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THE ORBITAL PERIOD OF THE WOLF-RAYET BINARY IC 10 X-1: DYNAMIC EVIDENCE THAT THE COMPACT OBJECT IS A BLACK HOLE

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ABSTRACT

IC 10 X-1 is a bright ($L_X = 10^{38}$ ergs s^{-1}) variable X-ray source in the Local Group starburst galaxy IC 10. The most plausible optical counterpart is a luminous Wolf-Rayet star, making IC 10 X-1 a rare example of a Wolf-Rayet X-ray binary. In this Letter, we report on the detection of an X-ray orbital period for IC 10 X-1 of 34.4 hr. This result, combined with a reexamination of optical spectra, allows us to determine a mass function for the system of $f(M) = 7.8\ M_\odot$ and a probable mass for the compact object of 24–33 $M_\odot$. If this analysis is correct, the compact object is the most massive stellar-mass black hole known. We further show that the observed period is inconsistent with Roche lobe overflow, suggesting that the binary is detached and that the black hole is accreting the wind of the Wolf-Rayet star. The observed mass-loss rate of [MAC92] 17A is sufficient to power the X-ray luminosity of IC 10 X-1.

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

Online material: color figure

1. INTRODUCTION

Models of the evolution of high-mass X-ray binaries predict the existence of helium star+compact object pairs (van den Heuvel & de Loore 1973). Such systems should form at the very end of the X-ray binary evolution, after the secondary (donor) star has been stripped of its hydrogen through either Roche lobe overflow or mass loss via a strong wind. In either case, a luminous helium star with a compact companion is formed (Ergma & Yungelson 1998). These systems are expected to be rare. Ergma & Yungelson (1998) predict ∼100 helium star+black hole pairs in the Galaxy. However, only a small number of these are expected to form accretion disks and be visible as X-ray sources. Identification of such rare systems is important, because they have the potential to put strong constraints on the evolution of massive binary pairs. There are currently only three candidates: Cyg X-3, NGC 300 X-1 (Carpano et al. 2007b), and IC 10 X-1.

IC 10 X-1 is a bright ($L_X = 10^{38}$ ergs s^{-1}) variable X-ray source in the Local Group metal-poor starburst galaxy IC 10 (Brandt et al. 1997; Bauer & Brandt 2004). It is surrounded by a shell of nonthermal radio emission (Yang & Skillman 1993) and X-ray emission (Wang et al. 2005; Brandt et al. 1997) that may be associated with the supernova that produced the compact object in IC 10 X-1. There are four possible optical counterparts to the X-ray source, with the most plausible being the bright Wolf-Rayet star [MAC92] 17A (Crowther et al. 2003). Spectroscopic observations of [MAC92] 17A reveal prominent He II line emission, suggesting an identification as a WNE star (Clark & Crowther 2004). In this Letter we report the discovery of an X-ray orbital period in IC 10 X-1 using data from *Swift* and *Chandra* (Prestwich et al. 2006). In § 2 we describe the *Chandra* and *Swift* observations, and in § 3 we discuss the constraints that the period puts on the accretion mechanisms and mass of the compact companion.

2. OBSERVATIONS AND DATA ANALYSIS

IC 10 X-1 was observed with *Chandra* on 2006 November 2 and4 for approximately 45 ks per observation (ObsIDs 7802 and 8458). Data were processed using standard CIAO analysis software, version 3.4. After extraction of a light curve, we observed a large (factor of 7) flux increase in the first *Chandra* observation, followed by a similar flux decrease in the second observation (see Fig. 1). The large flux change and sharp profile of the flux modulations suggested that we were observing eclipses in IC 10 X-1. We immediately applied for, and were generously awarded, a *Swift* target-of-opportunity observation of 100 ks. IC 10 X-1 was observed with *Swift* beginning 2006 November 21 for approximately 700 s per 90 minute *Swift* orbit for a total of 97 ks spanning 246 hr. Data were processed by the *Swift* pipeline and screened using standard procedures outlined in the X-Ray Telescope (XRT) Data Reduction Guide.

2.1. *Timing Analysis*

In order to search for periodic signals in the *Swift* observations of IC 10 X-1, we merge the *Swift* event files using the CIAO tool `dmmerge`. We extract the events in a 60″ radius around the *Chandra* source position; this is reasonable due to both the extent of the *Swift* point-spread function and the sparsity of nearby sources, as observed in the *Chandra* observations. A Lomb-Scargle (LS) periodogram of IC 10 X-1 is shown in Figure 2. The periodogram shows no evidence of increased noise at low frequencies (“red noise”), indicating that the LS method can be used to search for peaks in the power spectrum. The full data range was searched from the Nyquist frequency (twice the 2.5073 s XRT readout rate) to half the full observation duration of 123 hr. The normalization used in the LS method is the total variance of the data (Horne & Baliunas 1986). The LS periodogram determines a period of 34.40 hr. Following the method of Horne & Baliunas (1986), we determine a period uncertainty of ± 0.83 hr.

Two sets of simulations were carried out to ascertain the

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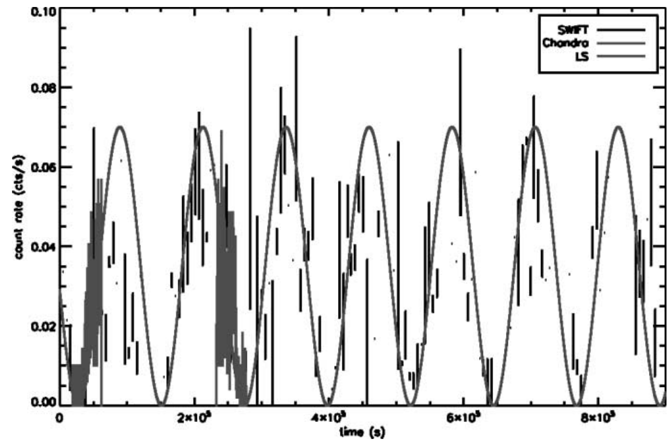

FIG. 1.—*Swift* light curve of IC 10 X-1 in 100 s time bins. Overplotted in gray is the *Chandra* light curve in 1000 s bins. The *Chandra* count rate is reduced by a factor of 5 to approximate the lower effective area of *Swift*. The *Chandra* data are also shifted forward in time by 13*P*, where *P* is the Lomb-Scargle period. Times are relative to the start of *Swift* observations, 2006 November 21 at 05:11:05 UTC. The black curve is the period derived by the Lomb-Scargle periodogram. [*See the electronic edition of the Journal for a color version of this figure.*]

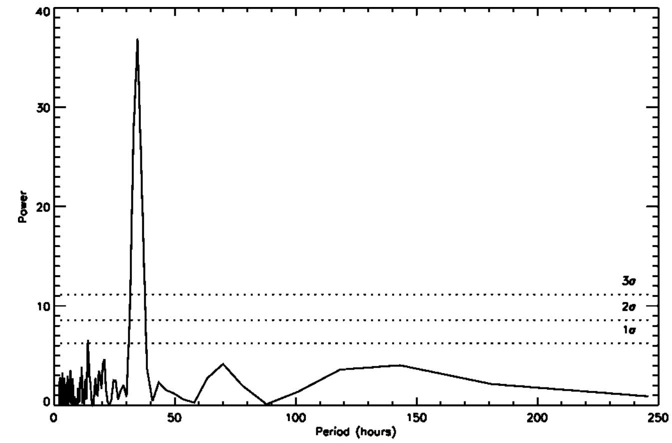

FIG. 2.—Power spectrum of IC 10 X-1. The horizontal dotted lines correspond to the false-alarm probability corresponding to 1, 2, and 3 σ significance.

false-alarm probability (FAP) of the signal. The first was a Monte Carlo simulation, in which fake spectra were generated with Gaussian noise set to the standard deviation of the actual data. The second was a bootstrap method, which creates a fake periodogram by randomly rearranging real data values. Observation times were taken from the real data, and 1×10^5 fake spectra were generated for each method. The number of simulated spectra with peak amplitudes greater than the observed peak amplitude (i.e., the FAP) was 0 in both Monte Carlo and Bootstrap simulations. Thus, the FAP was $<1 \times 10^{-5}$, and the significance was $>4.5\ \sigma$.

IC 10 X-1 was observed in 2003 by both *Chandra* and *XMM-Newton*. The 30 ks *Chandra* observation of IC 10 X-1 showed the source to be variable, but it did not show any evidence of an eclipse (Bauer & Brandt 2004). A sharp increase in the X-ray flux of IC 10 X-1 during the 45 ks *XMM-Newton* observation was probably due to an eclipse egress (Wang et al. 2005). The data in these observations are consistent with the period derived in this Letter.

3. DISCUSSION

The most plausible explanation for the regular flux modulations is that orbital eclipses of the X-ray–emitting object by the donor star were observed. It is unlikely that the observed period is superorbital (e.g., due to a precessing warped accretion disk) because it is shorter than most superorbital periods (most are 10–100 days; e.g., Clarkson et al. 2004). Although we cannot rule out an alternative explanation without a fully sampled optical radial velocity curve, for this Letter, we assume that the modulation is orbital.

3.1. *Constraints on the Accretion Mechanism*

The period can be used to constrain the accretion mechanism, in particular, to determine whether the donor fills its Roche lobe or whether accretion occurs via a wind. Here we test the hypothesis that the accretion is the result of Roche lobe overflow by determining whether the observed period is consistent with theoretical values of the period for compact object masses in the range 1–100 $M_\odot$.

The orbital period (P) is related to the mass of the primary (M_1), the mass of the donor (M_2), and the separation between them (a) via Kepler's third law:

$$P = \frac{2\pi a^{3/2}}{[G(M_1 + M_2)]^{1/2}}. \tag{1}$$

Here we assume that the inclination of the system is close to 90°, as implied by the existence of an eclipse. If we assume that the donor fills its Roche lobe, then we can make the simplifying assumption that the Roche lobe radius ($R_{\rm RLO}$) is equal to the donor radius (R_2). The separation can then be expressed as (Eggleton 1983)

$$a = R_2 \frac{0.6q^{2/3} + \ln(1 + q^{1/3})}{0.49q^{2/3}}, \tag{2}$$

where $q = M_2/M_1$. If the mass and radius of the donor star are known, then equations (1) and (2) can be used to determine values of the period for plausible masses of the compact object.

The mass of [MAC92] 17A derived from spectroscopic data is $\sim 35\ M_\odot$ (Clark & Crowther 2004). The uncertainty on this value is large. It is possible (but unlikely) that [MAC92] 17A might have a mass as low as 17 $M_\odot$. The radius of [MAC92] 17A is derived using standard mass-radius values for Wolf-Rayet (WR) stars taken from Langer (1989). Assuming that [MAC92] 17A is indeed the donor star, we find that for $M_1 = 1$–$100\ M_\odot$, the period derived using equations (1) and (2) is 2–3.5 hr. These conclusions still apply if the mass of [MAC92] 17A is closer to 17 $M_\odot$ than 35 $M_\odot$. Clearly, the observed period is inconsistent with Roche lobe overflow and implies that accretion is the result of a wind, as seen in many other high-mass X-ray binaries.

3.2. *The Mass of the Compact Object*

The standard method for measuring the mass of stars in a binary system is to determine the mass function (e.g., McClintock & Remillard (2006):

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

where K_2 is the half-amplitude of the velocity curve of the secondary. The mass function is the minimum mass of the compact

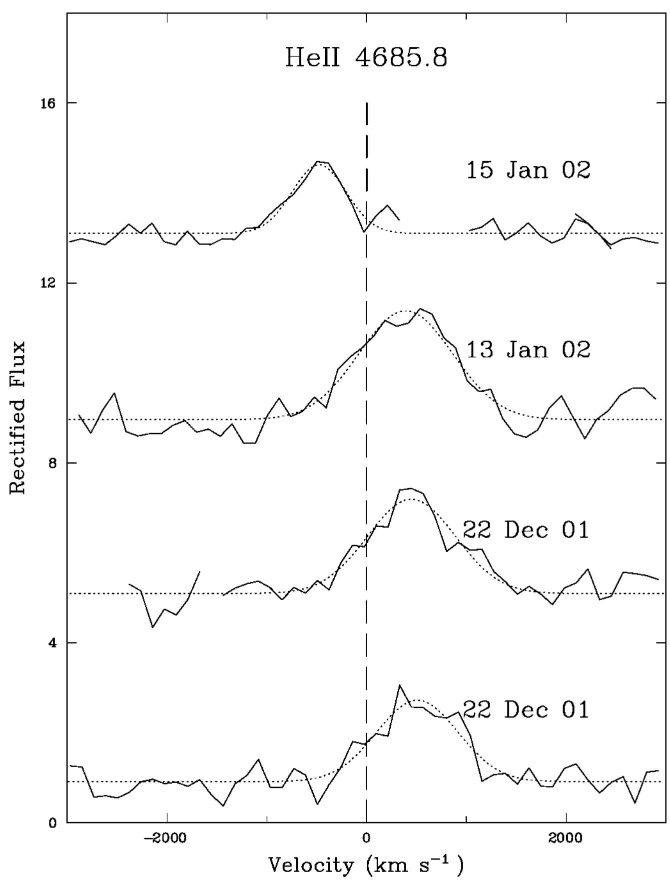

FIG. 3.—He II λ4686 line in [MAC92] 17A. Four individual spectra are shown. Zero velocity is shown as the dashed line. There is clear evidence that the line centroid has shifted.

primary. In the case of the IC 10 X-1 system, we have reasonable estimates for the orbital period and the inclination, but we require a value for K_2 to secure the mass function. The centroid of the He II λ4686 line is commonly used to determine the radial velocity of WR+OB binaries because it is formed in the inner wind, close to the star. In the light of the discovery of the orbital period in IC 10 X-1, we reexamined the optical spectra presented by Clark & Crowther (2004) to search for shifts in the centroid of the He II λ4686 line that might be due to the orbital motion. We note that the spectrum of [MAC92] 17A is characteristic of a WN star and does not show evidence of features seen in accretion-driven outflows (e.g., H I, He I, and Fe II). We are therefore reasonably confident that the He II λ4686 line in [MAC92] 17A is associated with the donor star and that there is minimal contribution from any accretion disk.

Individual Gemini Multi-Object Spectrograph spectra of [MAC92] 17A were re-extracted relative to the IC 10 nebular [O III] λ5006.8 line. Figure 3 shows the individual spectra, together with Gaussian fits to the He II λ4686 line. Two 1 hr exposures were taken sequentially on the night of 2001 December 22, and two additional spectra were obtained on the nights of 2002 January 13 and 15. As might be expected for a binary system with a period of 34.4 hr, there is no evidence of a shift in the velocity centroid of the stellar He II λ4686 line within IC 10 for the two exposures taken on 2001 December 22. However, the line centroid on 2002 January 15 is definitely shifted substantially relative to the other data sets. The FWHM of the fitted Gaussian for the 2002 January 15 data set is narrower than that determined for the other epochs (10 Å vs. 15–17 Å). This may be due to a CCD defect that contaminates the red component of the 2002 January 15 line. Our best estimate for the centroid of the He II λ4686 line on 2002 January 15 is ~ -300 km s^{-1}, compared to $\sim +450$ km s^{-1} for the other epochs.

We make the assumption that the shift in the He II λ4686 line centroid of approximately 750 km s^{-1} is due to the radial velocity of [MAC92] 17A. We further assume that 750 km s^{-1} corresponds to the maximum possible velocity displacement. We find that $K_2 = 375$ km s^{-1} and that the mass function $f(M) = 7.8\ M_\odot$. This value of the mass function implies that the compact object is a black hole.

We can further constrain the mass of the compact object by using equation (3) and by assuming a range of reasonable values for the mass of the donor star and the inclination of the system, as shown in Table 1. The mass of [MAC92] 17A derived by Clark & Crowther (2004) from spectroscopic data is $\sim 35\ M_\odot$. There is considerable uncertainty in this estimate, and so we use a conservative lower limit of 17 $M_\odot$. The existence of deep eclipses suggests that the inclination of the system is close to 90°; however, we cannot rule out the possibility that the inclination is considerably less, and therefore we use 45° as a lower limit. Table 1 demonstrates that the minimum mass of the black hole is $\sim 23\ M_\odot$, to satisfy the constraints of equation (3). Assuming that the inclination of the system is close to 90°, we find that the mass of the black hole is most plausibly in the range 23–34 $M_\odot$. However, if the inclination is much lower than expected (close to 45°), then the black hole mass can be as high as $\sim 57\ M_\odot$.

TABLE 1
BLACK HOLE MASS (IN UNITS OF SOLAR MASS) AS A FUNCTION OF INCLINATION AND DONOR MASS

Inclination (deg)	Donor Mass ($M_\odot$)		
	17	25	35
90	23	28	34
60	29	35	41
45	43	49	57

If the mass of the compact object in IC 10 X-1 is indeed $>23\ M_\odot$, then it is the most massive stellar-mass black hole known with a dynamically determined mass (the record is currently held by GRS 1915+105, with a mass 10–18 $M_\odot$; Remillard & McClintock 2006). Most models predict that the remnants of a supernova explosion have masses below 20 $M_\odot$ (Fryer & Kalogera 2001). It is possible that the black hole in IC 10 X-1 has increased its mass by accreting material from [MAC92] 17A (Podsiadlowski et al. 2003). The low metallicity of IC 10 may also be conducive to the formation of higher mass black holes (Fryer & Kalogera 2001). Detailed theoretical models need to be developed to understand the evolutionary history of IC 10 X-1.

3.3. *Is the Model of IC 10 X-1 Self-consistent?*

The results from this and previous studies of the IC 10 X-1 system suggest that it is a detached binary composed of a massive ($\sim 35\ M_\odot$) Wolf-Rayet star with a 23–34 $M_\odot$ black hole companion. X-rays are produced as material from the wind of [MAC92] 17A is accreted via an accretion disk onto the black hole. It is important to test the self-consistency of this model and to show that such a system is indeed capable of forming an accretion disk and producing X-rays.

A black hole in a detached binary system can form an accretion disk (and hence be a strong X-ray source) if the following condition is met (e.g., Ergma & Yungelson 1998):

$$P < 4.8(M_{\rm BH}/M_\odot)v_{1000}^{-4}\delta^2, \quad (4)$$

where $M_{\rm BH}$ is the mass of the black hole, v is the velocity of the wind impacting the compact object in units of 1000 km s^{-1}, P is the period in hours, and δ is a dimensionless parameter of order unity. If the mass of the black hole is 24–34 $M_\odot$, then we find that this condition is satisfied if $v \leq 1400$–1500 km s^{-1}. The terminal wind velocity of [MAC92] 17A was estimated by Clark & Crowther (2004) to be $v_\infty = 1750$ km s^{-1}. The velocity of the wind impacting the black hole will be less than the terminal velocity; the upper limit of 1400–1500 km s^{-1} is consistent with the wind structure of a Wolf-Rayet star (Carpano et al. 2007a).

The energy released by material falling onto a compact object via an accretion disk is given by $L = \eta\dot{M}c^2$, where $\dot{M}$ is the accretion rate and η is the efficiency (Shakura & Syunyaev 1973). If we assume that $\eta = 0.1$, then the mass accretion rate required to sustain an X-ray luminosity of $L_{\rm X} \sim 2 \times 10^{38}$ ergs s^{-1} is $\sim 3.5 \times 10^{-8}$ $M_\odot$ yr^{-1}. The mass-loss rate of [MAC92] 17A derived by Clark & Crowther (2004) is $\sim 10^{-5}$ $M_\odot$ yr^{-1}. We therefore conclude that direct wind-fed accretion is consistent with the observed X-ray luminosity.

3.4. *IC 10 X-1 and the Star Formation History of IC 10*

Both the mass of the donor and the mass of the compact object in IC 10 X-1 indicate that this system is less than 10 Myr old. This is consistent with the suggestion that ~3–4 Myr ago, there were pockets of star formation that may still be ongoing (Hunter 2001). There are several dozen WR stars in IC 10 that also indicate recent star formation (Massey & Holmes 2002; Crowther et al. 2003). The fact that the donor is a He-core WR star indicates that its initial mass was much higher (probably in excess of 60 $M_\odot$; Meynet & Maeder 2005), in which case the system could have formed in one of the more recent star formation events. The presence of a shell of ionized gas around the system, probably related to supernova activity, indicates that there is still ongoing star formation in that region. The formation of the very massive progenitors of this binary requires a very flat initial mass function (IMF). Hunter (2001) finds that such a flat IMF is consistent with a star formation scenario of widespread activity ~40 Myr ago and more recent (~3–4 Myr) localized events.

4. SUMMARY AND CONCLUSIONS

We have used *Swift* and *Chandra* to determine the orbital period of the bright Wolf-Rayet X-ray binary IC 10 X-1 to be 34.4 hr. Using this value of the period, and the mass of the donor star derived by Clark & Crowther (2004) from optical spectroscopy, we use Kepler's laws to show that the donor star almost certainly does not fill its Roche lobe. We cannot derive the mass function of the binary system or the mass of the compact companion from the period alone. However, a reexamination of published optical data reveals a shift in the centroid of the He II λ4686 line that is most likely due to the orbital motion of the donor star. If this is the case, then the mass function $f(M) \sim 7.8$ $M_\odot$, and the compact object is a black hole. Assuming that the mass of the donor star is 17–35 $M_\odot$, we calculate that the black hole mass is ~24–34 $M_\odot$. If confirmed, this makes IC 10 X-1 the most massive black hole binary known. We show that it is possible for an accretion disk to form and that the observed mass-loss rate can power the X-ray luminosity.

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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
Carpano, S., Pollock, A.M.T., Prestwich, A., Crowther, P., Wilms, J., Yungelson, L., & Ehle, M. 2007a, A&A, 466, L17
Carpano, S., Pollock, A. M. T., Wilms, J., Ehle, M., & Schirmer, M. 2007b, A&A, 461, L9
Clark, J. S., & Crowther, P. A. 2004, A&A, 414, L45
Clarkson, W. I., Charles, P. A., Coe, M. J., & Laycock, S. 2004, Nucl. Phys. B Proc. Suppl., 132, 588
Crowther, P. A., Drissen, L., Abbott, J. B., Royer, P., & Smartt, S. J. 2003, A&A, 404, 483
Eggleton, P. P. 1983, ApJ, 268, 368
Ergma, E., & Yungelson, L. R. 1998, A&A, 333, 151
Fryer, C. L., & Kalogera, V. 2001, ApJ, 554, 548
Horne, J. H., & Baliunas, S. L. 1986, ApJ, 302, 757
Hunter, D. A. 2001, ApJ, 559, 225
Langer, N. 1989, A&A, 210, 93
Massey, P., & Holmes, S. 2002, ApJ, 580, L35
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
Meynet, G., & Maeder, A. 2005, A&A, 429, 581
Podsiadlowski, P., Rappaport, S., & Han, Z. 2003, MNRAS, 341, 385
Prestwich, A. H., Kilgard, R. E., Carpano, S., Saar, S., Page, K., Roberts, A. P. T., Ward, M., & Zezas, A. 2006, ATel, 955
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Shakura, N. I., & Syunyaev, R. A. 1973, A&A, 24, 337
van den Heuvel, E. P. J., & de Loore, C. 1973, A&A, 25, 387
Wang, Q. D., Whitaker, K. E., & Williams, R. 2005, MNRAS, 362, 1065
Yang, H., & Skillman, E. D. 1993, AJ, 106, 1448