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☉), 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 nebulosity 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 \( M_2 \approx 1.26 M_\odot \), consistent with that of Prestwich (7.8 M⊙). This, combined with the previously estimated (from spectra) mass of 35 M⊙ for the WR star, yields a minimum primary mass of 32.7 ± 2.6 M⊙. Even if the WR star has a mass of only 17 M⊙, the minimum primary mass is 23.1 ± 2.1 M⊙. 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 \( 10^{34} \) erg 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 λ 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⊙). 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 \( \sim 3800–5550 \) Å, and all observations had a FWHM spectral resolution of \( \sim 3.5 \) Å (\( \sim 220 \) 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. 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 Hα and He 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,
that the emission does not arise from an accretion disk. Broad emission from relatively low-excitation species suggest by Prestwich et al. [2007]. Thus, the accretion must flow of 9.0–15.9 hr, which differs from the 2–3.5 hr period (We, however, derive an expected period for Roche lobe over-
masses of [MAC92] 17A and its compact binary companion. 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

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 4686 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).

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-
or 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 4686 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 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-

| HJD\n\nLaughlin 2007 UT Date\n\nExposure\n\nAir Mass\n\nSeeing\n\nPhase\n\nHe ii \n\nHe ii FWHM\n| \n| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 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 11.428 | 1800 | 0.8 | 1.5 | 0.7132 | 96 ± 43 | 16.3 ± 1.7 |
| 2454416.724 | Nov 13.320 | 1800 | 1.30 | 1.5 | 0.3260 | 132 ± 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 | 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 |

* Heliocentric Julian Date at midpoint of exposure.
* UT date at midpoint of exposure.
* Air mass at midpoint of exposure.
* Approximate full width at half-maximum intensity (FWHM), arcseconds.
* Using \( P = 34.93 ± 0.04 \) hr and \( T_e = 2007 \) November 9.935 ± 0.014 (the UT date of maximum radial velocity).
* Radial velocity calculated relative to the [O iii] \( \lambda5007 \) line.
* This is the only observation with a long slit of width 1.0"; all others used a slit of width 0.7".

![Fig. 1.—Unphased combined spectra of RSMV 2 (top) and [MAC92] 17A (bottom), and their superposed \( H \beta \) 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.](image-url)
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 1σ 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 1σ, 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.

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 $K_p = 370 \pm 20$ km s$^{-1}$ and a period of $P = 34.93 \pm 0.04$ hr (consistent with the X-ray period of $34.40 \pm 0.83$ 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 $\chi^2$ versus trial period for our complete set of 10 observations. It is clear that the two periods that best fit the data are $\sim 34.9$ hr ($\chi^2 \approx 2.43$) and $\sim 35.7$ hr ($\chi^2 \approx 2.50$).

We have chosen to adopt the 34.9 hr period since (1) it has the lowest value of $\chi^2$ (although the $\chi^2$ 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 2σ away from this value; and (3) it is surrounded by the lowest values of $\chi^2$ in Figure 4 (yet the value of $\chi^2$ begins to rise dramatically at periods just larger than 35.7 hr). The fact
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_1). The standard method of measuring stellar masses in binary systems is to calculate the mass function, f(M) (e.g., McClintock & Remillard 2006),

\[ f(M) = \frac{PK_1^2}{2\pi G} \left(1 + q^2\right)^{1/2}, \]

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) 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_1 (see § 4.1 above), we calculated the mass function for the system. For the mass function, 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 ± 1.26 M_⊙, consistent with that of Prestwich et al. (2007) (7.8 M_⊙). 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_⊙, 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_⊙. 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_⊙, and it very well might be 32.7 M_⊙ or larger. In any case, this is much larger than the mass of the BH in M33, 15.65 ± 1.45 M_⊙ (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

| INCLINATION (deg) | 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°              | 27.1 ± 2.5 | 32.3 ± 2.8 | 37.9 ± 3.2 |

* If the mass of [MAC92] 17A is 35 M_⊙, inclinations less than ~78° will not yield X-ray eclipses.

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_⊙, and more likely ~32.7 M_⊙. 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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References

Bauer, F. E., & Brandt, W. N. 2004, ApJ, 601, L67
Brandt, W. N., Ward, M. J., Fabian, A. C., & Hodge, P. W. 1997, MNRAS, 291, 709
Clark, J. S., & Crowther, P. A. 2004, A&A, 414, L45
Crowther, P. A., Drissen, L., Abbott, J. B., Royer, P., & Smartt, S. J. 2003, A&A, 404, 483
Filippenko, A. V. 1982, PASP, 94, 715
Foley, R. J., et al. 2003, PASP, 115, 1220
Horne, K. 1986, PASP, 98, 609
Huchra, J. P., Vogeley, M. S., & Geller, M. J. 1999, ApJS, 121, 287
Lozinskaya, T. A., & Moiseev, A. V. 2007, MNRAS, 381, L26
Matheson, T., Filippenko, A. V., Ho, L. C., Barth, A. J., & Leonard, D. C. 2000, AJ, 120, 1499
McClintock, J. E., & Remillard, R. A. 2006, in Compact Stellar X-Ray Sources, ed. W. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 157
Oke, J. B., et al. 1995, PASP, 107, 375
Orosz, J. A., et al. 2007, Nature, 449, 872
Prestwich, A. H., et al. 2007, ApJ, 669, L21
Silverman, J., & Filippenko, A. V. 2008, AAS Meeting Abstracts, Vol. 211, 161.06
Wade, R. A., & Horne, K. 1988, ApJ, 324, 411

TABLE 2

| Derived Black Hole Mass (M_⊙) |
|-------------------------------|
| INCLINATION (deg) | 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°              | 27.1 ± 2.5 | 32.3 ± 2.8 | 37.9 ± 3.2 |

* If the mass of [MAC92] 17A is 35 M_⊙, inclinations less than ~78° will not yield X-ray eclipses.