CYGNUS X-3

AN EVOLUTIONARY MISSING LINK FOUND?

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Abstract. I review the properties of the X-ray source Cygnus X-3, and the evidence that is available that indicates that its companion is a Wolf-Rayet star. I focus on the interpretation of spectra of its infrared counterpart. Considering all data, I conclude that the companion is indeed a WR star, and I discuss the ramifications of this conclusion for our understanding of WR stars in general.

Key words: stars: Wolf-Rayet – close binaries – individual: Cygnus X-3

1. The two Wolf-Rayet phases in the evolution of a massive close binary

In the course of the evolution of close binaries composed of two massive stars, there are two phases in which one of the components can be observed as a Wolf-Rayet star. Following van den Heuvel (1976, 1983), I will briefly summarise the evolution leading to these. The first WR phase occurs after the originally more massive component has reached core-hydrogen exhaustion and has started to expand. At some point, it will overflow its Roche lobe and start to transfer mass to the secondary. This mass transfer is unstable on a thermal time-scale (*e.g.*, Savonije 1983) but, if the secondary is massive enough* ($q = M_2/M_1 \gtrsim 0.5$), it will probably be able to accrete a large fraction of the mass that is tranferred to it. The mass transfer will continue until almost all of the hydrogen-rich mantle of the primary has been transferred, and a system is left that is composed of the helium core of the primary and a now more massive, hydrogen-burning secondary. Such a system could be observed as a WR+O binary.

The helium star will eventually explode as a supernova. In general, the system will not be disrupted, since less than half the total mass of the system is ejected in the explosion. The remaining system, composed of a compact object and an early-type star, can be observed as a high-mass X-ray binary (if enough wind material is accreted onto the compact object).

* Secondaries that are less massive will not be able to accrete all the matter that is transferred to them. Probably, a common envelope will form and the stars will spiral-in towards each other. As a result, the two stars could either merge, or a system composed of a WR star and a relatively low-mass companion will form. Such systems might be identified with WR stars like WR6 (HD 50896) or WR46 (HD 104994), which show a periodicity which is most likely orbital (Koenigsberger, these proceedings), but for which the companion is not directly observed.

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Eventually, the secondary will in turn reach core-hydrogen exhaustion, expand and start to overflow its Roche lobe. This time, the mass transfer will not be conservative, since the mass-transfer rate will far exceed the maximum (Eddington) rate that the compact object can accrete. Hence, most likely a common envelope will form, and the compact object will start to spiral-in.

The spiral-in process is poorly understood. It is possible that the compact object will reach the core of its companion. In this case, a so-called Thorne-Żytkov object will have been formed (Thorne & Żytkov 1977). However, it could also be that all of the hydrogen envelope has been expelled before the compact object reaches the helium core. In this case, a stable, short-period system composed of a helium star and a compact object will have been formed. The former would be observable as a WR star and hence this is the second WR phase in the evolution. If matter accretes from the WR wind on the compact object, the system could be observable as an X-ray source. On the basis of this scenario, van den Heuvel and de Loore suggested already in 1973 that the short-period X-ray binary Cyg X-3 was in this evolutionary stage.

Indirect evidence for the existence of such systems was obtained with the discovery of the PSR 1913+16 (Hulse & Taylor 1975), a radio pulsar that is in a short-period, highly eccentric orbit around another neutron star. Flannery & van den Heuvel (1975) realised that such a system would be the natural descendant of a binary in the second WR phase, in which the helium star had exploded as a supernova.

2. The X-ray binary Cygnus X-3

Cygnus X-3 is an X-ray source discovered in 1966 (Giacconi *et al.* 1967), which drew world-wide attention in 1972, when it was found to be at the source of a huge radio outburst (Gregory *et al.* 1972; see the special issue of Nature Phys. Sciences, Vol. 239, Oct. 23, 1972; for reviews, see Bonnet-Bidaud & Chardin 1988; van Kerkwijk *et al.* 1994). During similar outbursts in the eighties, evidence for a relativistic jet was found (Geldzahler *et al.* 1983; Spencer *et al.* 1986), with an expansion velocity of about $0.35c$. At the time of the 1972 radio outburst, the source was also identified with an infrared source of $K = 11$ mag (Becklin *et al.* 1972).

The X-ray flux shows a smooth modulation with a 4.8-hr orbital period. This modulation shows considerable variation from cycle to cycle, but averaged over intervals of weeks, it is remarkably stable (see van der Klis 1993 and references therein). Therefore, arrival times can be determined accurately. From these arrival times, it was found that the period is slowly increasing (Manzo *et al.* 1978), on a time-scale of about $7\,10^5$ yr (Kitamoto *et al.* 1992). The modulation is often, but not always, observed in the in-

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frared too, and when it is, it is in phase with the X-ray modulation (Becklin *et al.* 1973, 1974; Mason *et al.* 1976, 1986). From 21 cm H I absorption spectra, it has been inferred that Cyg X-3 lies at a distance of at least 10 kpc, behind three spiral arms (Dickey 1983; using a distance to the Galactic centre of 8.5 kpc). For this distance, its intrinsic 2–12 keV X-ray luminosity gets up to $2\,10^{38}\,\mathrm{erg\,s^{-1}}$. In the K band the source varies between 11^{th} and 12^{th} magnitude. Since the interstellar extinction in the K band is about 2 magnitudes (Becklin *et al.* 1972; van Kerkwijk *et al.* 1994), the lower limit to the distance implies $M_K \lesssim -5$.

There have been numerous claims of detections of Cyg X-3 at very high energies (tens of MeVs to PeVs; see the review by Bonnet-Bidaud & Chardin 1988 and references therein). However, recent instruments more sensitive than those used previously haved failed to confirm these detections both in the MeV (*EGRET*: Michelson *et al.* 1992) and TeV range (*Whipple Observatory*: O'Flaherty et al. 1992).

3. The Wolf-Rayet component in Cygnus X-3

For the WR model of Cyg X-3, it is predicted that the infrared component shows WR features. This prediction has been confirmed by the discovery of strong, broad lines of He I and He II in I- and K-band spectra (van Kerkwijk *et al.* 1992, hereafter Paper I). In subsequent observations (van Kerkwijk 1993a, hereafter Paper II), again WR-like features were found, but this time the lines were much weaker and the line ratios indicated a much higher degree of ionization. Furthermore, the lines showed wavelength shifts as a function of orbital phase, with maximum blue-shift occurring at the time of X-ray minimum and maximum red-shift half an orbit later (see the figures in Paper II).

In Fig. 1, strong and weak-lined I- and K-band spectra of Cyg X-3 are shown, together with spectra of 'normal' WR stars. Comparing the spectra of Cyg X-3 with these WR spectra and with others taken from the literature (Hillier *et al.* 1983; Hillier 1985; Vreux *et al.* 1989, 1990), one finds that when the lines are strong, the spectra are rather similar to those of a WR star of spectral type WN6/7, although the lines are somewhat weaker than average. A line that is very different, though, is He I $\lambda 2.058\mu$m, which in WN stars usually has an absorption component that is stronger than the emission component, while in Cyg X-3 we have observed it strongly in emission* (Paper I; see Fig. 1). When the lines are weak, the line ratios indicate spectral subtype WN4/5, but the lines are much weaker than is observed for normal WN stars (see Fig. 1). It was proposed in Paper II that the weakness of the lines and their modulation with orbital phase in

* It has also been observed in absorption – near orbital phase 0 – in a new series of spectra in which the source showed weak lines (van Kerkwijk *et al.* 1994)

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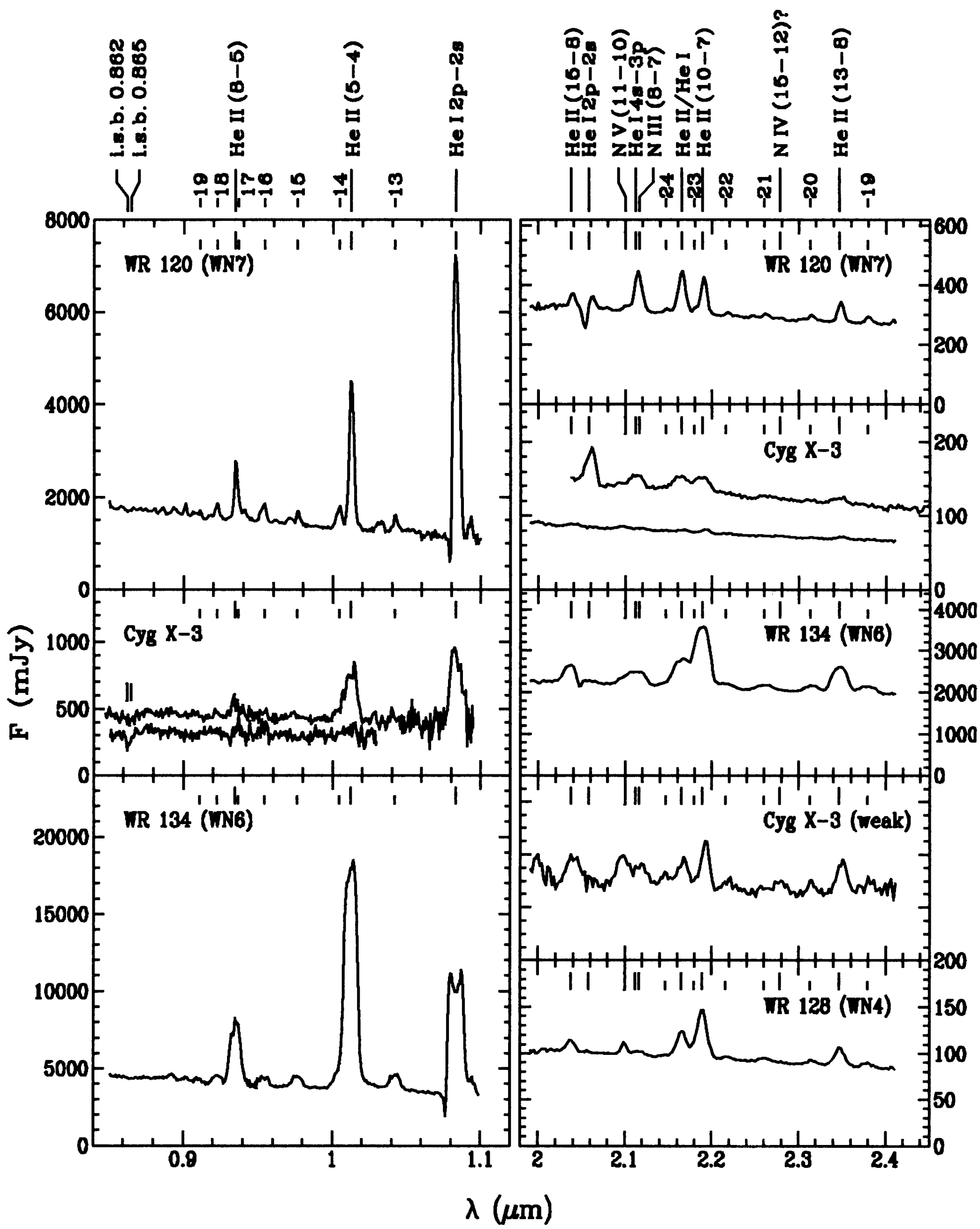

Fig. 1. Comparison of the I-band (left) and K-band (right) spectra of Cyg X-3 with those of 'normal' WR stars. All spectra have been dereddened using the interstellar extinction law of Mathis (1990), with $A_J = 5.5$ for Cyg X-3 (van Kerkwijk *et al.* 1994), $A_J = 0.28$ and 0.41 for WR128 and WR134, respectively (using the values of E_{B-V} listed by Morris *et al.* 1993) and $A_J = 1.3$ for WR120 (estimated from the $b - v$ colour listed by van der Hucht *et al.* 1981). For Cyg X-3, both a spectrum in which the lines are strong and one in which the lines are weak are shown. For the K band, the spectrum showing weak lines is shown enlarged in the fourth panel, so that it can be compared more easily.

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the second set of observations, was due to the fact that at that time the WR wind was highly ionized by the X-ray source, except for the part shadowed by the helium star. If this were the case, the line emission would arise mainly in the shadowed part, and hence at superior conjunction of the X-ray source (X-ray minimum), one would observe maximum blueshift.

It was argued that in the context of this model also the modulation of the infrared continuum could be understood. In the infrared, the continuum is mainly due to free-free emission, which gets less efficient with increasing temperature. Hence, the hot part of the wind will be less opaque than the cool part. This will not lower the total flux to a large extent when the wind changes from mostly non-ionized to highly ionized, since the smaller effective radius of the hot part is compensated by the higher temperature (for an isothermal, spherically-symmetric, constant-velocity wind, the total free-free flux is independent of temperature; see Wright & Barlow 1975). However, the cooler, more opaque part of the wind can partly eclipse the hotter, less opaque part. This will lead to a minimum in the infrared light-curve at superior conjuction of the X-ray source, *i.e.,* simultaneous with X-ray minimum, as observed. In Paper II, it was shown that one could not only qualitatively understand the infrared light curve in this way, but also reproduce it quantatatively with a simple model.

Based on this model, it was predicted in Paper II that the emission lines would be modulated when they are weak, but not when they are strong. This prediction has in the meantime been confirmed by new I-band observations (van Kerkwijk *et al.* 1994). It was also predicted that the strong-lined state would correspond to X-ray low state and the weak-lined state with X-ray high state. However, Kitamoto *et al.* (1994a) found that the X-ray source was in high state at the time of the first set of observations, in which the lines were strong, and most likely in low state at the time to the second set of infrared spectra, in which the lines were weak.

Kitamoto *et al.* (1994a) propose that the properties of Cyg X-3 in radio, infrared and X-ray are all correlated with wind density. When the wind density is highest, most matter is accreted onto the compact object and the X-ray flux is highest, getting so close to the Eddington limit that at times some mass is ejected in the form of jets, which is observed as a radio outburst. At the same time, the high wind density will lead to a large infrared flux. For lower wind densities, the accretion rate would be less, and hence also the X-ray flux would be less, the radio source would be less variable, and the infrared flux would be lower. Kitamoto *et al.* suggest that the difference in strength and degree of ionization of the lines is due to the fact that when the wind is less dense, the wind will be optically thin for X rays, so that the X-ray source is able to ionize a large fraction of the wind, while when the wind is denser, the wind becomes optically thick to X rays, so that the ionization state will decrease, even though the X-ray flux is higher.

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4. Ramifications and conclusions

From the infrared spectra, it is clear that a strong, helium-rich wind is present in the system. At times, the spectra are similar to those of WR stars, but at other times, the lines are much weaker. As shown in Paper II and indicated above, in a model where the companion is a WR star, the change in spectral appearance can be understood qualitatively by considering the influence of the X-ray source on the state of ionization of the WR wind. Taking this influence into account, the modulation of the infrared continuum follows naturally, and can even be reproduced quantatatively. In general, in the context of the WR model, most of the main properties of Cyg X-3 can be understood. These properties include the increase of the orbital period, the brightness in the infrared, the modulation of the X-ray intensity (although not the details of the shape of the light-curve; see Hertz *et al.* 1978), the modulation of the infrared intensity in phase with that seen in X rays, and, as dicussed here, the infrared spectrum. Other observations worth mentioning in this regard are the presence of strong emission lines in the X-ray spectrum (unique among X-ray binaries), including lines of low-ionization, helium-like and hydrogen-like Iron (Kitamoto *et al.* 1994b), and the fact that the X-ray source shows no significant variability at frequencies above 1 Hz (Kitamoto *et al.* 1992; Berger & van der Klis 1994). Both these observations indicate that a strong scattering medium (wind) is present in the system. Assuming that the companion of Cyg X-3 is in fact a WR star, a strong constraint on the radius of this star can be derived from the short orbital period of the system (Paper I; Cherepashchuk & Moffat 1994). For instance, for a 5, 10 or $20\,M_\odot$ WR star with a $1.4\,M_\odot$ compact companion, the Roche-lobe radius is 1.3, 1.8 or $2.4\,R_\odot$, respectively. These radii are consistent with the hydrostatic helium-star radii (*e.g.,* Langer 1989 finds 0.6, 0.9 and $1.4\,R_\odot$, respectively), but inconsistent with the 'zero-velocity' radii derived from model fitting to WR spectra (*e.g.,* Schmutz *et al.* 1989). Schmutz (1993) analysed the spectra showing strong lines that were presented in Paper I, and came to the conclusion that the WR star in Cyg X-3 would have a radius of $11\,R_\odot$, and hence that it would not fit within the system. In order to solve this discrepancy, he proposed that the system was much closer to us than inferred from the 21 cm observations. In this case, the luminosity would be lower and the star would be as small as needed. He suggested that the 21 cm absorption spectrum could be produced in circumstellar shells. However, it seems somewhat much of a coincidence to have absorption features at exactly the right velocities for the local, Perseus and outer arms in our Galaxy (see Chu & Bieging 1973; Dickey 1983), and hence the possibility of a much smaller distance can almost certainly be rejected. Instead, the apparent discrepancy is probably related to the following two points. The first is that, as stressed in Paper I, the atmospheric models use an *assumed*

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velocity law, which most likely is not valid for WR stars, especially close to the star (*e.g.,* Kudritzki & Hummer 1990; see also contributions of Schmutz and others to these proceedings). A less steep velocity law than the one assumed (a β-law with $\beta = 1$), would likely lead to smaller inferred radii. The second point is that the observed lines may well be weakened due to the influence of the X-ray source even in the strong-lined state, as indicated perhaps by the fact that they are somewhat weaker than is observed for normal WR stars. For stronger-lined stars, such as those in the WNE-B subclass, Schmutz *et al.* (1989) derive radii that are substantially smaller (although still about a factor 2 too large to fit within the Cyg X-3 system).

An estimate of the wind mass-loss rate in Cyg X-3 can be made on the basis of the infrared luminosity. In Paper II, a value of $4\,10^{-5}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ was derived from a simple analysis (*cf.* van Kerkwijk *et al.* 1994). Schmutz (1993) found a very similar value, $5\,10^{-5}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ from his spectral analysis. Another estimate of the mass-loss rate can be obtained from the increase of the orbital period, *viz.*, $\dot{M} = 0.8\,10^{-6} M_{\mathrm{tot}}\,\mathrm{yr}^{-1}$ (Paper I), where M_{tot} is the total mass of the system. For reasonable values of M_{tot} (10–20 $\mathrm{M}_\odot$), this dynamical estimate is lower than the estimate derived from the infrared luminosity by at least a factor 3. This is very similar to what is found in V444 Cyg (St-Louis *et al.* 1993 and references therein), and might be attributed to the presence of inhomogeneities in the wind, which cause an enhancement of the free-free flux, and hence result in a mass-loss rate estimate based on the infrared luminosity that is artificially large.

In conclusion, it seems fair to state that the present data on Cyg X-3 indicate that its companion is a WR star (WR 145a, van der Hucht, private communication). The presence of a WR star in this system provides us with a unique opportunity to constrain the physical parameters of a WR star – such as its size and its mass-loss rate – as well as the structure of a WR wind, using the X-ray source as a probe.

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DISCUSSION:

Cherepashchuk: Did you detect P Cyg absorption for the HeI line?
van Kerkwijk: Yes, in K-band observations taken in 1993, we observed an absorption component of HeI 2.058 blue shifted by about 1500 km s^{-1}. This was only observed in two spectra taken close to superior conjunction of the X-ray source. No clear emission component was observed in any of the five spectra we took that run.
Kaper: What would change in your conclusions about the stellar parameters of the WR star if the companion is a black hole (which might be more massive than a neutron star), as suggested by van der Klis et al. (priv.comm.) based on Cyg X-3's X-ray variability?
van Kerkwijk: Not very much, except that the constraint on the radius would be a little bit tighter: for a 2,5,10 or 20 M⊙ Wolf Rayet star and a 10 M⊙ black hole, the Roche lobe radius would be 0.9, 1.2, 1.5 or 2.0 R⊙. For a 1 M⊙ neutron star, the radius would be 1.1, 1.3, 1.4 or 2.4 R⊙, respectively. For both compact companions, the hydrostatic helium-star radii are smaller than the radii of the Roche lobe.
Schmutz: The spectral analysis of the 1991 spectrum by Schmutz (1993) showed that the stellar parameters agree with those of a WN7 star. However, the photospheric radius turned out to be much larger than the orbital separation. The only possibility to bring the two radii into agreement would be to bring the system much closer, say to 2 kpc. Alternatively, the emission lines could be produced by the X-ray and the HeI lines would form in the shadowed region. But the fact that the object does allow HeI lines to be formed implies that it is cool. A cool object that needs X-rays for the formation of emission lines is certainly not a WR star. Cyg X-3 is certainly a WR-line object from its appearance, but I do not think it belongs to the Population I WR objects.
van Kerkwijk: I cannot exclude the possibility that the Wolf Rayet line spectrum originates from a wind coming from the accretion disk (notice that there has to be a wind to explain both HeI emission lines and infrared luminosity). However, the spectrum is not like that of other X-ray binaries at all. To me, it seems that, all properties of Cyg X-3 considered, the Wolf-Rayet model for the system is a simple one that is at the same time very successful in explaining its properties. Using Occam's Razor, I therefore favour it over models which involve a wind from an accretion disk or so, for which one has to make a lot of assumptions to explain also the increase of the orbital period, infrared luminosity, etc.
Hillier: Is there hydrogen in the spectrum? If hydrogen is present the star will have a considerably larger radius than a pure He star. The presence of hydrogen will also influence any analysis of the asmospheric properties of this system.
van Kerkwijk: There is no evidence for hydrogen in the spectrum. In the strong-lined state, the HeII (14-8) line, which coincides with HI (7-4), seems stronger than HeII (13-8), but this could be due to a contribution from HeI (7-4) lines. In the weak-lined stare, when there is no HeI emission, HeII (14-8) is of comparable strength as HeII (13-8).

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Hamann: I would not or not yet call Cyg X-3 a Wolf-Rayet binary. Its hydrogen deficiency, as a constitutive property of WR stars, is not yet established. Secondly, WR stars ought to show a persistent emission line spectrum, while in Cyg X-3 the strong emission lines are encountered only occasionally. Especially, no conclusions can be drawn from identifying Cyg X-3 with single WR stars, nor with models for them. You derived a spectral classification as "WN7" from the HeI-HeII-line ratio, and then you concluded that there is a contradiction to the radii which we obtain for typical WN7 single stars from our spectral analysis. However, the atmosphere of Cyg X-3 certainly has a completely different geometry, and thus any comparison with spherically-symmetric models is misleading.
van Kerkwijk: I do not quite agree with the remark that we cannot classify the companion of Cyg X-3 as a Wolf-Rayet. I think there is evidence for a hydrogen deficiency, and to me it seems that the fact that we cannot always see the Wolf-Rayet spectrum in full, is not a strong argument, if there is one can understand why this is the case. However, I agree with your remark that one should not compare the spectra of Cyg X-3 with results derived from models that assume spherical symmetry, etc. Still I do think that the fact that from the models one does not find any Wolf-Rayet star radius that is small enough to fit in the system, tells one that something is wrong with the models, most likely the velocity law.
Meurs: I wonder whether you could obtain additional support for the idea that Cyg X-3 is in a second WR stage from the mild runaway velocity that the system may have acquired. Can you say anything about at least a radial velocity component from your spectra?
van Kerkwijk: From my spectra, I do not think it is possible. In general, it will be very hard given the large variability of the line profiles. Its position and distance correspond to a height above the galactic plane of only about 100pc, so this gives no strong constraints either.
Niemela: Have you compared your spectrum with that of other X-ray binaries, e.g. SS 433?
van Kerkwijk: Yes, I took infrared spectra of both low and high-mass X-ray binaries for that purpose. Their spectra are very different. Especially, all lack strong HeII lines (usually, they only show the very strongest HeII lines, like HeII 4686). In the infrared, LMXBs show emission in Br γ and HeI 2.058 (if anything at all). SS 433 shows strong Br γ emission.
Moffat: Would not a crucial argument in favour of Cyg X-3 containing a genuine Pop I WR (i.e. WNL) star is that during X-ray low, as in 1991, the emission-line spectrum becomes enhanced, i.e. reverts more to an unperturbed WN7 star?
van Kerkwijk: I hope this is not a crucial argument, because it has been found by Kitamoto et al. (1994) that in 1991, when the lines were strong, the X-ray source was in its high-intensity, soft-spectrum state, while in 1992, when the lines were weak, it was probably in its low-intensity, hard-spectrum state. They attribute this to changes in X-ray optical depth: when the wind is denser, the X-ray luminosity goes up, but also the optical depth increases. If the latter effect is more important, the wind might get less influenced in this state, and hence show stronger lines.
Conti: The K band spectrum of Cyg X-3 looks to me very much like that of other WN stars for which there are K band spectra. It seems to me that if it looks like a duck, quacks like a duck, and associates with other ducks, it's probably a duck. Of course, it still might be a goose! But, in this context, what is a goose?
Hillier: 1. Spectrum I believe is unique. I am unaware of WN stars which show very strong HeI 2.058 and strong HeII emission but a unique spectrum may not be surprising given the complexity of the system.
2. Symbiotic stars and other systems sometimes show WR spectra.

van Kerkwijk: I agree the behaviour of HeI 2.058 is exceptional. However, given the metastable level involved, this is maybe not that strange, given as you said the complexity of the system. Regarding the symbiotics, etc., that sometimes show a Wolf-Rayet spectrum as well, it should be noticed that their lines are usually much less broad, and also their absolute luminosities much lower.

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