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Letter to the Editor

On the Wolf-Rayet counterpart to IC 10 X-1

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Abstract. Recent CHANDRA observations of the starburst galaxy IC 10 have resulted in an improved position for the bright ($>10^{38}$ erg s^{-1}) X-ray source IC 10 X-1. We discuss arguments in favour of the Wolf-Rayet star #17-A from Massey et al. and Crowther et al. being the optical counterpart; alternative possibilities are also considered. We discuss the properties of Massey et al. 17-A, finding it to be amongst the most luminous – and hence massive – WNE stars known and make comparisons with Cyg X-3. Finally we examine evolutionary constraints relating to the nature of the compact companion, finding that a putative neutron star companion would place stringent constraints on the minimum progenitor mass required to form a black hole in close binaries.

Key words. galaxies: individual: IC 10 – stars: Wolf Rayet – X-rays: binaries

1. Introduction

While the population of X-ray binaries in the Galaxy has been extensively studied, the absence of high spatial resolution X-ray observations have hindered the investigation of X-ray sources in external galaxies other than the Magellanic Clouds. Brandt et al. (1997) identify a luminous ($L_{0.1-2.5\ \mathrm{kev}}$ = 2–4 × 10^{38} erg s^{-1}) variable X-ray point source in the local starburst galaxy IC 10, which they propose to be an accreting binary and advance the Wolf Rayet (WR) star #17 (Massey et al. 1992) as a possible optical counterpart. Subsequently, as part of a survey of the WR population of IC 10, #17 was reobserved by Crowther et al. (2003; hereafter C03) and was found to be a composite of 2 objects; the WR component being [MAC92] 17-A, adopting the notation of C03.

Recent 30 ks *Chandra* observations of IC 10 X-1 revealed significant X-ray variability, albeit with no evidence for periodic modulation (Bauer & Brandt 2003). However, the X-ray luminosity, lack of pulsations and the hardness of the X-ray spectrum suggest that the accreting object is possibly a black hole (Bauer & Brandt 2003). Comparison of the *Chandra* observations to new *HST* ACS observations of the field placed IC 10 X-1 $0.23'' \pm 0.30''$ from [MAC92] 17-A, with three further objects $0.3'' < d \leq 0.4''$ from the X-ray position (see Table 1).

Given the proximity of the optical sources to IC 10 X-1, we analyse the available datasets to infer stellar and putative binary properties. In particular, we employ a tailored NLTE model atmosphere fit for [MAC92] 17-A, the first time such a technique has been employed for the (probable) mass donor in an extragalactic X-ray binary. The likely association of IC 10 X-1 with [MAC92] 17-A is of particular importance given that it would be the first *unambiguous* confirmation of the post-supernovae evolutionary scenario for high mass X-ray binaries of Van den Heuvel & De Loore (1973).

Table 1. *HST* broadband photometry and angular offset from the *Chandra* X-ray position for the four possible counterparts to IC 10 X-1 (kindly provided by Franz Bauer 2003, priv. comm.); note that objects J002029.0+591651.6 and J002029.1+591651.7 are not identifiable in the Hunter (2001) dataset.

Star	Angular Offset	*B*	*V*	*I*
[MAC92] 17-A	0.23″	23.19	22.55	21.81
J002029.0+591651.6	0.33″	>27	25.28	24.42
J002029.1+591651.7	0.37″	>27	25.86	23.97
[MAC92] 17-B	0.42″	22.87	22.28	21.79

2. Observations and data analysis

Four 3600 s spectroscopic observations of [MAC92] 17-A and [MAC92] 17-B were made with the 8 m Gemini-N and GMOS between 2001 December 22 – 2002 January 15. While a full description of the observations and data reduction employed may be found in C03, we briefly summarize them here. In all observations the B600 grating (centred at 560 nm) and a 1.0 arcsec slit were employed, yielding a 2 pixel spectral resolution of 5 Å. Spectral extraction was performed on a

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narrow (~5 pixel) region in order to avoid contamination from the other object.

The mean and four individual spectra of [MAC92] 17-A, are shown in Fig. 1. The two observations on 22 Dec. 2001 were taken concurrently. [MAC92] 17-A shows prominent He II 4686 Å emission, plus He II 5411 Å, and we tentatively identify weak N V 4603–20 Å emission. The absence of prominent N IV 4058 Å emission indicates a WN3 spectral type. No emission from comparatively low excitation species such as H I and He I is present.

We highlight the apparent changes in the He II 4686 Å line profile between the four spectra of [MAC92] 17-A. Given the difficulties encountered during spectral extraction due to the proximity of [MAC92] 17-A and the presence of a cosmic ray in the spectrum obtained on 2002 January 15 we refrain from claiming variability but highlight it as a possibility that requires further investigation.

With the exception of possible weak Hβ absorption, the four spectra of [MAC92] 17-B are featureless at the S/N of the present observations. As such are not shown, although we discuss a potential classification as an OB star further in Sect. 3.2.

Finally, *BVI* photometry of all four objects obtained from *HST* observations (2002 October 12, Bauer & Brandt 2003) are presented in Table 1. We note that *HST WFPC V* band magnitudes of [MAC92] 17-A and [MAC92] 17-B obtained on 1999 June 9 (Hunter 2001) are identical within the observational errors.

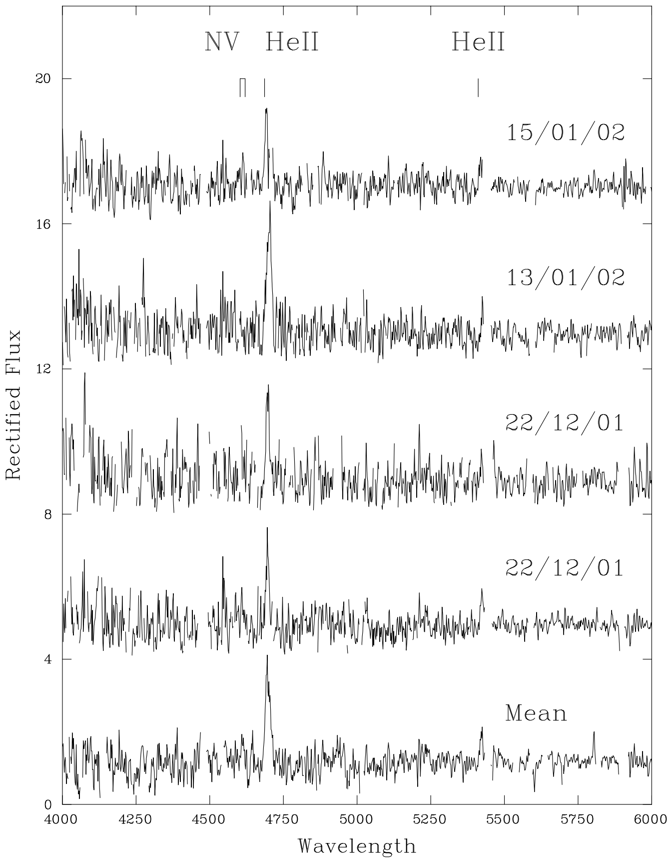

Fig. 1. Mean and 4 individual spectra of [MAC92] 17-A; note the lack of emission from low excitation species such as H I and He I, and the possible variability in the line profiles of the He II 4686 Å and 5411 Å transitions.

3. Stellar properties of potential counterparts to IC 10 X-1

3.1. [MAC92] 17-A

Due to its proximity to IC 10 X-1 and unusual spectroscopic appearance, [MAC92] 17-A represents the strongest candidate for the correct optical counterpart; here we present an analysis of the *mean* spectrum in order to contrain its physical parameters. C03 find that the spectrum of [MAC92] 17-A is *consistent* with an identification as a WNE star, based on the presence and strength of the He II 4686 Å line ($EW \sim -30$ Å). Note that no low excitation features – such as H I, He I or Fe II – are present to suggest that the emission arrises in an accretion driven outflow (cf. A0538-66; Charles et al. 1983); hence we believe that [MAC92] 17-A is a *bona fide* WNE star. As in C03, we adopt a distance of 590 kpc to IC 10 (DM = 23.86 mag; Borissova et al. 2000). From ACS imaging, $B - V = 0.7$ mag, implying $E(B - V) = 1.0$ mag, using a typical early-type WN intrinsic colour of $(B - V)_0 = -0.3$ mag. Consequently, we estimate $M_V = -4.4$ mag for [MAC92 17-A].

We have calculated representative synthetic WNE spectra using the Hillier & Miller (1998) line-blanketed, non-LTE model atmospheric code. Relatively simple atomic species are considered in detail, namely H, He, C, N, O, Si and Fe. Given the poor quality and limited spectral range of the observations, a unique spectral fit may not be claimed. Nevertheless, a model with the following stellar parameters – $T_* = 85\,000$ K, $\log(L/L_\odot) = 6.05$, $\dot{M} = 4 \times 10^{-6}\ M_\odot\,\mathrm{yr}^{-1}$, $v_\infty = 1750\ \mathrm{km\,s}^{-1}$ – reproduces the observed He II λ4686 plus weak N V $\lambda\lambda$4603–20 emission. Clumping is accounted for in a crude manner (see Hillier & Miller 1999) with a (maximum) volume filling factor of 10%, such that the derived mass-loss rate is equivalent to a homogeneous mass-loss rate of $\sim 1 \times 10^{-5}\ M_\odot\,\mathrm{yr}^{-1}$. Several early-type WN stars in the SMC, with a metallicity comparable to IC 10, have been analysed in an identical manner (Abbott 2003, priv. comm.) and were found to possess similar properties. Under the assumption that [MAC92] 17-A is hydrogen free – justified in Sect. 4 – we can use the Schaerer & Maeder (1992) mass-luminosity relation for H-free WR stars to derive a present mass of $\sim 35\ M_\odot$, implying a progenitor mass some 2–3 times larger.

If [MAC92] 17-A is the mass donor in IC 10 X-1, the evolutionary requirements for the formation of a WR+compact companion (cc) system – see Sect. 4 – imply that it would closely resemble the WNE+cc binary Cyg X-3 (van Kerkwijk 1993)[1]. Intriguingly, significant line profile variability is observed in Cyg X-3 and is attributed to time dependent ionization of the stellar wind by the variable X-ray flux (van Kerkwijk et al. 1996; Fender et al. 1999). Confirmation of the line profile variability potentially present in our dataset would therefore provide compelling evidence for an association of [MAC92] 17-A with IC 10 X-1.

[1] However Mitra (1998) argues that the mass donor in Cyg X-3 is not a high mass WR descendant of an O star.

A 4.8 hr orbital period has been inferred for Cyg X-3 from modulation of the X-ray flux (Parsignault et al. 1972). Given the small orbital separation this implies, the compact object accretes material directly from the powerful ($\dot{M} > 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$; van Kerkwijk et al. 1996) wind of the WNE star, equivalent to the (homogeneous) mass-loss rate of [MAC92] 17-A. Therefore, we conclude that if IC 10 X-1 has a similarly short orbital period, direct wind fed accretion onto a solar mass compact object is consistent with the observed X-ray luminosity.

3.2. Remaining candidates

No strong features are present in the optical GMOS spectrum of [MAC92] 17-B, except for probable Hβ absorption, such that it is a candidate OB star. Unfortunately, the S/N is insufficient to identify He I-II features for firmer conclusions. The observed $B-V$ colour for [MCA92] 17-B is identical to 17-A, which implies an equivalent reddening of $E(B-V) = 1.0$ mag if this star is an O or early B star, with an intrinsic colour of $(B-V)_0 = -0.3$ mag. In turn, this implies an absolute magnitude of $M_V = -4.6$ mag, which is typical of a late O dwarf (Conti et al. 1983). For an assumed spectral type of O8V, and current temperature calibration of Martins et al. (2002), [MAC92] 17-B would have a bolometric luminosity of $\log(L/L_{\odot}) \sim 5$, and current mass of $\sim$35 $M_{\odot}$. If [MAC92] 17-B is the counterpart to IC 10 X-1 its mass loss rate ($\sim 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$) is clearly insufficent to power the X-ray luminosity via direct wind fed accretion, instead mass transfer must occur via Roche lobe overflow (RLOF). Such a system would then be a compact binary, with an orbital period of between 1−2 days, an example being LMC X-4 (O8III-V mass donor; Negueruela & Coe 2002).

Finally, we turn to J002029.0+591651.6 and J002029.1+591651.7. If the magnitudes quoted in Table 1 are representative of their stellar continua, these stars are consistent with mid-B main sequence stars, with $M_V \sim -1.6$ mag and $M_V \sim -1.0$ mag respectively. Despite their visual magnitudes we do not consider identification as classical Be X-ray binaries as likely, due to the earlier spectral types and lower X-ray luminosities typical for such objects. Consequently, the putative binary would then be a short period system accreting via RLOF; a suitable template being LMC X-3 – a 1.7 day mid B + black hole system with a comparable X-ray flux to IC 10 X-1 (Negueruela & Coe 2002). Alternatively, we might suppose a long period LMXB in outburst, where the accretion disc dominates the optical luminosity. Piro & Bildstein (2002; and references therein) show that for a suitable low mass system with period of ∼10 days, the accretion disc will indeed dominate the optical output, resulting in a blue object with $M_V = -2$, again consistent with present data.

If any of these 3 objects are the correct counterpart we might expect significant photometric variability due to changes in the accretion rate or the geometrical aspect of the accretion disc and possible ellipsoidal modulation of the mass donor. Transient line emission from the accretion disc or an accretion driven outflow may also be present; we note that no such features were present in any of our spectra of [MAC92] 17-B.

4. Evolutionary history

With the residual uncertainty in the identity of the mass donor in Cyg X-3, the confirmation of [MAC92] 17-A as mass donor would validate the evolutionary scenario for massive binaries first proposed by Van den Heuvel & De Loore (1973). WR+cc binaries evolve from OB+cc binaries as the mass donor leaves the main sequence, leading to RLOF, common envelope evolution and the spiral in of the black hole. If the 2 components avoid a merger (leading to a Thorne-Zykov object) the dissipation of orbital energy will lead to the ejection of the H rich mantle of the OB star, leaving a short period WR+cc binary (note the ejection of the H rich mantle justifies our use of the Schaerer & Maeder 1992, mass luminosity relationship in Sect. 3.1).

Unfortunately, quantitative conclusions regarding the system history are difficult to make, due to the occurence of at least one episode of common envelope evolution – of which the physics is poorly undertood – and the uncertainty in the mass of the cc. Nevertheless, we may identify two distinct pre-SN evolutionary scenarios for the putative binary, one with quasi-conservative and one with non conservative mass transfer[2].

For a conservative, pre-SN evolutionary scenario, we propose case A mass transfer proceeding in an analagous manner to that proposed by Wellstein & Langer (1999) for GX 301-2, albeit with significantly more massive ($\sim$40 $M_{\odot}$) progenitors. Such an evolutionary scenario has the advantage that it leads to wide pre- and post-SN orbits, thus decreasing the chances of the merger of the post-SN binary components. While very massive stars ($\geq$40 $M_{\odot}$) are not expected to pass through a red supergiant phase, subsequent post-SN common envelope evolution would proceed via an LBV like phase (e.g. Vanbeveren et al. 1998), with the weakly bound atmosphere of the progenitor of [MAC92] 17-A ejected during the spiral in of the cc. Due to the enhanced mass loss rate of the "naked" cc progenitor – cf. Wellstein & Langer (1999) – we would expect the formation of a neutron star rather than a black hole.

An alternative, non-conservative, pre-SN evolutionary scenario would imply higher initial masses for both binary components and a much smaller post-SN orbital separation. While such a scenario would permit the formation of a black hole – the core of the SN progenitor would be exposed for far less time than under a case A mass transfer scenario – preventing merger of both components in the post-SN common envelope phase might prove problematic (Wellstein & Langer 1999).

5. Conclusions

The proximity of the WR star [MAC92] 17-A to the new *Chandra* position for IC 10 X-1 and *possible* spectral variability identify it as the prime candidate for the mass donor in IC 10 X-1. With a luminosity of $\log(L/L_{\odot}) = 6.05$, [MAC92] 17-A is one of the most luminous WNE stars known,

[2] We adopt the nomenclature used in Wellstein & Langer (1999 and references therein), with Case A, B and C evolution corresponding to mass transfer during core hydrogen burning, after core hydrogen burning but before core helium exhaustion, and after core helium burning, respectively.

with a present day mass of ~35 $M_\odot$. If it is the correct counterpart we predict a short orbital period (~5−10 hrs) resulting – depending on the orbital inclination – in orbital modulation of the X-ray continuum and, by analogy with Cyg X-3, significant line profile and line ratio variability, probably correlated with the X-ray flux. Clearly confirmation of the apparent line profile variability in the He II 4686 Å line of our spectra is of great importance. Such observations are challenging however, given that even for 8 m class telescopes the integration time is a substantial fraction of the expected orbital period.

A binary containing [MAC92] 17-A would unambiguously confirm the evolutionary scenario for OB+cc binaries first proposed by Van den Heuvel & de Loore (1973). Adopting the non conservative pre-SN mass transfer scenario of Vanbeveren et al. (1998) implies an initial mass for [MAC92] 17-A of ≥70 $M_\odot$, suggesting that it is the most massive mass donor yet identified for *any* X-ray binary. However, with the short, post-SN orbital period this would imply, doubts remain as to whether such a binary could escape merger during the subsequent common envelope phase required to form the present day WR+cc binary. Alternatively, if the pre-SN evolution proceded via case A mass transfer, the initial, pre-mass transfer masses of both MS progenitors would be significantly smaller (~40 $M_\odot$). Given the enhanced mass loss of the SN progenitor post mass transfer, we would expect the formation of a neutron star, rather than a black hole, with the wide post-SN orbit enhancing survival against merger.

Clearly, confirmation of the identity of the cc in IC 10 X-1 is of great interest since it will enable us to distinguish between the differing pre-SN evolutionary scenarios for this system. Given the current mass of [MAC92] 17-A, identification of a neutron star accretor in IC 10 X-1 would provide the most stringent constraint yet determined from *any* binary system for the minimum progenitor mass required to form black holes in close binaries (cf. Wellstein & Langer 1999).

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