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# Infrared helium emission lines from Cygnus X-3 suggesting a Wolf–Rayet star companion

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**CYGNUS X-3 is one of the most luminous X-ray sources in the Galaxy[1,2], a bright infrared source[3] and a radio source that undergoes huge outbursts[4]. The system is a binary, presumably a neutron star plus companion, with a 4.79-h orbital period that modulates the X-ray and infrared emission[5,6] and that increases on a 600,000-year timescale[7,8]. Radio observations reveal the presence of a relativistic jet[9]. The nature of Cyg X-3 has remained unclear, however, in part because the large interstellar extinction[3] in its direction prevents optical spectroscopy. Upper limits on spectral features in the near infrared have been reported previously[10], but only with recent instrumental improvements have we become able to identify spectral features in the near infrared I and K bands. These are found to be characteristic of Wolf–Rayet stars: strong, broad emission lines of He I and He II, but no strong hydrogen lines. These observations strongly suggest the presence of a dense wind in the Cyg X-3 system, and may indicate that the companion is a fairly massive helium star, as had been predicted[11] by a model in which the present system is a descendant of a massive X-ray binary.**

The I-band spectrum (Fig. 1) was obtained in service time on 22 June 1991, with ISIS on the 4.2-m William Herschel Telescope on La Palma. The K-band spectrum (Fig. 2) was taken with the CGS4 on the United Kingdom 3.8-m Infrared Telescope (UKIRT) on Hawaii, during service observations on 29 June 1991. The spectra show a number of strong, very broad emission features. For each line the identification, equivalent width and full width at half-maximum are listed in Table 1. All the lines can be identified as either He I or He II lines, except the line at 2.166 μm. Given the strength of the He II line at 2.347 μm (13–8), the 2.166-μm line cannot be due solely to He II (14–8). Other possible contributors are H I(7–4) (Brγ) and several lines of the He I (7–4) transition array.

TABLE 1 Characteristics of the observed features

| $\lambda$ (μm) | Identification | −EW (Å) | FWHM* ($10^3$ km $s^{-1}$) |
|---|---|---|---|
| 1.0120 (4) | He II (5 − 4) | 90 (20) | 2.7 (3) |
| 2.060 (1) | He I $2p^1P^0 - 2s^1S$ | 50 (10) | 2.1 (3) |
| 2.112 (1) | He I $4s^3S - 3p^3P^0$<br>He I $4s^1S - 3p^1P^0$<br>He II (14 − 8) | 20 (6) | 2.4 (3) |
| 2.166 (1) | He I (7 − 4)<br>H I (7 − 4) | 26 (3) | 2.9 (7) |
| 2.188 (1) | He II (10 − 7) | 29 (4) | 2.9 (7) |
| 2.346 (2) | He II (13 − 8) | 12 (2) | 2.6 (4) |

Errors indicate 90% confidence levels. EW is equivalent width; FWHM is full width at half maximum.
* As observed; not corrected for the instrumental resolution.

The strong, broad emission lines of both He I and He II, and the lack of strong hydrogen emission, are reminiscent of a Wolf–Rayet (WR) spectrum (for a definition, see for example refs 12, 13). We have therefore compared our spectra with infrared spectra of WR stars[14-19]. The absence of carbon emission lines such as C III at 0.971 μm and C IV at 2.075 μm indicates that the spectra are not of the carbon-rich WC spectral sequence[14,19]. For the nitrogen-rich WN sequence, however, all expected lines are observed[14-18]. (Possible nitrogen lines are expected to be weak. If present, they are blended with the He I line at 2.112 μm.) Both the relative and absolute strengths of He I at 2.112 μm and He II at 2.188 μm indicate spectral subtype WN7. The equivalent widths of the other He II lines are consistent with this classification, but the He I line at 2.058 μm is stronger than in any of the eight WN spectra we have available for comparison[15-18]. The blend at 2.166 μm is somewhat weaker than in the two available WN7 spectra[16,18], possibly indicating a lower hydrogen abundance in Cyg X-3. The widths of the lines are similar to those observed in WN stars[12,14-18].

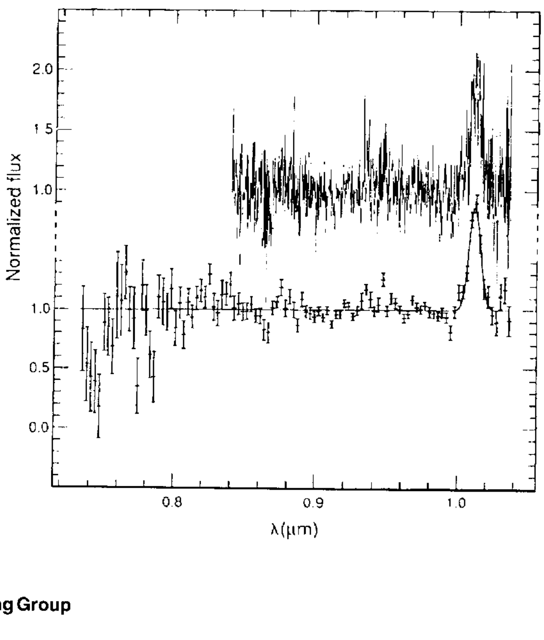


FIG. 1 The I-band spectrum obtained on 22 June 1991, 4:45 UT. The reduced, normalized spectrum, with the noisy short-wavelength portion omitted, is shown at the top. The resolution is ~200 km $s^{-1}$. The emission feature at 1.012 μm is He II (5-4). The full spectrum, averaged over 11 pixels, is at the bottom, with a gaussian fit to the line superposed. In our data reduction, we used the spectrum of the nearby star A (see finding chart in ref. 29; the slit had been positioned on stars A and C to be certain that Cyg X-3 was observed), with its stellar features (Paschen and Ca II absorption) artificially removed, to correct for the telluric features in the Cyg X-3 spectrum. As a plot of log $F_\lambda$ against log $\lambda$ for the ratioed continuum is linear, the spectrum was divided by a power-law fit to produce the result shown here.

The presence of lines of relatively low excitation in the infrared spectrum seems inconsistent with any model for Cyg X-3 that requires a very high temperature ($>10^6$ K) in the infrared-flux-producing region (such as an accretion disc corona model[20], or, more generally, any model in which the size of the infrared object is comparable to, or smaller than, the orbital separation[5]). Instead, the WR spectrum probably indicates[13] that a strong wind is present in Cyg X-3, which in the infrared is optically thick out to radii much larger than the orbital separation. Such a wind might be due to X-ray irradiation of either the accretion disc or a low-mass companion. Alternatively, it could be intrinsic to the companion: that is, the companion could be a WR star. For lack of predictions, the irradiation models are currently difficult to test. Below, we therefore confine ourselves to the WR model.

If the companion is a WR star, then given the absolute K magnitude of Cyg X-3 of $<-5$ (ref. 3), it can only be a 'classical' WR star[21]: the remnant helium core of a massive O-type or early B-type star that has lost (most of) its hydrogen-rich envelope, and is now in the stage of helium burning or beyond. Hence, the system would be composed of a compact object and a helium star. This was proposed earlier by Van den Heuvel and De Loore[11], who predicted the existence of such systems from considerations of the evolutionary fate of massive X-ray binaries such as Cen X-3 and SS 433. In these binaries the primary is a massive, early-type star, which expands in the course of its evolution, and eventually overflows its critical surface (Roche lobe). The resulting mass-transfer to the secondary is unstable, and causes the orbit to shrink on a thermal timescale. If the original orbit was wide enough the system can stabilize, but only after almost the whole hydrogen-rich envelope of the primary has been expelled. The remaining helium star is likely finally to explode as a supernova. If the system is not disrupted, a binary such as the Hulse-Taylor pulsar PSR1913+16, composed of two neutron stars in a highly eccentric orbit, could be formed[22].

Stellar model calculations[23,24] show that a helium star in Cyg X-3 would fit well inside its Roche lobe: the radius of a 1, 5, 10, 20 or $60 M_\odot$ helium star is 0.2, 0.6, 0.9, 1.4 or $2.6 R_\odot$, respectively[24], whereas the radius of the Roche lobe would be 0.6, 1.3, 1.7, 2.3 or $3.8 R_\odot$, respectively (for a $1.4 M_\odot$ compact object, the canonical mass of a neutron star). On the other hand, the 'zero-velocity' radii derived from model fitting to WR spectra[25], which should also be a measure of helium star radii, are never smaller than $2\text{-}3 R_\odot$, and in most cases range from 5 to $20 R_\odot$. The cause of this discrepancy is unknown. It may indicate that the velocity law assumed for the WR atmosphere, which is used to extrapolate from the radius at which the continuum and the emission lines are observed to the 'zero-velocity' radius, is not correct.

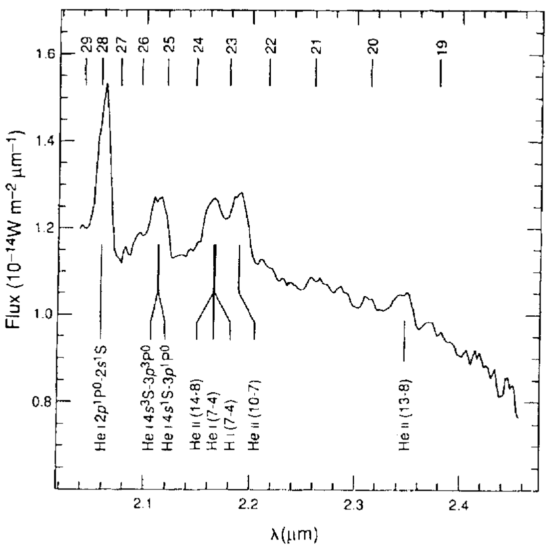


FIG. 2 The K-band spectrum obtained on 29 June, 1991, 15:00 UT. Shown is the reduced spectrum, corrected for telluric absorption and flux-calibrated using a spectrum of HR7796 (with its H I Br$\gamma$ absorption line artificially removed). The resolution is ~1,500 km s$^{-1}$. Below the spectrum, the identifications of the stronger lines are given. Above the spectrum, the rest wavelengths of the He II ($n$-9) lines are shown, as several of these coincide with marginally significant emission features in the spectrum. A possibly real feature is also seen at 2.286 μm. For this line no likely identification has been found. (It may have the same origin as the unidentified feature at 2.287 μm observed in spectra of planetary nebulae[30].)

The observed rate of increase of the orbital period of Cyg X-3 (ref. 8) allows one to estimate the rate of stellar-wind mass loss from the companion. For spherically symmetric mass loss one obtains[26]

$$\frac{\dot{M}}{M} = \frac{\dot{P}}{2P} = 0.8 \times 10^{-6}\,\mathrm{yr}^{-1}$$

where $\dot{M}$ is mass-loss rate, and $M$ the total mass of the system. For a $1.4 M_\odot$ compact object and a $10 M_\odot$ WR star, we find $\dot{M} \approx 0.9 \times 10^{-5}\, M_\odot\,\mathrm{yr}^{-1}$, well within the range $(0.8\text{-}8) \times 10^{-5}\, M_\odot\,\mathrm{yr}^{-1}$ found for WR stars[12].

The mass-loss rate can be used to check whether the column density in the WR wind between the compact object and the observer is such that the observed modulation of the X-ray flux along the orbit can be obtained. Previous modelling has shown[27,28] that this requires the electron-scattering optical depth $\tau_{es}$ to be close to unity. A first-order estimate of $\tau_{es}$ can be made under the assumption of a spherically symmetric pure helium wind that flows at a constant velocity $v_w$. It is easy to show that at ascending and descending node (both stars in the plane of the sky)

$$\tau_{es} \approx 0.35\gamma \left(\frac{\dot{M}}{10^{-5} M_\odot\,\mathrm{yr}^{-1}}\right)\left(\frac{M}{11.4 M_\odot}\right)^{-1/3} \times \left(\frac{v_w}{1{,}000\ \mathrm{km\,s}^{-1}}\right)^{-1}$$

where $\gamma$ is the number of electrons per helium ion. The main contribution to $\tau_{es}$ comes from the region close to the compact object, in the inner part of the wind. In this region the wind will be almost completely ionized ($\gamma = 2$), and its velocity a few tenths of the terminal velocity of ~2,000 km s$^{-1}$ (as indicated by the widths of the lines; in WN stars 1,500-4,000 km s$^{-1}$ is observed[12]). Hence, $\tau_{es}$ will be about unity, as required.

We conclude that the infrared spectra of Cygnus X-3 presented here indicate that a strong wind is present in the system, which in the infrared is optically thick up to well outside the system. We have shown that such a wind may originate from a WR companion. If this is the case, the system is in a later evolutionary stage of massive X-ray binaries[11]. □

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1. Giacconi, R., Gorenstein, P., Gursky, H. & Waters, J. R. *Astrophys. J.* **148**, L119-127 (1967).
2. Dickey, J. M. *Astrophys. J.* **273**, L71-73 (1983).
3. Becklin, E. E., Kristian, J., Neugebauer, G. & Wynn-Williams, C. G. *Nature phys. Sci.* **239**, 130-131 (1972).
4. Gregory, P. C. *et al. Nature phys. Sci.* **239**, 114-117 (1972).
5. Becklin, E. E. *et al. Nature* **245**, 302-304 (1973).
6. Mason, K. O. *et al. Astrophys. J.* **207**, 78-87 (1976).
7. Manzo, G., Molteni, D. & Robba, N. R. *Astr. Astrophys.* **70**, 317-318 (1978).
8. Van der Klis, M. & Bonnet-Bidaud, J. M. *Astr. Astrophys.* **214**, 203-208 (1989).
9. Molnar, L. A., Reid, M. J. & Grindlay, J. E. *Astrophys. J.* **331**, 494-508 (1988).
10. Katz, J. I., Wright, E. L. & Lawrence, C. R. *Astr. J.* **89**, 1604-1605 (1984).
11. Van den Heuvel, E. P. J. & De Loore, C. *Astr. Astrophys.* **25**, 387-395 (1973).
12. Conti, P. S. & Underhill, A. B. *O-type Stars and Wolf-Rayet Stars* (NASA SP-497, 1988).
13. Conti, P. S. in *IAU Symp.* No. 99: *Wolf-Rayet Stars: Observations, Physics, Evolution* (eds de Loore, C. W. H. & Willis, A. J.) 3-19 (Kluwer, Dordrecht, 1990).
14. Conti, P. S., Massey, P. & Vreux, J. M. *Astrophys. J.* **354**, 359-371 (1990).
15. Williams, P. M. in *IAU Symp. No.* 99: *Wolf-Rayet Stars: Observations, Physics, Evolution* (eds de Loore, C. W. H. & Willis, A. J.) 73-78 (Kluwer, Dordrecht, 1990).
16. Hillier, D. J. in *IAU Symp. No.* 99: *Wolf-Rayet stars: Observations, Physics, Evolution* (eds de Loore, C. W. H. & Willis, A. J.) 225-228 (Kluwer, Dordrecht, 1990).

17. Hillier, D. J., Jones, T. J. & Hyland, A. R. *Astrophys. J.* **271**, 221-236 (1983).
18. Hillier, D. J. *Astr. J.* **90**, 1514-1518 (1985).
19. Smith, L. F. & Hummer, D. G. *Mon. Not. R. astr. Soc.* **230**, 511-534 (1988).
20. White, N. E. & Holt, S. S. *Astrophys. J.* **257**, 318-337 (1982).
21. Van der Hucht, K. A., Conti, P. S., Lundström, I. & Stenholm, B. *Space Sci. Rev.* **28**, 227-306 (1981).
22. Flannery, B. P. & Van den Heuvel, E. P. J. *Astr. Astrophys.* **39**, 61-67 (1975).
23. Divine, N. *Astrophys. J.* **142**, 824-840 (1965).
24. Langer, N. *Astr. Astrophys.* **210**, 93-113 (1989).
25. Schmutz, W., Hamann, W.-R. & Wessolowski, U. *Astr. Astrophys.* **210**, 236-248 (1989).
26. Davidsen, A. & Ostriker, J. P. *Astrophys. J.* **189**, 331-338 (1974).
27. Pringle, J. E. *Nature* **247**, 21-22 (1974).
28. Bonnet-Bidaud, J. M. & Van der Klis, M. *Astr. Astrophys.* **101**, 299-304 (1981).
29. Wagner, R. M., Kreidl, T. J., Bus, S. J. & Williams, W. *Astrophys. J.* **346**, 971-975 (1989).
30. Geballe, T. R., Burton, M. G. & Isaacman, R. *Mon. Not. R. astr. Soc.* **253**, 75-79 (1991).

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# Three-dimensional motion in the radio jet of the binary system R Aquarii

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**R AQUARII is a symbiotic binary system surrounded by a complex extended optical nebulosity[1]. At radio and optical wavelengths a jet is seen to emerge from the central binary system[2,3]. We have observed R Aqr using the Very Large Array. Comparison with earlier radio observations shows that five out of six bright components in the radio jet have moved. One radio component has the same proper motion as the optical Mira, the primary star of the binary. At a distance of 200 pc (refs 1, 4), the proper motions of the other components correspond to a tangential velocity of 44 to 160 km s$^{-1}$ with respect to the Mira. By combining these measurements with radial velocity determinations, we obtain a true three-dimensional velocity map of the radio jet, provided only that the observed proper motions indeed correspond to physical motions of emitting material. Our results rule out the possibility that the radio components in the jet were formed in a single explosive event, and suggest instead that they are 'bullets' ejected at ~20-yr intervals into a narrow cone. Alternatively, if the components move along the jet and are accelerated during the whole of their passage through the inner 7 arcsec (1,400 AU) of the system, ejection at ~40-yr intervals would lead to the disposition observed at present.**

Symbiotic systems are long-period binaries consisting of a cool giant primary and a hot secondary star. R Aquarii is a unique symbiotic system because it contains as a primary a Mira variable with a period of 387 days. From its variability a distance of 250 pc has been estimated[4]. Kinematic studies of the outer and inner optical nebulosities[1] yield an estimated distance of 180 pc. Here we adopt a distance of 200 pc.

The radio continuum flux density ~8 mJy was measured[5-7] in the late 1970s. A core-jet structure detected at optical wavelengths[8,9] was also apparent in the first Very Large Array (VLA) measurements[2,3]. Later VLA observations[10-12] showed that the system consists of five components (A′, C1, C2, A, B). In 1986 a new jet component, D, was revealed[13,14] by narrow-band H$\alpha$ imaging. The Mira is also a SiO maser source in radio wavelengths[15-17], implying that the system is losing mass.

We observed R Aqr on 18 August 1991 for 196 minutes and 198 minutes at wavelengths of $\lambda = 3.6$ and 6.2 cm, respectively, with 19 operational antennas of the radio telescope in its largest, A configuration. The data were edited and calibrated using the program AIPS at the National Radio Astronomy Observatory Arrays Operation Center in Socorro, New Mexico. The CLEANed 3-cm and 6-cm maps had a r.m.s. noise level of $\sigma = 31$ μJy and 33 μJy, respectively.

The 3-cm map shows four obvious components which we identified as A′, C1, C2 and A. In addition to these, the 6-cm map shows structure corresponding to components B and D. We have thus detected component D at radio wavelengths. Components A′, C1, C2, and A have sizes smaller than the 3-cm beam. Components C1 and A seem to be extended along position angles (PA) ~50° and ~14°, respectively. Components B and D are very extended and mostly resolved out in the untapered 3-cm map.

A comparison with earlier observations[10-12] showed that the positions of five of the six radio components had changed. We calculated for each component its proper motion, that is, its apparent motion perpendicular to the line of sight (Tables 1 and 2). The components clearly do not have a common proper motion. Component A′ has a position close to that of the previous epoch. From the marginal proper motion alone, we cannot judge whether this component is a background source or a component of a 'counter-jet'. But the similarity of its radio spectrum to C2 and A, and the presence of a counter jet in optical[18] and ultraviolet observations[19], lead us to believe that it is associated with the R Aqr jet system. Details of the radio spectra of all the components will be discussed elsewhere (D.R.H.J. and H.J.L., manuscript in preparation). Component C1 has the smallest proper motion of the other five components, and because this is the same as the optical proper motion of the Mira star[20,21] we believe that it represents the Mira, and that it is close to the base of the jet.

A previous model for the optical nebulosity[1] suggests that the inner optical nebulosity and the radio structure were created in a single explosion. The positions of the components extrapolated to the past should coincide at the location and time of the explosion. No such unique location or time is compatible with our measurements of proper motion.

The model of Kafatos *et al.*[22] explains the radio and optical components as being ejected at periastron passage of the binary, at intervals of ~44 yr. In this model, radiation pressure from the central hot star on the dust in the components accelerates them to a terminal velocity within the first ≲30 AU ≈ 0.15″. If radiation pressure is important, then the different proper motions that we observe imply either that the dust properties vary from one component to another, or that the column density of the dust varies, being highest in the components with highest relative proper motions, B and D. As the proper motions of the central star and the components were not available when this model[22] was proposed, it is not surprising that the details of their geometry are not in agreement with our observations.

Assuming that each component had stayed at a constant velocity for most of its lifetime, we solved simultaneously from the observed positions of C1, C2, A, B and D for their respective proper motion vectors, times of zero separation, and the present position ($\alpha_0$, $\delta_0$) of the core C1. The times of zero separation from this fit are 20.3, 40.0, 63.4 and 56.7 yr ago. The best solution for the proper motion of the core (+0.0029, −0.031) is slightly discordant with the optical proper motion. The best solutions for absolute proper motions for components C2, A, B and D are 0.076, 0.115, 0.129, 0.158″ yr$^{-1}$, in good agreement with the observed values. The calculated position angles of the absolute proper motion, which are the position angles of the ejection of the components, are +98°, +74°, +58° and +41° for components C2, A, B and D. If the components are ejected near the periastron of an eccentric orbit, then the orbital period of the system should be ~20 yr, or about half of the claimed period of 44 yr (ref. 23). Excess mass transfer and the ejection of the component could occur when the Mira is attempting to reach its maximum size in its 387-day cycle, causing strong Roche-lobe overflow. It

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