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ON IC 10 X-1, THE MOST MASSIVE KNOWN STELLAR-MASS BLACK HOLE

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ABSTRACT

IC 10 X-1 is a variable X-ray source in the Local Group starburst galaxy IC 10 whose optical counterpart is a Wolf-Rayet (WR) star. Prestwich and coworkers recently proposed that it contains the most massive known stellar-mass black hole (23–34 $M_\odot$), but their conclusion was based on radial velocities derived from only a few optical spectra, the most important of which was seriously affected by a CCD defect. Here we present new spectra of the WR star, spanning 1 month, obtained with the Keck I 10 m telescope. The spectra show a periodic shift in the He II λ4686 emission line as compared with IC 10 nebular lines such as [O III] λ5007. From this, we calculate a period of 34.93 ± 0.04 hr (consistent with the X-ray period of 34.40 ± 0.83 hr reported by Prestwich) and a radial velocity semiamplitude of 370 ± 20 km s^{-1}. The resulting mass function is 7.64 ± 1.26 $M_\odot$, consistent with that of Prestwich (7.8 $M_\odot$). This, combined with the previously estimated (from spectra) mass of 35 $M_\odot$ for the WR star, yields a minimum primary mass of 32.7 ± 2.6 $M_\odot$. Even if the WR star has a mass of only 17 $M_\odot$, the minimum primary mass is 23.1 ± 2.1 $M_\odot$. Thus, IC 10 X-1 is indeed a WR/black-hole binary containing the most massive known stellar-mass black hole.

Subject headings: black hole physics — galaxies: starburst — stars: Wolf-Rayet — X-rays: binaries

1. INTRODUCTION

IC 10 X-1 is a bright, variable X-ray source in the Local Group metal-poor starburst galaxy IC 10 with an X-ray luminosity of 10^{38} ergs s^{-1} (Brandt et al. 1997; Bauer & Brandt 2004). Lozinskaya & Moiseev (2007) suggested that IC 10 X-1 is the compact remnant of a hypernova, based on the nature of the synchrotron superbubble in IC 10. There are four possible optical counterparts to the X-ray source, the most likely being the luminous Wolf-Rayet (WR) star [MAC92] 17A (Crowther et al. 2003). Previous spectroscopic observations of [MAC92] 17A show prominent He II line emission; Clark & Crowther (2004) classified it as a WNE star.

Prestwich et al. (2007) recently proposed that IC 10 X-1 and [MAC92] 17A are a WR/black-hole (BH) binary containing the most massive known stellar-mass black hole (23–34 $M_\odot$). Unfortunately, their conclusion was based on radial velocity measurements from only a few optical spectra, and the observation showing an apparent spectral shift was seriously affected by a CCD defect, casting some doubt on the reality of the shift. They also assumed that the observed X-ray period of IC 10 X-1 (34.40 ± 0.83 hr) is equal to the orbital period of the binary system.

Here we present radial velocities from 10 new optical spectra of the WR star spanning 1 month; our results confirm the conclusions of Prestwich et al. (2007). In § 2 we describe the observations and data reduction, in § 3 we discuss our analysis of the spectra, and in § 4 we present our results. A preliminary report on this work is given by Silverman & Filippenko (2008).

2. OBSERVATIONS AND DATA REDUCTION

[MAC92] 17A was observed with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) mounted on the Keck I 10 m telescope in 2007 during the nights of November 11–13 (UT dates are used throughout this Letter), November 16, and December 12; a journal of observations is given in Table 1. LRIS is now equipped with an atmospheric dispersion compensator; thus, differential light losses (Filippenko 1982) were not a problem, even at high air masses.

Fortuitously, the long slit included RSMV 2, another WR star in IC 10 (Crowther et al. 2003). Unfortunately, the light from this second object fell between the two chips on the blue side of LRIS in the observations on November 11.492 and 13.320.

All data were taken using a 5600 Å dichroic and a 600/4000 grism on the blue side of the spectrograph. All but one observation employed a long slit of width 0.7″; the observation on 2007 November 16.242 used a long slit of width 1.0″. The slit was always oriented at a position angle (PA) of 162°, through another star readily visible on the acquisition and guider image, in order to facilitate object acquisition and to minimize contamination from adjacent stars. The spectra span a wavelength range of ∼3800–5550 Å, and all observations had a FWHM spectral resolution of ∼3.5 Å (∼220 km s^{-1}).

The data were reduced using standard techniques (e.g., Foley et al. 2003). Routine CCD processing and spectrum extraction for the data were completed with IRAF.[1] The data were extracted with the optimal algorithm of Horne (1986). We obtained the overall wavelength scale from low-order polynomial fits to calibration-lamp spectra. Small wavelength shifts were applied to individual spectra after cross-correlating night-sky lines with a template sky spectrum. Using our own IDL routines, we fit spectrophotometric standard-star spectra to flux-calibrate our data and remove telluric lines (Wade & Horne 1988; Matheson et al. 2000).

The unphased combined spectra of RSMV 2, from 8 epochs, and of [MAC92] 17A, from all 10 epochs, are shown in Figure 1. The radial velocity of IC 10, −348 ± 1 km s^{-1} (Huchra et al. 1999), has been removed.

In the spectra of both objects, there are strong nebular emission lines of Hγ, Hβ, and [O III] (and Hδ and Hϵ in RSMV 2) from H II regions in the slit. One can also see the relatively broad He II λ4686 emission and the weaker He II λ5411 emission which comes from the WR stars themselves. In addition,

[1] IRAF, the Image Reduction and Analysis Facility, is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation (NSF).

TABLE 1
Journal of Observations and Radial Velocities

HJD[a]	2007 UT Date[b]	Exposure (s)	Air Mass[c]	Seeing[d]	Phase[e]	He II v[f] (km s^{-1})	He II FWHM (Å)
2454415.865	Nov 11.361	1400	1.33	0.8	0.9801	384 ± 29	14.3 ± 0.9
2454415.882	Nov 11.378	1400	1.36	0.8	0.9918	362 ± 24	13.3 ± 0.8
2454415.996	Nov 11.492	1800	1.95	1.5	0.0701	325 ± 40	14.1 ± 1.5
2454416.761	Nov 12.257	1800	1.35	0.7	0.5957	−312 ± 44	18.1 ± 1.7
2454416.932	Nov 12.428	1800	1.53	0.8	0.7132	−85 ± 43	16.3 ± 1.7
2454417.824	Nov 13.320	1800	1.30	1.5	0.3260	−182 ± 26	15.5 ± 0.9
2454420.708	Nov 16.205	1500	1.46	1.0	0.3081	−77 ± 113	19.7 ± 4.6
2454420.726	Nov 16.223	1500	1.40	1.1	0.3205	−148 ± 52	13.6 ± 2.0
2454420.745	Nov 16.242[g]	1500	1.36	1.0	0.3335	−133 ± 51	14.0 ± 1.9
2454446.761	Dec 12.258	1200	1.31	1.4	0.2074	91 ± 51	24.6 ± 2.1

[a] Heliocentric Julian Date at midpoint of exposure.
[b] UT date at midpoint of exposure.
[c] Air mass at midpoint of exposure.
[d] Approximate full width at half-maximum intensity (FWHM), arcseconds.
[e] Using $P = 34.93 \pm 0.04$ hr and $T_0 = 2007$ November 9.935 ± 0.014 (the UT date of maximum radial velocity).
[f] Radial velocity calculated relative to the [O III] λ5007 line.
[g] This is the only observation with a long slit of width 1.0″; all others used a slit of width 0.7″.

the fainter N V λλ4603–4620 and N III λλ4634–4642 emission features from [MAC92] 17A and RSMV 2 (respectively) are seen. Broad emission from relatively low-excitation species such as H I and He I is not present in [MAC92] 17A, suggesting that the emission does not arise from an accretion disk.

3. ANALYSIS

The X-ray period found by Prestwich et al. (2007) and our measured period (see § 4.1) are substantially larger than the period needed for Roche lobe overflow, given reasonable masses of [MAC92] 17A and its compact binary companion. (We, however, derive an expected period for Roche lobe overflow of 9.0–15.9 hr, which differs from the 2–3.5 hr period suggested by Prestwich et al. [2007].) Thus, the accretion must be the result of a wind from the WR star, as is often seen in high-mass X-ray binaries. Furthermore, the He II λ4686 emission line is formed in the inner part of the WR wind (close to the star), justifying its use when determining radial velocities of WR binaries (Prestwich et al. 2007).

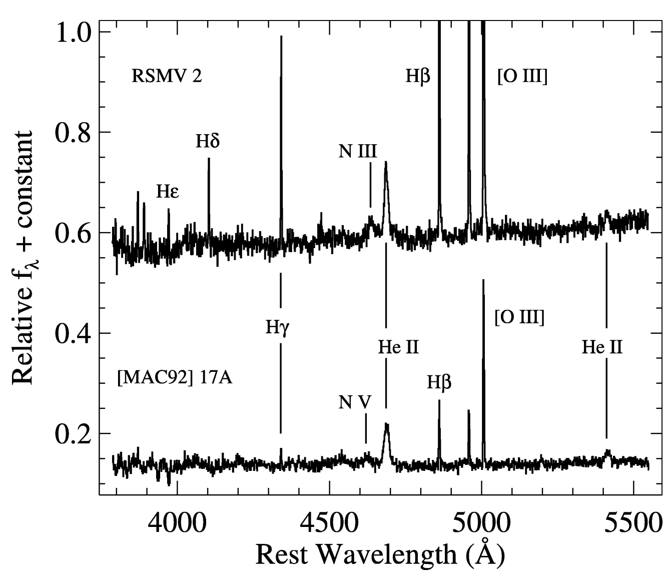

Fig. 1.—Unphased combined spectra of RSMV 2 (*top*) and [MAC92] 17A (*bottom*), and their superposed H II regions. Both nebular and WR line identifications are discussed in the text. The spectrum of RSMV 2 has been shifted up by 0.45 units for clarity.

For each observation we fit a Gaussian profile to the nebular [O III] and Hβ lines, as well as to the He II line of [MAC92] 17A. To remove possible errors introduced by our wavelength and flux calibrations, the profiles were fit to the raw, one-dimensional (1D) extracted spectra (i.e., neither wavelength- nor flux-calibrated). Owing to the small number of emission lines available in the calibration-lamp spectra, the wavelength solution was found to vary quite a bit from spectrum to spectrum, when in fact nothing was actually changing except perhaps the zero point. Fitting profiles to this raw 1D data is reasonable for our purposes because the radial velocity of the WR star only depends on the *relative* change in the spacing between the He II line and the (stationary) nebular lines.

Figure 2 shows three spectra, centered on the He II λ4686 spectral feature, in velocity space (as calculated relative to the [O III] λ5007 line). The signal-to-noise ratio (S/N) of the observations is typical of our entire data set. It is clear that the centroid of the He II line is shifted between the three observations.

The FWHM of the He II line appears to change with time in Figure 2. As seen in the last column of Table 1, the only observation that actually has a substantially different FWHM is the one from 2007 December 12.258 (the middle spectrum in Fig. 2). Prestwich et al. (2007) note that most of their epochs were well fit by a Gaussian with a 15–17 Å FWHM, which matches our data quite well (we have a mean of ∼16.3 Å). They also mention that one of their observations had a FWHM of only 10 Å, but that the narrowness of this observation is likely due to a "CCD defect that contaminates the red component." None of our derived FWHM values are within 1 σ of 10 Å, suggesting that their assessment is correct. However, this is also the only spectrum from which Prestwich et al. (2007) deduced a radial velocity variation in [MAC92] 17A, casting some doubt on the claimed shift.

From our Gaussian fits we calculated the separation in pixels between the centroids of the He II feature and each host-galaxy nebular line. These were then converted to a difference in wavelength by using the dispersion value we derived from low-order polynomial fits to calibration-lamp spectra (0.621 Å pixel^{-1}). Next, we performed a nonlinear least-squares fit to the differences in wavelength. The resulting cosine yielded the period of the He II line and its systemic wavelength shift, which is equivalent to the zero point of the cosine. Finally, each spectrum's deviation from this systemic wavelength shift was con-

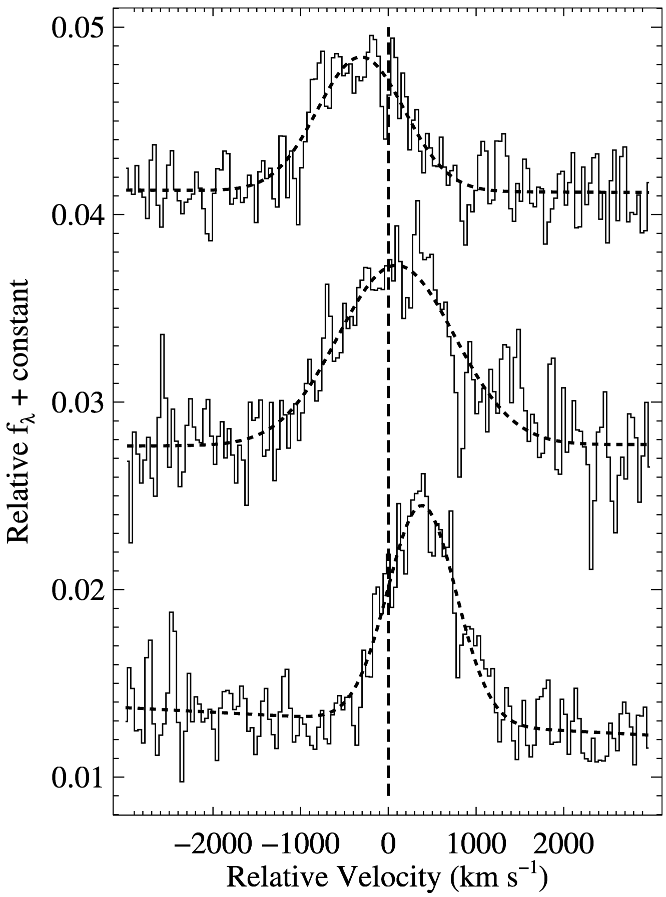

FIG. 2.—Spectra of the He II emission line from [MAC92] 17A obtained on 2007 November 12.257 (*top*), 2007 December 12.258 (*middle*), and 2007 November 11.361 (*bottom*). The data have been deredshifted and converted into velocity space. The vertical long-dashed line is where the He II feature of [MAC92] 17A would be centered if at rest. The short-dashed lines show our Gaussian fits to the data. The centroid of the He II line clearly shifts with time.

verted into a radial velocity. Similarly, the semiamplitude of the fit was converted from a wavelength to a velocity.

4. RESULTS

4.1. *Radial Velocity Curve*

Figure 3 shows the radial velocity curve of [MAC92] 17A. Two complete periods, each with 10 observations, are shown. The velocities in Figure 3 were calculated with respect to the [O III] λ5007 line. We also determined radial velocities and an associated cosine fit with respect to the nebular Hβ line. These radial velocities differed from the ones derived using the [O III] line by much less than 1 σ at each epoch. In addition, the period of the curve derived using the Hβ line differed by only 0.01% from the curve shown in Figure 3, and the semiamplitude differed by ~0.3%. These differences led to a mere 0.5% difference in the final BH mass.

Since [O III] had a somewhat higher S/N than Hβ (as seen in Fig. 1), the Hβ Gaussian fits had slightly larger uncertainties in their centroids and thus led to larger overall uncertainties. Thus, we have chosen to present only the velocities derived relative to the [O III] line.

The error bars shown represent 1 σ, and were calculated by considering the uncertainty in the centroids of our Gaussian fits to both the He II line as well as the [O III] nebular line.

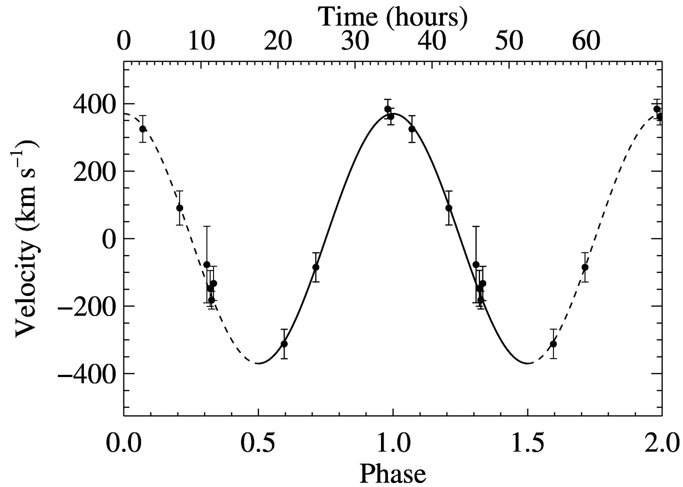

FIG. 3.—Radial velocity curve of [MAC92] 17A using velocities relative to the [O III] λ5007 spectral line. Two cycles are shown for clarity. Formal velocity error bars are 1 σ. See the text for values of the fit parameters.

The point in Figure 3 with the relatively large error bar is due to a low S/N spectrum.

The four-parameter fit (zero point, semiamplitude, period, and phase) yielded a semiamplitude of $K_2 = 370 \pm 20$ km s^{-1} and a period of $P = 34.93 \pm 0.04$ hr (consistent with the X-ray period of 34.40 ± 0.83 hr reported by Prestwich et al. [2007]). However, the phasing of our radial velocity curve with the X-ray light curve (Prestwich et al. 2007, Fig. 1) is unknown because of the substantial uncertainty in the X-ray period.

We examined the distribution of possible periods resulting from our observations in order to test whether our calculated period suffers from any ambiguity in the number of cycles between observations. Figure 4 shows χ^2 versus trial period for our complete set of 10 observations. It is clear that the two periods that best fit the data are ~34.9 hr ($\chi^2 \approx 2.43$) and ~35.7 hr ($\chi^2 \approx 2.50$).

We have chosen to adopt the 34.9 hr period since (1) it has the lowest value of χ^2 (although the χ^2 from the 35.7 hr period is close to this value); (2) it is consistent with the X-ray period derived by Prestwich et al. (2007) whereas the 35.7 hr period is 2 σ away from this value; and (3) it is surrounded by the lowest values of χ^2 in Figure 4 (yet the value of χ^2 begins to rise dramatically at periods just larger than 35.7 hr). The fact

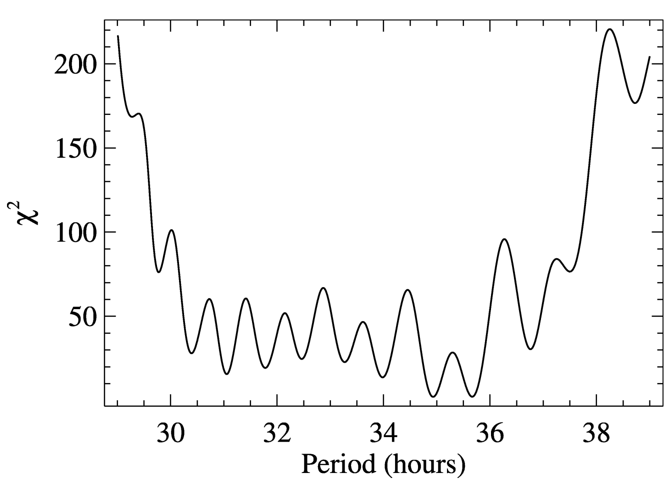

FIG. 4.—Value of χ^2 vs. trial period for [MAC92] 17A, using all 10 spectra discussed in the text.

that we cannot completely discern between the two periods is the result of a half-cycle ambiguity between our November and December observations. Clouds precluded a second exposure on December 12 which would have almost certainly eliminated this uncertainty.

4.2. *Determination of the Black Hole Mass*

Given a radial velocity curve of the secondary star, two parameters are necessary to calculate the minimum mass of the companion BH: the period (P) and the semiamplitude (K_2). The standard method of measuring stellar masses in binary systems is to calculate the mass function, $f(M)$ (e.g., McClintock & Remillard 2006),

$$f(M_1) \equiv \frac{PK_2^3}{2\pi G} = \frac{M_1 \sin^3 i}{(1+q)^2}, \quad (1)$$

where i is the inclination of the binary's orbit and $q = M_2/M_1$; here, M_1 is the mass of the putative BH and M_2 is the mass of the WR donor. Physically, $f(M_1)$ is the smallest possible BH mass; it is equal to the BH mass only if $i = 90°$ and $q = 0$.

Using our measured values of P and K_2 (see § 4.1 above), we calculated the mass function for the system. Finally, we assumed a range of reasonable masses for the WR star, which then allowed us to calculate a range of possible BH masses.

Adopting our calculated period and semiamplitude, the resulting mass function using equation (1) is $7.64 \pm 1.26\ M_{\odot}$, consistent with that of Prestwich et al. (2007) ($7.8\ M_{\odot}$). If we assume a mass for the WR companion and an inclination for the orbit, then we can calculate a mass for the BH.

The spectroscopic mass of the WR star was calculated by Clark & Crowther (2004) to be $35\ M_{\odot}$, but there is much uncertainty in this value. Prestwich et al. (2007) point out the small possibility that [MAC92] 17A could have a mass as low as $17\ M_{\odot}$. They also note that since this system is observed to have deep X-ray eclipses, the inclination of the system should be close to 90°.

Table 2 shows possible BH masses assuming a reasonable range of values for both the mass of [MAC92] 17A and the orbital inclination (similar to Prestwich et al. 2007, Table 1). Given these ranges and our calculated values for the period and semiamplitude of the radial velocity curve, the BH in IC 10 X-1 must have a mass of *at least* $23.1\ M_{\odot}$, and it very well might be $32.7\ M_{\odot}$ or larger. In any case, this is much larger than the mass of the BH in M33, $15.65 \pm 1.45\ M_{\odot}$ (Orosz et al. 2007), arguably the most massive previously identified stellar-mass BH, which was announced very shortly before the BH mass of IC 10 X-1 (Prestwich et al. 2007).

TABLE 2
DERIVED BLACK HOLE MASS ($M_{\odot}$)

INCLINATION (deg)	WOLF-RAYET MASS ($M_{\odot}$) 17	25	35
90	23.1 ± 2.1	27.7 ± 2.3	32.7 ± 2.6
78	23.9 ± 2.1	28.6 ± 2.4	33.8 ± 2.8
65[a]	27.1 ± 2.5	32.3 ± 2.8	37.9 ± 3.2

[a] If the mass of [MAC92] 17A is 35 $M_{\odot}$, inclinations less than ~78° will not yield X-ray eclipses.

Note that if we had used the period of 35.7 hr mentioned in § 4.1 and its associated semiamplitude of 390 km s^{-1}, we would have derived a mass function of $9.15 \pm 1.45\ M_{\odot}$, yielding minimum BH masses of ~25.5–35.8 $M_{\odot}$ (given the previously assumed range of WR masses, 17–35 $M_{\odot}$).

5. CONCLUSION

In this Letter, we present new spectra of the WR stars [MAC92] 17A and RSMV 2 in the nearby starburst galaxy IC 10. [MAC92] 17A has been shown to be in a binary system with the variable X-ray source IC 10 X-1 (Prestwich et al. 2007). From our Keck spectra of [MAC92] 17A, we have constructed a compelling radial velocity curve. The measured orbital period and semiamplitude of [MAC92] 17A imply that the mass of the BH companion is at least $23.1\ M_{\odot}$, and more likely ~$32.7\ M_{\odot}$. Thus, we have shown that IC 10 X-1 is indeed a WR/BH binary containing the most massive known stellar-mass BH.

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