61.19 ± 15.5 | -86.64 ± 21.0 |
| 878.85228 ...... | 1998 Mar 6 | 1100 | 2.58 | 0.52515 | -476.1 ± 12.0 | 75.89 ± 25.1 |
| 878.89168 ...... | 1998 Mar 6 | 1100 | 2.37 | 0.66329 | -229.7 ± 17.2 | 63.71 ± 22.3 |
| 878.90475 ...... | 1998 Mar 6 | 1100 | 2.35 | 0.70912 | -120.3 ± 15.8 | 40.81 ± 20.7 |
| 878.91785 ...... | 1998 Mar 6 | 1100 | 2.36 | 0.75505 | 11.61 ± 21.8 | 86.20 ± 18.5 |
| 1199.97900 ...... | 1999 Jan 21 | 1200 | 2.52 | 0.46778 | -476.9 ± 12.0 | 14.13 ± 41.8 |
| 1200.00574 ...... | 1999 Jan 21 | 1200 | 2.38 | 0.56154 | -451.1 ± 8.61 | 27.51 ± 50.5 |
| 1200.01881 ...... | 1999 Jan 21 | 1100 | 2.35 | 0.60736 | -370.1 ± 12.8 | 31.60 ± 66.0 |
| 1200.03255 ...... | 1999 Jan 21 | 1200 | 2.35 | 0.65554 | -272.4 ± 27.6 | 14.54 ± 63.6 |

*a HJD = 2,450,000 at midpoint of exposure.
*b Air mass at midpoint of exposure.
*c Using \( P = 0.285206 \) days and \( \tau_{\odot} = 2,450,835.0661 \).
*d Secondary radial velocity.
*e Hz centroid radial velocity, from fit to emission-line wings.

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extracted the same rows (3–5) in the right wing of star A’s spatial profile, and subtracted this spectrum from that of the nova. We found that star A usually contributed 40% (65% on January 21) of the flux in the original extraction of Nova Vel 1993. In general (but, surprisingly, not on January 21), the subsequent analysis worked best on these fully decontaminated spectra of the nova, whose typical signal-to-noise ratio (S/N) per final 0.75 Å bin is 3.3 ± 0.4 in the continuum.

3. RESULTS

3.1. Unphased Average Spectra

Two unphased average spectra of Nova Vel 1993 are shown in Figure 3, with that of 1998 March 6 offset by 2.5 units. In the region of overlap, these resemble the spectra shown by Shahbaz et al. (1996). The strongest emission line is Hα, and there may be weak He I λ5876 on 6 March, although the latter line partially coincides with the Na I D absorption. Despite being in quiescence, Nova Vel 1993 still exhibits variability; the equivalent width (EW) of the Hα emission line, which is unaffected by errors in flux calibration, was somewhat larger on March 6 (76 Å) than on January 21 (60 Å). Note that this emission is considerably weaker than in GRO J0422+32 (EW ≈ 250 Å; Filippenko et al. 1995b), but comparable to that in GS 2000−25 (EW ≈ 40 Å; Filippenko et al. 1995a) and Nova Oph 1977 (EW = 25−85 Å; Filippenko et al. 1997). As in the previous objects we have studied, the Hα line has two peaks (Δv ≈ 1200 km s⁻¹), more obvious in March than in January.

3.2. Cross-Correlations

Following the procedure discussed in Filippenko et al. (1995b), we employed the FXCOR package (“Release 9/13/93”) in IRAF to cross-correlate the spectra of Nova Vel 1993 with the 13 velocity standards (shown in Fig. 4, along with two others from our previous studies). The correlation was done over the ranges 5980–6270 Å and 6320–6500 Å to avoid the Hα and He I λ5876 emission lines, Na I D absorption, the 6270 Å interstellar line, and poorly subtracted [O I] λ6300 night-sky emission. In almost all cases a definitive correlation peak was obvious. Typical values of the Tonry & Davis (1979) significance threshold were quite high, R ≳ 3, with a few as high as ~ 6. As in our previous studies, we adopted the FXCOR 1 σ uncertainties reduced by a factor of 2.77; the Fourier transform properties of Gaussians (the functions used in fitting the cross-correlation peaks) were used to determine that FXCOR overestimates the Tonry & Davis uncertainties by this amount.
Fig. 4.—Spectra of 15 radial velocity standards, arranged from early to late types (top to bottom)
The strongest formal correlation was obtained with BD +00°3090, which is officially listed as an M0 V star (Upgren et al. 1972), but over our spectral range it also looks very similar to K7 V and K8 V stars; see Figure 4. Indeed, the correlation was insignificantly lower with K7 V and K8 V stars, but far inferior with K5 V and M1 V stars. (We did not observe K6 V and K9 V stars.) Thus, we conclude that the secondary star lies somewhere in the range K7 V through M0 V, and possibly as early as K6 V. This is a slightly later spectral type than preferred by Shahbaz et al. (1996; late-G/early-K) and Della Valle et al. (1997; later than G5–K0), although the former authors note that their derived mean density for the secondary (2.4 g cm$^{-3}$) suggests a K5 V star. Our phased average spectrum of the secondary star (see below) supports the late-K classification.

Using the radial velocities evaluated from the correlations with BD +00°3090 (corrected for the radial velocity of BD +00°3090 itself: 46.6 km s$^{-1}$; Evans 1967), we conducted a nonlinear least-squares fit (i.e., a $\chi^2$ fit; Press et al. 1986, p. 521) to obtain the best cosine curve to match the data (Fig. 5). The four-parameter fit (zero point, semi-amplitude, period, and phase) yielded a systemic velocity of $\gamma_2 = 40.7 \pm 4.0$ km s$^{-1}$, a semiamplitude of $K_2 = 475.4 \pm 5.9$ km s$^{-1}$, a period of $P = 0.285206 \pm 0.0000014$ days (6.84 hr), and a starting time (heliocentric Julian day) for the phase of $T_0 = \text{HJD} 2,450,835.0661 \pm 0.0007$, where $T_0$ is defined as the point of maximum redshifted velocity. All the uncertainties are the formal 1$\sigma$ values derived from the $\chi^2$ fit, but that of $T_0$ may be an underestimate because the choice of the range in which to search for $T_0$ is unconstrained by the data. A better measurement of the systemic velocity is $\gamma_2 = 30.1 \pm 5.0$ km s$^{-1}$, the weighted average of values obtained with the nine best standard stars. Note that when star A (Fig. 1) was cross-correlated with the velocity standards, its derived velocities were constant to within $\pm 7$ km s$^{-1}$ (full range); thus, our results for Nova Vel 1993 are not an artifact of telescope position or instrument orientation, and our removal of the contamination by star A (spectral type $\sim$ K1) was effective.

It is interesting to examine the distribution of possible periods resulting from our series of observations. In Figure 6, which shows $\chi^2$ versus trial period, there are several major groups of possible periods; the structure within each group results from ambiguities in the counting of cycles between widely separated epochs of observation (for example, from 1998 January through March). Until we obtained the observations of 1999 January 21, the periods near 0.22 and 0.285 days were equally probable, with those near 0.18 and 0.4 days distinctly inferior. With the additional data, however, we are now confident that 0.285 days (6.84 hr) is correct. Based on observations of photometric modulation observed during the decline from outburst, Bailyn & Orosz (1995) had speculated that the orbital period might be 1.6 hr or $\sim$3 days, but these are clearly excluded by our radial velocity measurements. The possible presence of “superhumps” in the optical light curve obtained 4 months after the primary outburst led Della Valle et al. (1997) to deduce an orbital period of 4 hr, closer yet still incorrect. Our period is essentially identical that found by Shahbaz et al. (1996; 6.86 $\pm$ 0.12 hr) from Gunn R-band ellipsoidal modulations in quiescence. Note that the secondary in Nova Vel 1993 must be a dwarf; with an orbital period of only 6.84 hr, the compact primary would be inside a giant or subgiant.

The formal reduced $\chi^2$ ($\chi^2_r$) for the best fit is 1.55 (17 points, 13 degrees of freedom). Given that the velocity

![Figure 5](image1.png)

**Figure 5.**—Radial-velocity curve of the secondary star in Nova Vel 1993, derived from cross-correlations of individual spectra with those of the M0 V star BD +00°3090. Two cycles are shown for clarity. The radial velocity of the comparison star, 46.6 km s$^{-1}$, has been added to all values. The orbital period is 0.285206 $\pm$ 0.00000138 days. Formal velocity error bars are 1$\sigma$.

![Figure 6](image2.png)

**Figure 6.**—Value of $\chi^2$ vs. trial period for Nova Vel 1993, using the 17 spectra discussed in this paper. Only the lowest values of $\chi^2$ are shown; $\chi^2 \approx 10,000$ at typical periods near 0.35 days.
uncertainties given by the Tonry & Davis (1979) method do not reflect external errors such as miscentering of the object in the slit, they could easily be too small. In our case, increasing them by only 25% yields a reduced \( \chi^2 \) of 1.0. Moreover, had we assigned uncertainties to the adopted times (i.e., phases) of the observations, and performed the fit to simultaneously minimize residuals in both velocity and phase, we would have obtained a smaller value of \( \chi^2 \). (The effective times of the observations can differ from the calculated midpoints due to variations in observing conditions—seeing, transparency, etc.)

3.3. The Phased Average Spectrum

Having determined the orbital parameters of the secondary star, we obtained its master “rest-frame” spectrum by averaging the 17 spectra after Doppler shifting each one to zero velocity. This represents a total integration time of \( \sim 5 \) hr, but of course the S/N is lower than for a single 5 hr exposure (ignoring cosmic rays) due to the increase in readout noise. Note that the H\( \alpha \) and He I emission lines are smeared out by this process, since they are produced in the accretion disk around the compact primary star. Similarly, interstellar absorption lines become less distinct.

Figure 7 shows the phased average spectrum of Nova Vel 1993, in comparison with its typical spectrum (obtained at 11:14 UT on 1998 February 1), the unphased average around H\( \alpha \), and the spectrum of the M0 V velocity standard star. Scrutiny of the phased average spectrum reveals stellar absorption lines that are also present in the M0 V star (e.g., the Ca ++ Fe blend at 6498 Å), but those of Nova Vel 1993 are weak. While this could indicate that the spectral type of the secondary star is substantially earlier than M0, tests show that several other factors are likely to be more important: (1) rotational broadening, perhaps 50–100 km s\(^{-1}\) (e.g., Wade & Horne 1988; Harlaftis et al. 1996); (2)

![Spectra](image)

**Fig. 7.—** Spectra of Nova Vel 1993 compared with a scaled spectrum of a M0 V velocity standard. Constants have been added to the top three spectra for clarity. The “phased average” spectrum in the rest frame of the companion star was obtained by combining the 17 spectra after Doppler shifting each one to zero velocity. The narrow H\( \alpha \) absorption in the unphased average spectrum (top) must be produced by gas associated with the accretion disk, not the secondary star; otherwise, it would appear smeared out.
orbital broadening, typically $4K_a T/P = 80–90 \, \text{km s}^{-1}$ (Filippenko et al. 1995b); and, most importantly, (3) contamination by the featureless continuum of an accretion disk.

We attempted to quantify the contribution of the accretion disk in Nova Vel 1993 by comparing its phased average spectrum with that of the M0 V star, broadening and diluting the latter by various amounts. A good match to the depths of the narrow absorption lines was found with accretion disk contamination fractions of 60%–70% of the total flux density at $\sim 6300 \, \text{Å}$. Because of the uncertainties in the adopted parameters (broadening, spectral type) and the relatively low S/N of the Nova Vel 1993 spectrum, we cannot confidently exclude contributions somewhat outside this range, but it is clear that the accretion disk dominates the spectrum even in quiescence.

No absorption line of $\text{Li} \lambda 6708$ is visible in our phased average spectrum, to a 3 $\sigma$ upper limit of $\sim 0.1 \, \text{Å}$. An unexpectedly strong $\text{Li} \lambda 1$ line (EW $= 0.25–0.48 \, \text{Å}$) is seen in the spectra of several X-ray novae (Martin et al. 1994 and references therein; Filippenko et al. 1995a), but not in others (such as Nova Oph 1977; Filippenko et al. 1997; Harlaftis et al. 1997).

3.4. H$_\alpha$ Measurements

To investigate the motion of the compact primary in Nova Vel 1993, we fit a Gaussian to the high-velocity wings ($v \approx 800–2000 \, \text{km s}^{-1}$) of the H$_\alpha$ line in each individual spectrum using the IRAF task SPECFIT. The regions of the fit (including the continuum) were 6400–6545 Å and 6580–6710 Å; the double-horned core of the line (Fig. 3) was excluded. The velocity of the Gaussian peak and its formal 1 $\sigma$ uncertainty were adopted for each spectrum (Table 1).

As shown in Figure 8, the derived velocity tends to be low in the first half of the orbit and high in the second half, perhaps suggesting periodic behavior. We used a least-squares fit to determine the H$_\alpha$ radial-velocity cosine curve, forcing the data to have the period found for the secondary star (0.285206 days) but allowing all other parameters to vary. The formal results (Fig. 8; $\chi^2 = 1.34$) are as follows:

- $\gamma_1 = 4.6 \pm 6.2 \, \text{km s}^{-1}$,
- $K_1 = 65.3 \pm 7.0 \, \text{km s}^{-1}$,
- a zero point in the phase of HJD 2,450,834.9686 $\pm 0.0093$ days.

The value of $\gamma_1$ is inconsistent with that of $\gamma_2$, but this is often the case in X-ray novae (e.g., Nova Oph 1977; Filippenko et al. 1997).

Once again, the zero point in the phase is the maximum redshifted velocity; it implies that the compact object is 237$^\circ$ out of phase with the companion star, rather than the expected 180$^\circ$. This is comparable to the offsets in GRO J0422+32 (253$^\circ$; Filippenko et al. 1995b) and GS 2000+25 (260$^\circ$; Filippenko et al. 1995a), as well as in A0620–00 and Nova Mus 1991 (Orosz et al. 1994). To date, there is no satisfactory quantitative explanation for these distortions, but they suggest that the accretion disk often has a non-axisymmetric distribution of surface brightness, noncircular velocities, or a warp. They also cast some doubt on the use of H$_\alpha$ radial-velocity curves to determine the motion and mass of the primary star. On the other hand, the mass ratios determined in this manner are frequently quite consistent with those obtained with independent techniques (e.g., A0620–00: Orosz et al. 1994; GS 2000+25: Harlaftis et al. 1996; Nova Oph 1977: Harlaftis et al. 1997; GRO J0422+32: Harlaftis et al. 1999). Thus, here we will cautiously adopt the ratio of semiamplitudes as an estimate of the mass ratio: $q = M_2/M_1 = K_1/K_2 = 0.137 \pm 0.015$.

4. THE MASS OF THE COMPACT PRIMARY

From the semiamplitude ($K_2 = 475.4 \pm 5.9 \, \text{km s}^{-1}$) and period ($P = 0.285206 \pm 0.00000138 \, \text{days}$) of the radial velocity curve of the secondary star, we find a mass function $f(M_1) = 4\pi^2 G (K_2/2)^2 P^3 = 3.17 \pm 0.12 \, M_\odot$. This corresponds to the absolute minimum mass of the compact primary, and it is close to the maximum gravitational mass of a slowly rotating neutron star (3.0–3.2 $M_\odot$; see Chitre & Hartle 1976 and the discussion in Filippenko et al. 1995b).

No evidence for eclipses is seen in the data of Bailyn & Orosz (1995), Shahbaz et al. (1996), or Della Valle et al. (1997); similarly, we do not see significant variations in the apparent brightness of the secondary star over the orbital period. Hence, it is likely that the orbital inclination $i \approx 80^\circ$, and the relation $f(M_1) = M_2^3 \sin^3 i/(M_1 + M_2)^2$ then implies that $M_1 \gtrsim 4.2–4.4 \, M_\odot$ for nominal secondary-star masses of 0.5–0.65 $M_\odot$ (M0–K6 V; Allen 1976). Even if the secondary is quite undermassive (e.g., $M_2 = 0.3 \, M_\odot$), as in some X-ray binaries (e.g., van den Heuvel 1983), we derive
$M_1 \gtrsim 3.9 \, M_\odot$. The primary star is therefore almost certainly a black hole rather than a neutron star.

Adopting the mass ratio derived from the measured semi-amplitude of the radial velocity curve of the primary ($q = M_2/M_1 = K_1/K_2 = 0.137 \pm 0.015$), we find $M_1 = 3.64 - 4.74 \, M_\odot$ if $M_2 = 0.5 - 0.65 \, M_\odot$. The constraints from $q$ and the mass function yield $M_1 = 4.4 \, M_\odot$ and $i \sim 78^\circ$ if we use a normal K7–K8 secondary ($M_2 \approx 0.6 \, M_\odot$). Indeed, consistency cannot be achieved for $M_2 \lesssim 0.59 \, M_\odot$ if the maximum inclination estimate ($80^\circ$) is correct. We conclude that the secondary star cannot be substantially undermassive and that the orbital inclination is probably rather large, almost making Nova Vel 1993 an eclipsing binary. Our suggested inclination is significantly higher than the nominal value derived by Shahbaz et al. (1996) from their observed R-band ellipsoidal modulations ($i = 44^\circ \pm 7^\circ$). However, these authors admit that when contamination by light from the accretion disk is included, their allowed range for the inclination is $37^\circ$–$80^\circ$. Of course, in view of the unexplained phase offset between the expected and observed Hz radial velocity curves ($\S\,3.4$), it is also possible that our derived value of $q$ is erroneous, thereby affecting our estimate of $i$. Further studies are needed to accurately determine the inclination.

Recently, Bailyn et al. (1998) found that the distribution of masses of putative black holes in LMXBs is very strongly peaked at $\sim 7 \, M_\odot$, only V404 Cyg being a clear high-mass deviant. The number of objects in the sample is still quite small, but if our mass estimate for Nova Vel 1993 is correct, then it appears to be a low-mass counterexample ($M_1 \approx 4.4 \, M_\odot$). Another possible exception is GRO J0422 + 32 ($M_1 \approx 5 \, M_\odot$; Harlaftis et al. 1999). An independent measure of the mass ratio of Nova Vel 1993 from the rotational broadening of the secondary star’s absorption lines (e.g., Nova Oph 1977: Harlaftis et al. 1997; GRO J0422 + 32: Harlaftis et al. 1999), together with better constraints on the inclination derived from near-infrared ellipsoidal modulations (e.g., GS 2000 + 25: Callanan et al. 1996), would provide a very useful check on our estimated mass for the primary star.

When we calculate the effective Roche lobe radius ($R_L$) of the companion star from the relation of Paczyński (1971; see also Eggleton 1983) and Kepler’s third law, we find that $R_L = 0.7 \, R_\odot$ if $M_1 \approx 4.4 \, M_\odot$ and $M_2 \approx 0.6 \, M_\odot$. This is only slightly larger than the expected radius of a typical K8 dwarf ($R = 0.67 \, R_\odot$; Allen 1976). Thus, the secondary star may be just starting its evolution off the main sequence.

5. OBSERVATIONS OF MBX 1659–29 IN QUIESCENCE

As part of our effort to determine the mass functions of X-ray binaries, we observed the field of MBX 1659–29. This burst source was discovered in 1976 October with SAS 3 (Lewin et al. 1976). It was initially considered unusual because of its very stable burst intervals (Lewin 1977) and apparent absence of constant emission, but such emission was found a year later (Lewin et al. 1978; Share et al. 1978). An optical counterpart (now known as V2134 Oph) was discovered by Doysey et al. (1979) at $V = 18.3$ mag; it was quite blue and possibly exhibited emission lines of He ii $\lambda 4686$ and C IV$/$N IV $\lambda 4640$–$4650$. Figure 2 of Doxsey et al. (in which north is up and east to the left, although this is not stated) shows U-band and B-band finder charts for the object, from images taken on 1978 May 30 and June 1 with the Cerro Tololo Inter-American Observatory 4 m telescope.

We obtained three dithered R-band images (exposure times of 60, 60, and 30 s) of the MBX 1659–29 field on 1999 February 9 with LRIS/Keck II, at air mass 1.8–1.9. These were bias-subtracted, flattened, registered, and combined in the usual manner. A small subset of the resulting crowded image (Galactic latitude 7.3°) is shown in Figure 9a; the FWHM of stars is measured to be $\sim 0.9^\prime$. Star A is close to the apparent position of V2134 Oph indicated in the relatively shallow charts published by Doxsey et al. (1979). However, seven LRIS/Keck II long-slit spectra (P.A. = 160°) of this star, each with a typical exposure time of 900–1000 s, do not reveal any Hz emission characteristic of accretion disks. Moreover, cross-correlation of the individual spectra with the 13 velocity standards (G5 providing the best match) reveals no clear variability beyond the $\pm 15$ km s$^{-1}$ level and no systematic trend among consecutive exposures, casting further doubt on star A as the secondary. Hz emission is also weak or absent in our noisy spectrum of star B (Fig. 9a), and star E has a spectral type of M.

Shortly before the completion of this paper, MBX 1659–29 went into outburst again, after a hiatus of 21 years. During the interval 1999 April 2.06–3.47, the Wide Field Camera on BeppoSAX detected a transient X-ray source coincident with the position of MBX 1659–29 (in ‘t Zand et al. 1999). This object was confirmed on April 5.83–6.05 with the Rossi X-Ray Timing Explorer (Markwardt et al. 1999). Optical observations (Augusteijn, Freyhammer, & ‘t Zand 1999) on April 3.41 revealed a bright new source ($V = 18.3 \pm 0.1$) at that location, with a spectrum typical of LMXBs in an X-ray–bright phase (emission lines of H I, He II, C III, and N III). An image (exposure time 30 s) obtained on April 18 with LRIS/Keck II is shown in Figure 9b (stellar FWHM = 0.65′); the optical counterpart ($R = 18.2 \pm 0.05$) is marked “F.” This star is also visible at the center of the circle in Figure 9a, barely at the detection limit.

We measured the R magnitude of V2134 Oph in quiescence (Fig. 9a) with the technique of point-spread-function (PSF) fitting, where the PSF was determined iteratively by subtracting faint stars near the ones chosen for the PSF.
The zero point was obtained from twilight-sky observations of PG 1525–071A,C (Landolt 1992). Star F, which we identify with V2134 Oph in quiescence, has $R = 23.6 \pm 0.4$ mag. If star F is just a chance superposition, then the true optical counterpart is even fainter. Thus, any future attempts to obtain the mass function of MXB 1659–29 (V2134 Oph) will be extremely difficult to perform! As an aid for future photometry of this object, we note that the final magnitudes for stars A, B, C, D, and E are 19.6, 22.5, 23.1, 23.3, and 21.0, respectively. The $1\sigma$ uncertainty is about 0.05 mag at the bright end (primarily due to the dearth of photometric standards) and perhaps 0.2 mag for stars at $R \approx 23$.

**6. CONCLUSIONS**

Our observations of Nova Vel 1993 provide a definitive mass function of $3.17 \pm 0.12 M_\odot$ and a likely mass of around $4.4 M_\odot$ for the primary star. Thus, Nova Vel 1993 joins the small but growing list of secure Galactic black holes first identified as X-ray novae. However, its mass seems to be lower than that of other objects in its class, bridging the apparent gap between $\sim 3 M_\odot$ (the theoretical maximum mass of a neutron star, although observed masses almost always yield $M = 1.0–1.8 M_\odot$; Thorsett et al. 1993) and $\sim 7 M_\odot$ (the mass of most Galactic black holes in binary systems with well-determined parameters). It will be important to measure the mass ratio and orbital inclination of the system with techniques independent of the indirect ones used here, to confirm our estimates ($q = 0.137 \pm 0.015$; $i \approx 78^\circ$) and our derived mass.

A similar study of MXB 1659–29 (V2134 Oph) eliminates several candidate stars as the optical counterpart. The recent new outburst, which occurred just prior to the submission of this paper, allows us to identify the quiescent nova at $R = 23.6 \pm 0.4$ mag, unless this is an unrelated star superposed along the line of sight.

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