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CYGNUS X-3 AS A BENCHMARK FOR FUNDAMENTAL PROPERTIES OF WOLF-RAYET STARS

ANATOL M. CHEREPASHCHUK
Sternberg Astronomical Institute, Moscow University, Universitetsky Prospect 13, 119899 Moscow, Russia

AND

ANTHONY F. J. MOFFAT
Département de Physique, Université de Montréal, C.P. 6128, Succ. A, Montréal, Qc., Canada H3C 3J7; and Observatoire du mont Mégantic
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ABSTRACT

The recent IR discovery by van Kerkwijk and collaborators of a massive WN7 star in the unusual X-ray source Cyg X-3 has important, direct implications for the properties of WR stars. The short 4.8 hr orbital period leads to a small WR photospheric core radius (<3–$6\ R_\odot$) with high temperature (>70–90 kK) for a generous range of Population I WR masses, $M(\mathrm{WR}) \sim 10$–$50\ M_\odot$. These values are compatible with those expected for a massive helium star, as predicted by evolutionary models. They are in contradiction with most current wind models, which yield larger radii and lower temperatures.

It is argued that with Cyg X-3 one is lucky to have caught at least one system during the rapid spiral-in phase of a close WR + compact binary. It may eventually lead to a longer-lived, hence more common Thorne-Zytkov–like object, in which the compact companion has been completely engulfed. Candidates for such bizarre objects are speculated to be the unusual WN8 stars.

Subject headings: binaries: spectroscopic — stars: fundamental parameters — stars: individual: Cygnus X-3 — stars: Wolf-Rayet

1. INTRODUCTION

Recently, van Kerkwijk et al. (1992) have shown on the basis of IR spectroscopy that the unusual, highly reddened stellar X-ray source Cyg X-3 contains a Wolf-Rayet (WR) star, probably of underlying subtype WN7. Subsequently, van Kerkwijk (1993) has shown that the 4.8 hr period seen in radio, IR, and X-ray flux modulation must be orbital in origin: the X-ray heating effect on the emission-line spectrum shows variations with orbital phase based on this period. In fact, Cyg X-3 is a unique system containing the only known WR star that shows spectral subtype variations as a function of orbital phase.[1] Thus, Cyg X-3 provides for the first time a direct, model-independent method of determining severe limits on the size and hence also on other properties of a WR star. It is also the first time that a WR + c (c = compact companion, either a neutron star [NS] or black hole [BH]) system—a heretofore missing link in the evolution of massive binaries—has been detected with certainty.

Up until now, the most direct method for determining upper limits to the sizes of WR star cores has been from the analysis of eclipse light curves in WR + O systems such as V444 Cygni (Cherepashchuk 1975; Cherepashchuk, Eaton, & Khaliullin 1984), CX Cep (Lipunova & Cherepashchuk 1982), and CQ Cep (Lipunova & Cherepashchuk 1980). However, these are model dependent (although less so than the "standard" model of single WR-star atmospheres by Hamann and collaborators: e.g., Hamann & Schwarz 1992; Hamann, Schmutz, & Wessolowski 1988; Schmutz, Hamann, & Wessolowski 1989). In this *Letter*, we show how Cyg X-3 obliges one to accept the fact that WR stars are He stars with small, hot cores.

2. BASIC PARAMETERS OF THE WN7 STAR IN CYG X-3

While in 1992, the 2-μm IR spectrum of Cyg X-3 shows a wind dominated by very high ionization, the 1991 IR spectrum shows lower ionization, with a spectrum close to WN7 (cf. the IR spectra of recognized WNL stars of Hillier 1985). Assuming this epoch-dependent variation to be due to variable X-ray heating from the accreting compact companion, it is reasonable to assume that the underlying He-rich star is a Population I WN7 (or later) star. In support of its massive, Population I status is the large distance estimate (10 kpc: Dickey 1983), which is compatible with the high reddening ($A_K \sim 1.5$ mag; cf. Becklin et al. 1972; thus $A_V \sim 15$ mag) i.e. ~ 1.5 mag of visual extinction per kpc in the disk of the Galaxy. Combined with the observed magnitude, this makes the WN7 star in Cyg X-3 intrinsically very luminous ($M_K < -5$; see Becklin et al. 1972).

Unfortunately, the large phase-dependent Doppler shifts of the IR emission lines cannot be used to determine the orbital mass function, since they are dominated by distortions in the WR wind caused by the orbiting X-ray ionizing source. Nevertheless, the recognition that the $P = 4.8$ hr period is orbital, and that we are dealing with a Population I WN7 star, allows one to estimate the orbital separation using Kepler's third law:

$$a^3/P^2 = M(\mathrm{WR}) + M(c)\ ,$$

for a in AU, P in years, and masses in $M_\odot$. Since the masses of WN7 stars show considerable spread (Moffat 1989), we choose extreme values of M(WR) that will bracket all known possibilities. We take $10 < M(\mathrm{WR})/M_\odot < 50$. Since more massive stars are more likely to evolve to BHs, we assume as extreme limits that the compact companion to the 50 $M_\odot$ WR star is a 10 $M_\odot$ BH and to the 10 $M_\odot$ WR star is a 1.4 $M_\odot$ NS. Thus,

[1] One of the WR components of the 19 day SMC binary HD 5980 also appears to show subtype variations, but on a much longer timescale, possibly related to the much wider elliptical orbit of a third star in the system (Koenigsberger et al. 1994).

we adopt

$$11.4 < [M(\mathrm{WR}) + M(c)]/M_\odot < 60 .$$

With $P = 4.8$ hr, this yields

$$3.2 < a/R_\odot < 5.6 .$$

Since the compact star must be orbiting outside the WR core, these values of "a" provide an *upper (dynamical) limit to the core radius of the WR star* (r_d).

A consistency check of the WR radius can be made independently from the ratio of $\dot{M}$ and v_∞ for the WN7 star. The photospheric core radius of the WR star, r_c, can be obtained from the condition that the total electron scattering optical depth from the observer to the photospheric radius is unity, i.e.,

$$\int_{r_c}^{\infty} \sigma_\mathrm{T} n_e(r) dr = 1$$

(cf. Cherpashchuk & Moffat 1994), where σ_T is the Thomson cross section for an electron. Converting electron density to total density and applying the equation of continuity, one has

$$n_e(r) = \alpha \dot{M}/[4\pi m_p r^2 v(r)] ,$$

where $\alpha = 0.5$ for a fully ionized He^{++} envelope and $v(r)$ is the wind expansion law. A *lower* limit to r_c (i.e., r_{c0}) can be obtained immediately by taking $v(r) = v_\infty$, the terminal wind speed:

$$r_{c0} = \alpha \sigma_\mathrm{T} \dot{M}/(4\pi m_p v_\infty) .$$

A reliable, dynamic value of $\dot{M}$ comes from the mass-loss–induced period increase observed for Cyg X-3 (van Kerkwijk et al. 1992):

$$\dot{M} \sim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}[M(\mathrm{total})/10\ M_\odot] .$$

With the above limits to M(total) [$= M(\mathrm{WR}) + M(\mathrm{c})$], we thus find

$$1.1 \times 10^{-5} < \dot{M}/(M_\odot\ \mathrm{yr}^{-1}) < 6 \times 10^{-5} .$$

For the terminal velocity, we adopt a typical value for WN7 stars (Prinja, Barlow, & Howarth 1990): $v_\infty = 1800$ km s^{-1}. Therefore,

$$0.91 < r_{c0}/R_\odot < 4.8 .$$

With a more realistic $v(r)$ law, approximated by a power law in the inner wind

$$v(r) = v_\infty (r/r_\infty)^\gamma \quad \text{for} \quad r < r_\infty ,$$

and

$$v(r) = v_\infty \quad \text{for} \ r \geq r_\infty$$

and calibrated by observed WR core radii in eclipsing binaries (Cherepashchuk & Moffat 1994), we find

$$r_c = r_{c0}(K^\gamma + \gamma/K)/(1 + \gamma) ,$$

where $K = r_\infty/r_{c0}$, r_∞ is the radius of the accelerating part of the wind, and γ is a power-law constant. The best fit to known eclipsing WR + O binaries gives $r_c \sim 1.8 r_{c0}$ and therefore

$$1.6 < r_c/R_\odot < 8.6 .$$

Taking into account free-free and bound-free absorption may lead to larger values of the photospheric radius in the *infrared*: e.g., Wright & Barlow (1975). This range is entirely compatible with the more restricted upper limit found above from Kepler's law:

$$r_d/R_\odot < 3.2\text{–}5.6 .$$

Finally, this limit on the radius allows us to estimate a *conservative lower limit to the effective temperature at the photospheric radius* (T_d) from the Stefan-Boltzmann law, adopting the dynamic estimate of the core radius r_d:

$$L = 4\pi r_d^2 \sigma T_d^4 .$$

A conservative lower limit to the luminosity L can be estimated from (*a*) $M_v \sim -6$ for modest WN7 stars, compatible with the observed value of $M_K < -5$ for Cyg X-3 (van Kerkwijk 1993), combined with (*b*) a conservative estimate of the bolometric correction from atmospheric and evolutionary models of WN7 stars, BC ~ -4 (Smith, Meynet, & Mermilliod 1994). This yields $M_\mathrm{bol} \sim -10$ for the WR star in Cyg X-3, and thus $L \sim 3 \times 10^{39}$ ergs s^{-1}. With this conservative limit for L and the above upper limit for r_d, a clearly lower limit for the effective temperature is

$$T_\mathrm{eff} > T_d > 70\text{–}90\ \mathrm{kK} .$$

Note that for such a high temperature, the true BC could be even higher than that adopted, emphasizing the fact that this is a lower limit. This is in stark contrast with the low values of T_eff obtained from the "standard" atmospheric models of WR stars, T_eff(WN7) $\sim$ 30 kK (e.g., Schmutz et al. 1989). In fact, adopting $T_\mathrm{eff} = 30$ kK and the above radius from the 4.8 hr period, one would obtain a luminosity of $(3\text{–}9) \times 10^{37}$ ergs s^{-1} and thus a formal BC of $+0.9 \ldots -0.3$. Such low absolute BCs are clearly excluded by observations of Population I WR stars (Smith & Maeder 1989).

Another way of looking at the problem is as follows: If we take Schmutz et al.'s (1989) and Smith et al.'s (1994) parameters for WN7 stars ($T_\mathrm{eff} \sim 30$ kK, BC $= -4$), we get $r_c(\mathrm{WR}) \sim 32\ R_\odot$ for the WR star in Cyg X-3, which is much greater than the upper dynamical limit, $r_d < 3\text{–}6\ R_\odot$. Therefore, the model of WR winds applied by Hamann and collaborators cannot be valid, unless of course, the observed stellar component in Cyg X-3 is not a WR star (unlikely, given its spectrum and its periodic modulation).

3. DISCUSSION

Assuming (*a*) that the optical star in Cyg X-3 is a Population I WR star of subclass WN7 (van Kerkwijk et al. 1992) and (*b*) that the 4.8 hr period is a true orbital period (van Kerkwijk 1993) leads to the inevitable conclusion that the WR star has a small ($<3\text{–}6\ R_\odot$), hot ($>70\text{–}90$ kK) photospheric ($\tau_\mathrm{es} = 1$) radius. These are conservative values. In addition, the true hydrostatic core must be even smaller and hotter. This implies that WN7 stars must lie close to the He-burning sequence in the H-R diagram, as predicted by evolutionary models, but in contrast with the "standard" wind models, e.g., of Schmutz et al. (1989).

The reason for this discrepancy may lie with the high mass-loss rates estimated from He I/He II emission-line fluxes in single WR stars by Schmutz et al. These rates do not allow for the effects of clumping in the wind (see Antokhin, Nugis, & Cherepashchuk 1992), which could reduce $\dot{M}$ by a significant factor. In particular, both period change studies and polarimetric investigations in WR + O binaries lead to values of $\dot{M}$

for the WR component that are a factor $\gtrsim 3$ less than those determined from IR and radio data (Khaliullin 1974; Kornilov & Cherepashchuk 1979; St-Louis et al. 1993; Moffat & Robert 1994). Since the IR/radio methods (unlike the other methods) are sensitive to the square of the wind plasma density, this can be taken as an argument for clumping in WR winds, which will also have an effect on the recombination emission line fluxes. With lower values of $\dot{M}$, the photospheric radius r_c will be closer to the hydrostatic radius r_*, i.e., the effects of cooling in passing from r_* to r_c will be significantly diminished.

Because the bolometric luminosity ($L_{\rm bol} \sim 3 \times 10^{39}$ ergs s^{-1}) is normally significantly greater than the mean X-ray luminosity ($L_x \sim 10^{38}$ ergs s^{-1}), the effect of X-ray heating in the WR wind is usually relatively small, presumably as in the 1991 IR spectra (van Kerkwijk 1993). To produce considerable X-ray heating as in the 1992 IR spectra, Cyg X-3 must have been in a high X-ray state then, with $L_x \sim$ several times higher. Such high X-ray states are relatively frequent on a yearly timescale in Cyg X-3 (Bonnet-Bidaud & Chardin 1988).

Furthermore, because $L_{\rm bol}$(WR) $\sim 3 \times 10^{39}$ ergs s^{-1} and because the effect of X-ray heating is observed in the IR range (amplitude of periodic modulation 15%–30%—see Bonnet-Bidaud & Chardin 1988), the true intrinsic X-ray luminosity of the accreting relativistic object in Cyg X-3 must be significantly higher than the observed mean value of the hard X-ray luminosity $L_x \sim 10^{38}$ ergs s^{-1}. This fact favors the presence of an accreting BH, as opposed to a NS, in Cyg X-3.

Note that second-generation WR stars in binaries (WR + c) have been predicted by van den Heuvel & Heise (1972), van den Heuvel & DeLoore (1973) and Tutukov & Yungelson (1973a, b). In these works, evolution in a common envelope via spiral-in was proposed, leading to considerable loss of angular momentum and shrinking in the dimension of the orbit. The short orbital period in Cyg X-3 suggests that this object may also be in a post–common envelope spiral-in binary system. Since the timescale for this process is very short, such systems should be rare, in line with Cyg X-3's unique character as the only known strong X-ray source harboring a WR star.

The spiral-in mechanism opens up the possibility that in some massive binaries during second mass exchange due to high dynamical friction, the compact companion could reach the center of the normal star, forming a kind of Thorne-Zytkov (1977) object. Good candidates for such objects may be some or all WN8 stars, which show very unusual properties compared to other WR stars (Moffat 1989): they have relatively large (puffed-up?) core radii and winds; they are generally the most intrinsically variable of all WR stars; their WR + O binary frequency is probably nil; and they often show evidence as runaways. The recent detection of a unique short 3.5 hr period in the "single" WN8 star WR 66 (Antokhin et al. 1994) may be very significant in this respect: its short periodicity may be the result of (*a*) rotational distortion caused by a partially swallowed compact companion or (*b*) a compact companion orbiting closer to the (larger) WN8 photospheric level than in the case of Cyg X-3. Due to strong absorption in the stellar wind, X-rays would not be observed from the WN8 star.

According to Lipunov (1982), during the second mass exchange in massive binary systems, an accreting, magnetized NS will accumulate high angular momentum and begin to rotate very rapidly, with a period of <0.1 s. Due to the "propeller effect" in this case, accretion from the stellar wind of the secondary WR star may virtually cease. This may explain the low X-ray luminosity of many proposed WR + c systems. In the case of a BH, the propeller effect does not work. Thus, the small number of strong X-ray radiators (i.e., only one: Cyg X-3) among potential WR + c binaries may be explained by the fact that only in Cyg X-3 do we have a BH companion as opposed to a NS. From this point of view, one would accept the classical evolutionary scenario of massive, close binary systems, without modifying the evolutionary timescales.

As noted above, the small radius and high effective temperature of the WN7 star in the Cyg X-3 X-ray binary system are in excellent agreement with models of massive He stars (see Langer 1989). Such a small radius and high $T_{\rm eff}$ for the WN7 star strongly conflict with the notion that WR stars are pre–main-sequence stars, as proposed by Underhill (1991). The fact that the WN7 star is the "normal" component of the X-ray binary Cyg X-3 containing a highly evolved relativistic object also strongly suggests that the WN7 star is in a late evolutionary stage.

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REFERENCES

Antokhin, I. I., Bertrand, J.-F., Lamontagne, R., & Moffat, A. F. J. 1994, in preparation
Antokhin, I. I., Nugis, T., & Cherepashchuk, A. M. 1992, Soviet Astron., 36, 260
Becklin, E. E., Kristian, J., Neugebauer, G., & Wynn-Williams, C. G. 1972, Nature Phys. Sci., 239, 130
Bonnet-Bidaud, J. M., & Chardin, G. 1988, Phys. Rep., 170, 325
Cherepashchuk, A. M. 1975, Astr. Zh., 52, 81
Cherepashchuk, A. M., Eaton, J. A., & Khaliullin, Kh. F. 1984, ApJ. 281, 774
Cherepashchuk, A. M., & Moffat, A. F. J. 1994, in preparation
Dickey, J. M. 1983, ApJ, 273, L71
Hamann, W.-R., Schmutz, W., & Wessolowski, U. 1988, A&A, 194, 190
Hamann, W.-R., & Schwarz, E. 1992, A&A, 261, 523
Hillier, D. J. 1985, AJ, 90, 1514
Koenigsberger, G., Moffat, A. F. J., St-Louis, N., Auer, L. H., Drissen, L., & Seggewiss, W. 1994, ApJ, submitted
Khaliullin, Kh. F. 1974, Astr. Zh., 57, 395
Kornilov, V. G., & Cherepashchuk, A. M. 1979, Pis'ma Astr. Zh., 5, 398
Langer, N. 1989, A&A, 210, 93
Lipunov, V. M. 1982, Pis'ma Astr. Zh., 8, 358
Lipunova, N. A., & Cherepashchuk, A. M. 1980, Astr. Zh., 57, 1033
———. 1982, Astr. Zh., 59, 944
Moffat, A. F. J. 1989, ApJ, 347, 373
Moffatt, A. F. J., & Robert, C. 1994, ApJ, 421, 310
Prinja, R. K., Barlow, M. J., & Howarth, I. D. 1990, ApJ, 361, 607
St-Louis, N., Moffat, A. F. J., Lapointe, L., Efimov, Yu. S., Shakovskoy, N. M., Fox, G. K., & Pirola, V. 1993, ApJ, 410, 342
Schmutz, W., Hamann, W.-R., & Wessolowski, U. 1989, A&A, 210, 236
Smith, L. F., & Maeder, A. 1989, A&A, 211, 71
Smith, L. F., Meynet, G., & Mermilliod, J.-C. 1994, A&A, in press
Thorne, K., & Zytkov, A. N. 1977, ApJ, 212, 832
Tutokov, A. V., & Yungelson, L. R. 1973a, Nauch. Inform. Astrosoviet Acad. Nauk USSR, 27, 58
———. 1973b, Nauch. Inform. Astrosoviet Acad. Nauk USSR, 27, 70
Underhill, A. B. 1991, ApJ, 383, 729
van den Heuvel, E. P. J., & De Loore, C. 1973, A&A, 25, 387
van den Heuvel, E. P. J., & Heise, J. 1972, Nature Phys. Sci., 239, 67
van Kerkwijk, M. H. 1993, A&A, 276, L9
van Kerkwijk, M. H., et al. 1992, Nature Phys. Sci., 355, 703
Wright, A. E., & Barlow, M. J. 1975, MNRAS, 170, 41