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NGC 300 X-1 is a Wolf–Rayet/black hole binary

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ABSTRACT
We present Very Large Telescope/FORS2 time-series spectroscopy of the Wolf–Rayet (WR) star #41 in the Sculptor group galaxy NGC 300. We confirm a physical association with NGC 300 X-1, since radial velocity variations of the He II λ4686 line indicate an orbital period of 32.3 ± 0.2 h which agrees at the 2σ level with the X-ray period from Carpano et al. We measure a radial velocity semi-amplitude of 267 ± 8 km s⁻¹, from which a mass function of 2.6 ± 0.3 M⊙ is obtained. A revised spectroscopic mass for the WN-type companion of 26±47 M⊙ yields a black hole mass of 20 ± 4 M⊙ for a preferred inclination of 60°–75°. If the WR star provides half of the measured visual continuum flux, a reduced WR (black hole) mass of 15±45 M⊙ (14.5±3 M⊙) would be inferred. As such, #41/NGC 300 X-1 represents only the second extragalactic WR plus black hole binary system, after IC 10 X-1. In addition, the compact object responsible for NGC 300 X-1 is the second highest stellar-mass black hole known to date, exceeded only by IC 10 X-1.

Key words: stars: Wolf–Rayet – galaxies: individual: NGC 300 – X-rays: binaries – X-rays: individual: NGC 300 X-1.

1 INTRODUCTION
High mass X-ray binaries (HMXB) typically comprise OB stars plus either a neutron star or a black hole, in which high X-ray luminosities (∼10³⁸ erg s⁻¹) arise from accretion discs around the compact object. Accretion discs are fed through a combination of Roche-lobe overflow and stellar winds from the early-type companion. Accretion discs are revealed in the HeII λ4686 emission line. Section 2 in which variations are revealed in the HeII λ4686 emission line. Section 3 compares the inferred orbital period with X-ray light curves and derives a semi-amplitude for the WR star, from which a mass function is obtained. Section 4 provides a revised mass for the WR star, placing strict limits upon the mass of the compact companion. We conclude with a brief discussion in Section 5.

2 OBSERVATIONS
Here we present new VLT optical spectroscopy of #41 obtained with the Focal Reducer/Low Dispersion Spectrograph #2 (FORS2)


Table 1. Log of VLT/FORS2 spectroscopic observations of #41 in NGC 300. UT dates and MJDs refer to the start of the 1535 s exposures. We include individual radial velocities, \( v_r \), as measured from Gaussian fits to He II \( \lambda \)4686. Phases adopt a period of 32.3 h, where phase 0 refers to MJD 55118.975 ± 0.01554.

<table>
<thead>
<tr>
<th>UT Date</th>
<th>MJD</th>
<th>DIMM (arcsec)</th>
<th>( v_r ) ( \lambda )4686 (km s(^{-1}))</th>
<th>Phase</th>
</tr>
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<td>01:06 09 Oct 15</td>
<td>0.046180</td>
<td>1.2</td>
<td>1.29 347.0 ± 17.7 0.052</td>
<td></td>
</tr>
<tr>
<td>05:28 09 Oct 15</td>
<td>0.227922</td>
<td>2.3</td>
<td>1.08 364.6 ± 25.5 0.187</td>
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</tr>
<tr>
<td>01:40 09 Oct 16</td>
<td>1.069495</td>
<td>1.1</td>
<td>1.18 −64.2 ± 16.9 0.812</td>
<td></td>
</tr>
<tr>
<td>05:58 09 Oct 16</td>
<td>1.240073</td>
<td>1.7</td>
<td>1.14 136.0 ± 25.0 0.945</td>
<td></td>
</tr>
<tr>
<td>04:07 09 Oct 19</td>
<td>4.171590</td>
<td>0.7</td>
<td>1.03 369.0 ± 14.3 0.114</td>
<td></td>
</tr>
<tr>
<td>08:24 09 Oct 19</td>
<td>4.350382</td>
<td>0.8</td>
<td>1.98 456.6 ± 20.1 0.247</td>
<td></td>
</tr>
<tr>
<td>02:31 09 Oct 20</td>
<td>5.104896</td>
<td>0.9</td>
<td>1.06 −68.3 ± 12.1 0.807</td>
<td></td>
</tr>
<tr>
<td>06:41 09 Oct 20</td>
<td>5.278856</td>
<td>0.7</td>
<td>1.31 109.4 ± 17.3 0.936</td>
<td></td>
</tr>
<tr>
<td>00:14 09 Oct 25</td>
<td>10.010318</td>
<td>1.2</td>
<td>1.34 325.3 ± 25.7 0.447</td>
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</tr>
<tr>
<td>06:28 09 Oct 25</td>
<td>10.269520</td>
<td>0.7</td>
<td>1.33 10.4 ± 14.3 0.639</td>
<td></td>
</tr>
</tbody>
</table>


3 ORBITAL PERIOD

Several VLT/FORS2 spectroscopic observations in the vicinity of He II \( \lambda \)4686 are presented in Fig. 1, revealing large radial velocity variations. Gaussian profiles are fitted to individual \( \lambda \)4686 profiles, with individual centroids listed in Table 1.

In view of the sparsely sampled data sets, we have employed the string-length approach of Dworetsky (1983). The data are folded on a set of trial frequencies and the total length of ‘string’ required to join the observations in phase order is calculated. The smallest string length found from the search is assumed to correspond to the correct period. The resulting periodogram is shown in Fig. 2. The deepest trough corresponds to a period of 32.3 ± 0.2 h. The error on this period was computed by constructing 10 000 synthesized data sets and measuring the standard deviation of the positions of the deepest troughs in the resulting periodograms. The synthesized data sets were obtained by ‘jiggling’ each data point about its observed value by an amount given by its error bar multiplied by a number output by a Gaussian random-number generator with zero mean and unit variance.

It can be seen that our derived period is in agreement at the 2\( \sigma \) level with the Swift X-ray period of 32.8 ± 0.2 h (1σ; Carpano et al. 2007b), which gives us confidence that we have identified the correct value. Moreover, the minimum string length of our period (1.49) compares favourably with the string length of a perfect sinusoid (1.46) and the string length of a sinusoid with noise consistent with the error bars on the observed data added to it (1.48).

To further test the significance of our derived period, we used a randomization technique (Fisher 1935). The radial velocities were randomly reassigned to the times of observation, thereby preserving the data sampling and the mean and standard deviation of the
where

\[ f = \frac{PK^2}{2mG} = M_1 \sin^3 i (1 + q)^{-1} \]

where \( M_1 \) is the compact object mass and \( q = M_2/M_1 \). The derived mass function is \( f = \frac{2.63 \pm 0.03}{0.62 \pm 0.02} \), and would correspond to the compact object mass in a system viewed at an inclination of 90° whose companion mass is negligible. In the case of a massive companion star with \( q \sim 1 \), the compact object would have a minimum mass of 4 \( f(m) \). As such, the compact object in NGC 300 X-1 is indeed a black hole, such that this system represents the only second confirmed WR plus black hole binary.

4 WOLF–RAYET PROPERTIES

We present our new, combined (phase-corrected), rectified VLT/FORS2 spectrum of #41 in Fig. 4. This high quality spectrum confirms a weak-lined WN5 subtype, previously inferred by Crowther et al. (2007) from lower resolution, lower signal-to-noise ratio (S/N) spectroscopy obtained with VLT/FORS2 using the 300V grism in 2007 January. Overall, the visual spectrum of #41 is similar to other weak-lined WN5 stars, namely WR 49 in the Milky Way and Brey 65b (=NGC 2044 West 5C) in the LMC, taken from Hamann, Koesterke & Wessolowski (1995) and Walborn et al. (1999), respectively. The He \( \lambda \) 4686 equivalent width (\( W_\lambda \sim 56 \) Å) and linewidth [full width at half-maximum (FWHM) \( \sim 17 \) Å] in #41 are somewhat lower than LMC and Milky Way counterparts, \( W_\lambda = 110-140 \) Å and \( \text{FWHM} = 22-24 \) Å.

In order to reassess the mass of #41, we have calculated a synthetic model using the Hillier & Miller (1998) line-blanketed, non-local thermodynamic equilibrium model atmosphere code. With respect to Crowther et al. (2007), somewhat more sophisticated atomic models are considered, namely H, He, C, N, O, Ne, Si, P, S, Ar, Fe and Ni. Elemental abundances are set to 40 per cent of the solar value (Urbaneja et al. 2005), with the exception of H and CNO elements. Clumping is accounted for, albeit in an approximate manner, with a (maximum) volume filling factor of 10 per cent, such that the derived mass-loss rate is three times smaller than the value that would have been obtained by assuming a homogeneous wind.

In view of the weak He I line spectrum in #41, we have based our analysis upon He II (\( \lambda \) 4686, 5411) and N iv – v (\( \lambda \) 4603–4620, 4658, \( \lambda \lambda \) 7103–7129) line diagnostics. Overall good agreement is found, which is remarkable in view of the close proximity of the black hole to #41. The only significant discrepancies are that \( N_e \) at 4634–4641 is not reproduced in the synthetic spectrum and excess emission is observed in the upper Pickering–Balmer series, the latter potentially arising from the accretion disc.

In Fig. 5 we present our new combined flux-calibrated spectrum of #41, together with recalibrated spectroscopy from Crowther et al. (2007) for \( \lambda > 5800 \) Å. An optimum fit to the spectrum of #41 is included in the figure and reveals the following stellar parameters: \( T_\ast \sim 65 \) kK, \( \log(L/L_\odot) \sim 5.92, M_\ast \approx 5 \times 10^{-6} M_\odot \text{ yr}^{-1}, v_{\infty} \sim 1300 \text{ km s}^{-1} \), plus a nitrogen mass fraction of \( \sim 0.5 \) per cent, with negligible hydrogen adopted. With respect to Crowther et al. (2007), the main revision relates to a reduced absolute magnitude of \( M_V = -5.0 \) mag, on the basis of a lower interstellar reddening of \( E(B-V) = 0.4 \) mag. \( T_\ast \) should be reliable to \( \pm 5 \) kK, resulting in uncertainties of \( \pm 0.2 \) mag in bolometric corrections. Together with \( \pm 0.05 \) mag uncertainties in \( E(B-V) \), stellar luminosities should be reliable to \( \pm 0.14 \) dex.

From our derived parameters, we obtain a spectroscopic WR mass of \( 26_{-7}^{+3} M_\odot \) on the basis of the Schaerer & Maeder (1992) mass–luminosity relation for hydrogen-free WR stars. The principal uncertainty in our inferred WR mass relates to the absolute visual magnitude of the WR star. Since our adopted visual magnitude is based upon ground-based imaging, it is possible that other continuum sources are included in the photometry. In this case, the WR
stars in the Milky Way. In view of these issues, we shall evaluate estimated spectroscopic masses of 15–19 M_☉ for the WR luminosity would be reduced to log \((L/\text{⊙})\) \(\sim 2.5\) for the WR case, resulting from the WR star contributing 50 per cent of its Roche-lobe radius, \(r_L\) (Eggleton 1983). Therefore, the accretion disc may be fed primarily through Roche-lobe overflow. For comparison, the higher temperature obtained for the WN star in IC 10 X-1 by Clark & Crowther (2004) would favour a wind-fed accretion disc, since the WR radius is \(\sim 0.5\) \(r_L\) in that system.

IC 10 X-1 is an eclipsing X-ray system (Prestwich et al. 2007); therefore, geometric arguments imply that the black hole would be eclipsed for \(i \geq 78^\circ\) for the WR properties derived by Clark & Crowther (2004). If we adopt a radius of \(\sim 0.5\) \(r_L\) for the accretion disc, an eclipse of the X-ray emitting accretion disc would require \(i \geq 80^\circ\). NGC 300 X-1 does exhibit significant X-ray variability, but lacks a deep X-ray eclipse (Carpano et al. 2007b). Therefore, geometric arguments appear to rule out inclinations that would cause a total eclipse of the accretion disc \((i \leq 73^\circ \pm 2^\circ)\). However, a glancing eclipse would require \(i \geq 63.5^\circ \pm 3.5^\circ\) for the range of \(r_L\) radii obtained here. We therefore adopt \(i = 80^\circ \pm 9^\circ\) for IC 10 X-1 and \(i = 60^\circ \pm 7.5^\circ\) for NGC 300 X-1.

In Fig. 6 we present the host galaxy metallicity as a function of black hole masses for NGC 300 X-1 and IC 10 X-1, plus those for all HMXB systems for which the presence of a black hole is unambiguous, whose companion is an OB star with mass \(M_\star \geq 5\) M_☉, i.e. LMC X-3 (Val-Baker, Norton & Negueruela 2007), LMC X-1 (Orosz, Steeghs & McClintock 2003), M33 X-7 (Orosz et al. 2003). We limit our sample to classical HMXB, to ensure that their black hole masses for NGC 300 X-1 and IC 10 X-1 (Orosz, Steeghs & McClintock 2009), M33 X–7 (Orosz et al. 2003). According to Urbaneja et al. (2005), the oxygen content at this galactocentric distance in NGC 300 is log \((\text{O/H})\) \(\pm 12 \sim 8.44\),

The mass accretion rate required to sustain \(L_X = 2 \times 10^{38}\) erg s\(^{-1}\) is \(3.5 \times 10^{-8}\) M_☉ yr\(^{-1}\), if the adopted efficiency of gravitational release is \(\sim 10\) per cent (see Shakura & Sunyaev 1973). This is \(\leq 1\) per cent of our derived mass-loss rate of \(\dot{M}_\text{L}\). However, Table 2 also shows that the WR star would completely fill its Roche lobe for the 26 M_☉ case, resulting from the WR star contributing 50 per cent of its mass-loss rate unaffected, implying a spectroscopic mass corresponding to only 2.5–3.5 WR radii.

Table 2. Derived black hole mass, \(M_1\), in NGC 300 X-1 for \(i = 45^\circ\), 60° and 90°, for cases in which the WN star contributes either 50 per cent (\(M_2 = 15\) M_☉) or 100 per cent (\(M_2 = 26\) M_☉) of the visual light. We include the separation between the WR star, \(a\), and the WR radius, \(R_2\), as a fraction of the Roche-lobe radius, \(r_L\) (Eggleton 1983).

<table>
<thead>
<tr>
<th>(M_2) (WR)</th>
<th>(R_2) (WR)</th>
<th>(i)</th>
<th>(M_1) (BH)</th>
<th>(a)</th>
<th>(R_2/r_L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 &amp; 4.5 &amp; 45° &amp; 21.5 &amp; 10^\circ &amp; 0.81</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 &amp; 5 &amp; 60° &amp; 15.6 &amp; 10^\circ &amp; 0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 &amp; 2.5 &amp; 90° &amp; 12.6 &amp; 10^\circ &amp; 0.79</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 &amp; 7.2 &amp; 45° &amp; 27.8 &amp; 10^\circ &amp; 0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 &amp; 7.2 &amp; 60° &amp; 20.6 &amp; 10^\circ &amp; 0.98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 &amp; 7.2 &amp; 90° &amp; 16.9 &amp; 10^\circ &amp; 0.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(a\)The apparent glancing eclipse of the X-ray emitting accretion disc suggests \(i = 60^\circ \pm 7.5^\circ\).
i.e. relatively similar to the LMC for which log(O/H) + 12 = 8.37 (Russell & Dopita 1990). The only other HMXB whose black hole mass is known to greatly exceed 10 M⊙ is M33 X-7 (Orosz et al. 2007), for which a near identical oxygen content of log(O/H) + 12 = 8.42 is inferred at its location in M33 from the calibration of Magrini et al. (2007).

High black hole masses require that the progenitor star was very massive and experienced low mass-loss rates (Belczynski et al. 2009). Weak stellar winds is a natural consequence of low metallicity (Mokiem et al. 2007). However, orbital periods of IC 10 X-1 and NGC 300 X-1 are so short that the radius of the black hole progenitor star must have been larger than the present separation of the components. As such, the progenitor would have experienced extreme mass loss through Roche-lobe overflow. Therefore, reconciling high black hole masses with close orbital separations is a major challenge for binary evolution models.

In the standard picture, such systems involve a common-envelope phase, which would naturally lead to a merger (Podsiadlowski, Rappaport & Han 2003). Alternatively, de Mink et al. (2009) propose that the short orbital period results in tidal-locking of the stellar rotation, causing a chemically homogeneous evolution through rotational mixing (Maeder 1987). In this scenario, binary components would remain compact and so circumvent the high mass transfer rates of Roche-lobe overflow systems. If NGC 300 X-1 and IC 10 X-1 were to survive their second supernova explosion, they would form binary black hole systems, merging on a time-scale of a few Gyr. Binary black hole mergers have been considered by Sadowski et al. (2008), who argued that their detection rate may be much higher than double neutron star systems for current gravitational wave experiments.

In conclusion, new VLT/FORS2 time-series spectroscopy of the WN star #41 in NGC 300 is presented, which confirm that it is physically associated with the NGC 300 X-1 system. We find that NGC 300 X-1 hosts the most massive stellar-mass black hole known, with the exception of the other extragalactic WR/black hole system IC 10 X-1.