Astron. Astrophys. 333, 151–158 (1998)

ASTRONOMY AND ASTROPHYSICS

Cyg X-3: can the compact object be a black hole?

Ene Ergma[1,3] **and Lev R. Yungelson**[2,3]

[1] Physics Department, Tartu University, Ülikooli 18, EE2400 Tartu, Estonia (ene@physic.ut.ee)
[2] Institute of Astronomy of the Russian Academy of Sciences, 48 Pyatnitskaya Str., 109017 Moscow, Russia (lry@inasan.rssi.ru)
[3] Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

Received 26 June 1997 / Accepted 29 January 1998

Abstract. By means of population synthesis we find that the expected Galactic number of black holes with massive helium star companions is ~ 100 and depends on an assumed threshold for $M_{\rm pre-BH}$. The overwhelming majority of these systems has orbital periods in excess of 10 hr, with a maximum at ~ 100 hr, while under the Illarionov & Sunyaev(1975) disk formation criteria for accretion from the strong stellar wind of a Wolf-Rayet star, disk accretion is possible only for orbital periods below ~ 10 hr. However, the number of such short-period systems is vanishingly small. If the accretor in Cyg X-3 is a 10 $M_\odot$ black hole, then the accretion rate will be super-Eddington. Super-Eddington accretion may be responsible for the formation of jets in Cyg X-3 and may also support an X-ray luminosity as high as $\sim 10^{39}$ erg s^{-1}. From the orbital period distribution for neutron stars with massive helium companions we find that if during the common envelope phase a neutron star accretes at $\dot M_{\rm Edd}$ and spins-up to the equilibrium period, then in most systems the spinning neutron star acts as a"propeller" and accretion from the WR star wind is impossible. For the model with two massive helium stars as an immediate progenitor of Cyg X-3, the requirement of accomodation of two WR stars in the post-common-envelope orbit combined with severe mass loss by them prevents formation of BH+WR systems with orbital periods less than several days.

Key words: binaries: close – accretion, accretion disks – stars: Wolf-Rayet

1. Introduction

At present, three black hole candidates with massive early-type companions are known (Cyg X-1, LMC X-3 and LMC X-1). About half a dozen of black hole candidates with low-mass companion stars have been identified as the so-called X-ray transients (Tanaka & Lewin 1995; Tanaka & Shibazaki 1996). Yet another candidate may be the puzzling 4.8 hr orbital period X-ray binary Cyg X-3 (Giacconi et al. 1967). Its spectrum is hard, with a tail extending to ultra-high energy γ-rays (Lloyd-Evans et al. 1983). Cyg X-3 shows an asymmetric sinusoidal modulation in the low-energy X-ray emission (Mason et al. 1976). The same modulation is present in the infrared light curve (Becklin et al. 1973; Mason et al. 1986). Infrared spectroscopy has recently shown that the companion is a Wolf-Rayet star of the WN7 subtype (van Kerkwijk et al. 1992, 1996; van Kerkwijk 1993). Cyg X-3 has huge radio outbursts with evidence for jet-like emission expanding at $\sim 1/3$ of the light velocity (Gregory et al. 1972; Geldzahler et al. 1983).

The orbital period of Cyg X-3 is increasing on a time scale of 850 000 years (Kitamoto et al. 1995). With this $\dot P/P$ it is possible to estimate the stellar wind mass loss rate as $\dot M_{\rm dyn} = M_{\rm tot}(\dot P/2P) \approx 6 \times 10^{-6}(M_{\rm tot}/10M_\odot)$ M$_\odot$ yr^{-1}, where $M_{\rm tot} = (M_{\rm c} + M_{\rm WR})$, $M_{\rm c}$, and $M_{\rm WR}$ are the masses of the compact object and the WR star, respectively.

Another estimate of the mass loss rate can be made using the infrared flux $F_{\rm ff}$. Van Kerkwijk et al. (1996) estimated $\dot M_{\rm ff}$ using a simple relation $\dot M_{\rm ff}/v_{\rm w} \propto F_{\rm ff}^{3/4}$. For the wind velocity of 1450 ± 150 km s^{-1} and $F_{\rm ff}$ determined from the May 1992 infrared light curve they find $\dot M_{\rm ff} \approx 1.2\times10^{-4}$ M$_\odot$ yr^{-1}, an order of magnitude larger than the dynamical estimate $\dot M_{\rm dyn}$ (for $M_{\rm WR} = 10\ M_\odot$, $M_{\rm c} = 1.4M_\odot$). But as was already discussed by van Kerkwijk et al. (1996), $\dot M_{\rm ff} \sim 10^{-4}$ M$_\odot$ yr^{-1} that is inferred from the infrared flux should be regarded as highly uncertain. Due to the clumpiness of the wind, the true mass loss rate may be lower than $\dot M_{\rm ff}$ by a factor 2–3 and for Cyg X-3 the difference may be even larger (see also Cherepashchuk & Moffat (1994) and references therein for a discussion of the effect of clumps).

Cyg X-3 is a strong X-ray source with mean X-ray flux $F_{\rm X}(2-20\,{\rm KeV}) \approx 6.8 \times 10^{-9}$ erg s^{-1}cm^{-2}, i.e. $L_{\rm X} \approx 1.2 \times 10^{38}(d/12\ {\rm Kpc})^2$ erg s^{-1} (Kitamoto et al. 1995). Cherepashchuk & Moffat (1994) argue that since $L_{\rm bol}({\rm WR}) \sim 3 \times 10^{39}$ erg s^{-1} and because the effect of the X-rays is observed in the IR range, the true intrinsic X-ray luminosity of the accreting relativistic object in Cyg X-3 must be considerably higher than the observed mean value of the hard X-ray luminosity $L_{\rm X} \sim 10^{38}$ erg s^{-1}. In their opinion, "this fact favours the presence of an accreting black hole, as opposed to a neutron star, in Cyg X-3".

Recently, Schmutz et al. (1996) observed time-variations in the profiles of several infrared emission lines from Cyg X-3. They concluded that the variations are due to the orbital mo-

Send offprint requests to: E. Ergma

tion of the WR star and derive a mass function for Cyg X-3 of 2.3 $M_\odot$. Assuming reasonable values for the mass of the WR star and the inclination angle, they obtained a range of masses 7–40 $M_\odot$ for the compact object, with the most likely value of 17 $M_\odot$, from which they concluded that the compact component of Cyg X-3 is a black hole.

Van den Heuvel & De Loore (1973) were the first to suggest that Cyg X-3 may be a system in a post massive X-ray binary (MXRB) stage and may harbour a compact object (neutron star or black hole) and a helium star of several solar masses. Tutukov & Yungelson (1973a) independently suggested that the optical components of MXRB will in the later evolutionary stage become WR stars provided that they are massive enough.

In the present paper we attempt to model the Galactic population of black-hole + massive helium star systems and to show that the very short orbital period makes Cyg X-3 an extremely rare example of such systems detectable by X-ray observations. Also, we discuss the circumstances which prevent discovery of a large Galactic population of neutron star+helium star systems, which are probably quite numerous.

2. Cyg X-3 - a unique system with a black hole accretor?

2.1. Formation scenarios for BH + WR binaries

The calculations for the present study were made by means of the population synthesis code which was previously applied by one of the authors (LRY) for the modelling of different components of the binary star population of the Galaxy, among them binary Wolf-Rayet stars (Yungelson & Tutukov 1991; Vrancken et al. 1991), neutron stars (Tutukov & Yungelson 1993a,b) and high-mass X-ray binaries (Iben et al. 1995). The basic assumptions important for the present study are the following.

The initial mass function of the primaries in binary stars is a power-law $dN \propto M_1^{-2.5} dM_1$. The initial distribution of binaries over separation a is flat in $\log a$ for $0 \le \log(a/R_\odot) \le 6$. The orbits of close binaries are initially circular. The initial distribution of binaries over mass ratios of components $q_0 = M_2/M_1$ is flat for $0 < q_0 \le 1$. Discussion of the effects of the assumed distributions over a and q_0 upon the population of high-mass binaries in the Galaxy may be found elsewhere (*e.g.* Portegies Zwart & Verbunt 1995; Portegies Zwart & Yungelson 1998). They appear to be of no serious significance to the (mostly) qualitative conclusions of the present paper.

Normalization of the Galactic stellar birthrate function corresponds to the formation of one binary system with the initial mass of the primary greater than 0.8 $M_\odot$ per year. The rate of binarity of stars is assumed to be equal to 100 %.[1] With this normalization and the assumed rate of binarity our model gives a combined rate of SN Ib/c and SN II ~ 0.02 yr^{-1}, consistent with the sum of expected rates of Galactic SN Ib/c and SN II (Cappellaro et al. 1997).

Below, we were use the following notation: MS - main-sequence star, RLOF - stage of the Roche lobe overflow (stable or with formation of a common envelope), He - helium star remnant of a star which experienced a mass loss (in fact, a WR star), SN - supernova explosion, BH - black hole. Then all basic scenarios for the formation of black-hole + helium star binaries may be summarized as:

A. $\mathrm{MS_1 + MS_2 \to RLOF_1 \to He_1 + MS_2 \to SN_1 + MS_2 \to BH_1 + MS_2 \to RLOF_2 \to BH_1 + He_2}$

and

B. $\mathrm{MS_1 + MS_2 \to He_1 + MS_2 \to SN_1 + MS_2 \to BH_1 + MS_2 \to BH_1 + He_2}$.

Scenario A occurs in the systems in which stellar wind mass loss does not prevent significant expansion of stars and RLOF. In the opposite case scenario B occurs. In fact, in scenario B components of binaries evolve independently like single stars. In the absence of hydrodynamic calculations of the mass exchange, the upper mass limit of stars which may experience *classical* RLOF is, in fact, one of the free parameters of the problem (for discussion of this issue see, *e.g.* Sybesma 1986; Moffat 1995). Conventional computations of stellar evolution with stellar wind mass loss rates suggested by observations (*e.g.* Massevich et al. 1979; Sybesma 1986; Vanbeveren 1991) show that scenario A occurs in systems with the initial mass of the primary component below 35 - 50 $M_\odot$. However, depending on the mass accumulated in the $\mathrm{RLOF_1}$ event, the secondary in scenario A may avoid RLOF and, *vice versa*, the secondary in scenario B may encounter RLOF if its mass is sufficiently low. In the present study we assume that the border between scenarios A and B is at $M_1 = 50\ M_\odot$. Systems which evolve under the influence of stellar wind mass loss have larger orbital separations in the $\mathrm{BH_1 + He_2}$ stage than systems which evolved through nonconservative RLOF. Decrease of the abovementioned border to below $M_1 = 50\ M_\odot$ would make the conditions for the formation of Cyg-X3-like systems even less favourable than is found below (see Fig. 1).

The mass of the helium star immediately after the end of the mass exchange episode is given by the relation $M_{\rm He} = 0.066 M_{\rm MS}^{1.54}$, which represents a fit to the evolutionary calculations by Tutukov & Yungelson (1973b) and Iben & Tutukov (1985).

To estimate the variation in the separation of components in the common envelope stage we applied the equation suggested by Tutukov & Yungelson (1979):

$$\frac{(M_{10} + M_2)(M_{10} - M_{1f})}{2a_0} \approx \alpha_{ce} M_{1f} M_2 \left(\frac{1}{2a_f} - \frac{1}{2a_0} \right), \quad (1)$$

where subscripts 0 and f refer to the initial and final states, respectively, and α_{ce} is the parameter which measures the ratio of the binding energy of the common envelope and the change in the orbital energy of the binary (see e.g. Iben & Livio 1993; Livio 1996 for discussion). This equation implies that the spiral-in starts when the envelope surrounding the two cores expands to $\sim 2a_0$ and mass is actually ejected from the gravitational potential of both components. Computations were performed for

[1] For another birthrate normalization and other assumptions on the rate of binarity, all numbers of binaries given below have to be rescaled.

the common envelope parameter α_{ce}= 1, which gave reasonable results in our previous attempts to model the population of binary stars. When compared to the equation for a_f/a_0 derived by Webbink (1984), which is often applied for population synthesis studies, α_{ce}= 1 in Eq. (1) corresponds to $\alpha_{ce} \approx 4$ in Webbink's equation. For the latter this formally means that most of the energy for expulsion of a common envelope comes from sources other than the orbital energy of the binary. However, there are clear indications that with $\alpha_{ce} \sim 3-4$ (in Webbink's formulation) one would obtain more reasonable agreement with observations for several classes of descendants of massive binaries than with lower values of α_{ce} (Portegies Zwart & Yungelson 1998).

2.2. Masses of the Cyg X-3 components

The actual mass range of progenitors of black holes both in single stars and in binaries is, in fact, unknown. The main factors contributing to this are the uncertain mass loss rates of hydrogen- and helium-rich stars, poor understanding of mixing processes in stellar interiors and of processes during a supernova explosion, and a poorly known equation of state (see *e.g.* Woosley et al. 1995; Brown et al. 1996 and references therein). The "standard" assumption is that binary components more massive than 40 $M_\odot$ form black holes (van den Heuvel & Habets 1984). Recent calculations of Brown et al. seem to confirm this limit, while according to Woosley et al. (1995), who assume an extremely high mass-loss rate for helium stars, this limit may be as high as $\sim 60\,M_\odot$. Another implication of the Woosley et al. results is convergence of pre-supernovae masses to 3–4 $M_\odot$. Actually, significant spread in masses in observed candidate black holes in soft X-ray transients (4–16 $M_\odot$) suggests that there may be factors other than the initial mass which determine the fate of a star (Ergma & van den Heuvel 1998). Under the given circumstances, we treated the masses of black holes and their progenitors as an additional model parameter. Computations were performed on the assumption that black holes result from objects which have a mass exceeding 7 or 10 $M_\odot$ at the end of the helium star stage. Under the initial-final mass relation given in Sect. *2.1* and using Langer's (1989) mass loss rates for helium stars, these limits correspond to $M_{ZAMS} \approx 30$ or 50 $M_\odot$. We assumed that no mass is ejected during a massive helium star remnant collapse into BH (Burrows 1987; Woosley & Weaver 1995).

The mass of the WR component of Cyg X-3 is likewise uncertain. Cherepashchuk & Moffat (1994) suggest the range 10–50 $M_\odot$ based on the spread of estimates of masses of actually observed WN7 stars. One can use the estimated mass loss rate of the stellar wind to get some idea about the WR star mass in Cyg X-3. From the observations for five binary Wolf-Rayet stars, Abbott et al. (1986) derive $\dot{M}_{\rm w} \propto M_{\rm WR}^{2.3}$. Langer (1989) suggests, from the fits of stellar models to the observational data, that in the WR star core helium burning phase $\dot{M}_{\rm w} \approx (1{-}6)\times10^{-8}(M_{\rm WR}/M_\odot)^{2.5}$ $\rm M_\odot\ yr^{-1}$. If $\dot{M}_{\rm w} \sim 1/10\dot{M}_{\rm ff} \approx 1.2\times10^{-5}$ $\rm M_\odot\ yr^{-1}$ (van Kerkwijk et al. 1996) and $\dot{M}_{\rm w} \approx \dot{M}_{\rm dyn}$, then $M_{\rm tot} \sim 20 M_\odot$. A direct application of Langer's formulae gives $8 \lesssim M_{\rm WR}/M_\odot \lesssim 17$.

The rate of accretion onto a black hole may be estimated as

$$\dot{M}_{\rm acc} \approx \frac{\pi r_{\rm acc}^2}{4\pi a^2}\dot{M}_{\rm w}, \quad \text{where } r_{\rm acc} = \frac{2GM_{\rm BH}}{v_{\rm w}^2}. \qquad (2)$$

Then, according to Kepler's third law

$$\dot{M}_{\rm acc} \approx 0.14\frac{M_{\rm BH}^2}{v_{1000}^4}P_{\rm hr}^{\frac{4}{3}}(M_{\rm BH}+M_{\rm WR})^{\frac{2}{3}}\dot{M}_{\rm dyn}, \qquad (3)$$

where all masses are in $M_\odot$, P_{hr} is the orbital period in hours, and v_{1000} is the wind velocity in 1000 km s^{-1}. For $M_{\rm BH} = 10M_\odot$, $v_{1000} = 1.5$, $P_{\rm hr} = 4.8$, $M_{\rm WR} = 10M_\odot$ one gets $\dot{M}_{\rm acc} \approx 0.05\times\dot{M}_{\rm dyn} \approx 5.7\times10^{-7}$ $\rm M_\odot\ yr^{-1}$. The Eddington limit for the accreting black hole (helium accretion and $R = 3r_{\rm g}$) is $2.3\times10^{-8}(M_{\rm BH}/M_\odot)$ $\rm M_\odot\ yr^{-1}$ and for $M_{\rm BH} = 10M_\odot$ it is $\dot{M}_{\rm Edd} \approx 2.3\times10^{-7}$ $\rm M_\odot\ yr^{-1}$. Thus, in the latter case the accretion rate exceeds the Eddington limit. It is easy to find that if the accreting object is a neutron star, then

$$\dot{M}_{\rm acc}({\rm NS}) = \left(\frac{M_{\rm NS}}{M_{\rm BH}}\right)^2\left(\frac{M_{\rm WR}+M_{\rm NS}}{M_{\rm WR}+M_{\rm BH}}\right)^{\frac{2}{3}}\dot{M}_{\rm acc}({\rm BH}). \qquad (4)$$

For the same mass of the Wolf-Rayet star (10 $M_\odot$), but for a neutron star or low-mass black hole accretor (1.5 $M_\odot$, Brown 1995), it is simple to estimate by Eq. (4) that $\dot{M}_{\rm acc}$ is below the Eddington rate. However, if the accretion is super-Eddington, it may be responsible for the formation of jets in Cyg X-3. A high accretion rate may support an X-ray luminosity as high as $\sim 10^{39}$ erg s^{-1} which is consistent with Cherepashchuk & Moffat's (1994) estimate.

No kicks were imparted to the nascent BH. Even in the case of neutron stars the problem of natal kicks is still unsolved: observational data may be explained both on the assumption of the absence of kicks (Iben & Tutukov 1996) and of their presence (van den Heuvel and van Paradijs 1997). As an argument for the absence of kicks for BH one may consider the fact that black hole candidates in low-mass X-ray binaries (LMXB) share the radial velocities of their local rest frames in the Galaxy (with the exception of Nova Sco 1994). The dispersion of their distances to the Galactic plane is smaller than for LMXB with neutron stars by more than a factor 2. This indicates that any kick velocities that the black hole systems may have received at their formation are considerably smaller than those of neutron star systems (White & van Paradijs 1996).

2.3. Model populations of BH + WR and NS + WR binaries

Fig. 1 shows the distribution of BH + WR binaries over orbital periods and masses of WR stars for two assumptions on the progenitor mass of the BH. The minimum mass of the WR star is taken equal to $5M_\odot$. The difference between the two distributions may be due to the fact that for $M_{\rm pre-BH} \geq 30\,M_\odot$ both scenarios A and B operate, while for $M_{\rm pre-BH} \geq 50\,M_\odot$ only scenario B is effective, i.e. in the first case some pre-WR stars were able to accumulate some mass via stable RLOF. The

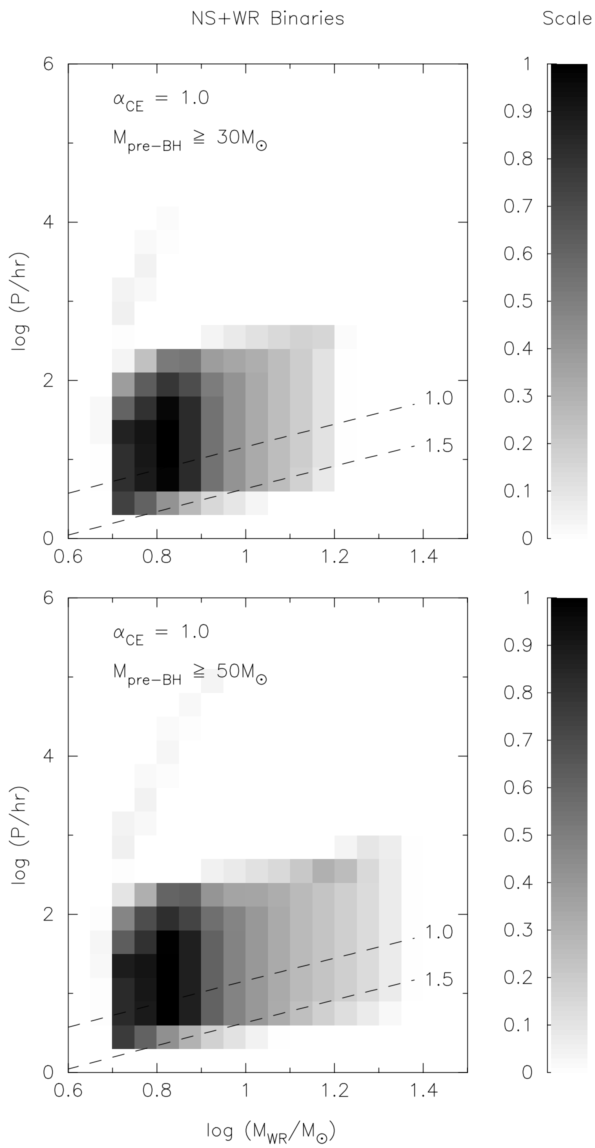

Fig. 1. Normalized number-density distribution of BH+WR systems over orbital periods and masses of WR components for two assumptions on the minimum mass of the progenitors of black holes - 30 $M_\odot$ (upper panel) and 50 $M_\odot$ (lower panel). Dashed line labelled by 1.0 gives the upper limit of orbital periods for which disk accretion onto BH is possible if $M_{\rm BH} = 10 M_\odot$ and $v_{1000} = 1.0$. Maximum of the gray-scale is the same for both panels and corresponds to $\frac{\partial^2 N}{\partial \log {\rm M} \partial \log P} = 274$, where N is the number of systems.

predicted numbers of BH + WR stars in the two cases are ~ 300 and ~ 100 respectively. These numbers can be considered only as giving an order of magnitude estimate on the potential number of the Galactic BH+WR systems. If natal kicks or mass ejection accompany the formation of BH, they may reduce the number of these systems, but they cannot be overly significant for the most massive binaries we are dealing with.

More important, in our opinion, is the fact that the overwhelming majority of these systems have orbital periods longer than 10 hours, with a maximum of ~ 100 hours. This may be helpful in to understanding why Cyg X-3 is unique. On the basis of the seminal Illarionov & Sunyaev's (1975) paper "Why the Number of Galactic X-Ray Stars Is So Small" one can make the following estimate: Illarionov & Sunyaev have shown that in the case of accretion of stellar wind matter in a detached binary system the specific angular momentum of the matter captured by the relativistic star is typically small. Therefore, no accretion disk is formed around the relativistic star. Consequently, very special conditions are required for a black hole in a detached binary system to be a strong X-ray source. A disk may form if the specific angular momentum of accreting matter exceeds the specific angular momentum of the particle in the last inner stable orbit with $R = 3r_{\rm g}$, which is equal to $Q_{\rm min} = \sqrt{3} r_{\rm g} c$. Thus, the disk formation criterion is

$$\frac{1}{4}\Omega R_{\rm A}^2 > \sqrt{3} r_{\rm g} c, \qquad (5)$$

where $R_{\rm A}$ is the capture radius of stellar wind matter by the relativistic star. This condition is fulfilled when the period of the binary system $P_{\rm orb} < 4.8 (M_{\rm BH}/M_\odot) v_{1000}^{-4} \delta^2$ hr, where $\delta \sim 1$ is a dimensionless parameter. Typical Wolf-Rayet stellar wind velocities range from 1000 km s^{-1} to 4000 km s^{-1} (Conti 1988). As a result, disk accretion is possible only for systems having a very short orbital period (Fig. 1). Curiously enough, if $M_{\rm BH} \approx 5 M_\odot$, and the wind velocity ~ 1500 km s^{-1} for Cyg X-3, the disk accretion condition is satisfied when $P_{\rm orb} \approx 4.8$ hr! (A similar conclusion was reached by Iben et al. 1995).

A Wolf-Rayet binary with $P_{orb} = 4\overset{d}{.}32$ and suspected BH-companion HD 197406 (Cherepashchuk 1991; Marchenko et al. 1996) may be a representative of the population of BH+WR binaries which do not show up as X-ray sources.

The population of BH + WR stars can be compared with the population of neutron stars accompanied by WR stars (henceforth, NS + WR). Fig. 2 shows $\log M_{\rm WR} - \log P$ plots for NS + WR stars similar to Fig. 1. The respective numbers of systems are ~ 570 and ~ 700 for $M_{\rm pre-NS} \leq 30$ and 50 $M_\odot$. These numbers provide upper limits for this possible population because no natal kicks were imparted to neutron stars. It is also worthwhile to note that natal kicks tend to influence more strongly the eccentricities of orbits of post-supernovae systems than their orbital periods.

One may ask why NS + WR systems are not observed. We would like to call attention to the following. If the WR component is formed via RLOF one can expect that a common envelope forms because of the high mass ratio of components at the instant of the RLOF by the progenitor of the WR star. As a rule, the common envelope stage lasts for $\sim 10^3 - 10^4$ yrs. During this stage the NS may accrete at the Eddington rate of 1.5×10^{-8} M$_\odot$ yr^{-1}. Accretion spins up the neutron star (Pringle & Rees 1972; Davidson & Ostriker 1973) to the equilibrium period

$$P_{\rm rot} = P_{\rm eq} \approx 4 B_{11}^{\frac{6}{7}} \dot{M}_{11}^{-\frac{3}{7}} M_{\rm NS}^{-\frac{5}{7}} \quad {\rm s}, \qquad (6)$$

where $B_{11} = B/10^{11}$ G, $\dot{M}_{11} = \dot{M}/1.5 \times 10^{-11}$ M$_\odot$ yr^{-1}, $M_{\rm NS}$ is the neutron star mass in $M_\odot$. The amount of matter required for the spin-up to $P_{\rm eq}$ is

$$\Delta(M/M_\odot) \approx 0.1 (P_{\rm eq}/1.5\,{\rm ms})^{-\frac{4}{3}}. \qquad (7)$$

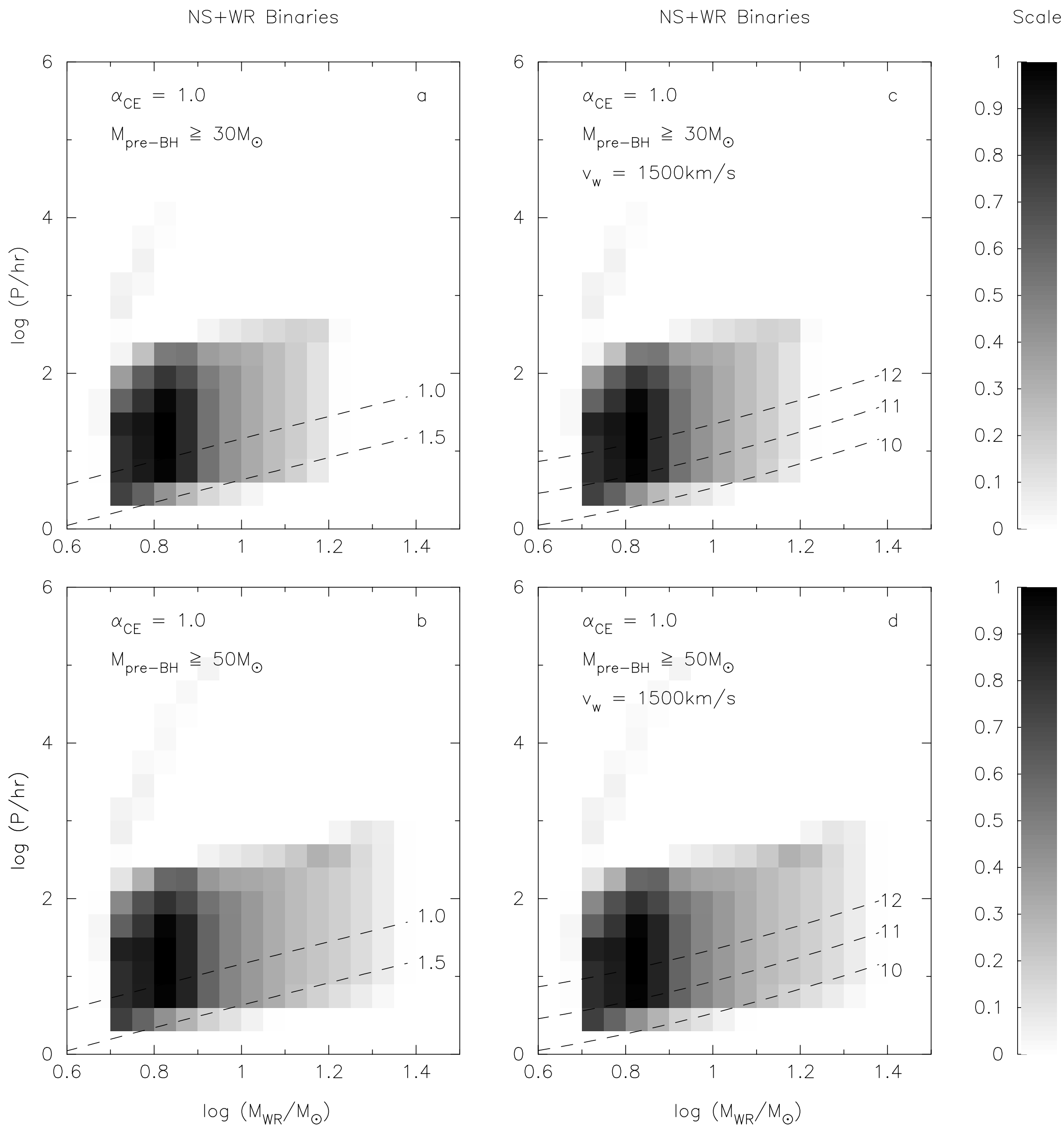

Fig. 2a–d. The same as in Fig. 1, but for NS+WR systems. In panels **a** and **b** dashed lines labelled by 1.0 and 1.5 give the upper limits of orbital periods for which the "propeller" effect does not prevent disk accretion onto the NS if $v_{1000} = 1.0 \text{ and } 1.5$, respectively. In panels **c** and **d** dashed lines labelled 10, 11, and 12 give the upper limits of the the orbital periods for which the spin deceleration timescale of a neutron star is shorter than the helium-burning time of its companion if the magnetic field strength is $B = 10^{10},\ 10^{11},\ \text{and } 10^{12}$ Gs, respectively. Maximum of the gray-scale is the same for all panels and corresponds to $\frac{\partial^2 N}{\partial \log \mathrm{M} \partial \log P} = 1160$.

For $B_{11} = 1, 10$ and $\dot{M}_{11} = 1000$, the equilibrium periods are 0.16 and 1.17 s, respectively. The amount of matter required for accretion is for these two cases $\Delta M = 1.9 \times 10^{-4}\ M_\odot$ and $1.4 \times 10^{-5}\ M_\odot$. These amounts may be easily accreted during the common envelope stage. After the common envelope is dispersed, the NS appears to be immersed in the strong wind of the WR star. Its initial rotational period is determined by Eq. (6) for accretion at $\dot{M}_{\rm Edd}$. Following Illarionov & Sunyaev (1976) (see also Lipunov 1982), accretion onto the surface of a rotating neutron star is possible only if its rotational period is $P_{\rm rot} \gtrsim P'_{\rm eq}$, where $P'_{\rm eq}$ is now an equilibrium period determined by the rate of accretion from the WR star wind. Then, from Eqs. (2) and (6), for $\dot{M}_{\rm WR} = 4 \times 10^{-8} M_{\rm WR}^{2.5}\ \mathrm{M_\odot\ yr^{-1}}$ (Langer 1989) and $\dot{M}_{\rm Edd} = 1.5 \times 10^{-8}\ \mathrm{M_\odot\ yr^{-1}}$, it follows that accretion is possible only for systems with

$$P_{\rm orb} \lesssim 7.3 B_{11}^{-\frac{3}{2}} M_{\rm NS}^{\frac{11}{4}} M_{\rm WR}^{\frac{15}{8}} M_{\rm tot}^{-\frac{1}{2}} P_{\rm rot}^{\frac{7}{4}} v_{1000}^{-3}\ \ \mathrm{hr} \tag{8}$$

or

$$P_{\rm orb} \lesssim 0.46 M_{\rm NS}^{\frac{3}{2}} M_{\rm tot}^{-\frac{1}{2}} M_{\rm WR}^{\frac{15}{8}} v_{1000}^{-3} \;\; {\rm hr}, \quad (9)$$

where $M_{\rm tot} = M_{\rm NS} + M_{\rm WR}$. For a higher $P_{\rm orb}$ a neutron star would act as a "propeller". Note that the critical value of $P_{\rm orb}$ does not depend on B [in Eq. (9)] after elimination of the equilibrium period of rotation in the common envelope. For $v_{1000} = 1$ and 1.5 the limiting $P_{\rm orb}$ is plotted in Fig. 2 [panels (a) and (b)]. It is evident that for the overwhelming majority of NS + WR systems the "propeller" effect may prevent accretion and hence X-ray emission. This result does not depend on the value of α_{ce} assumed in the population synthesis calculations, because the lower limit of the orbital periods of the systems under consideration is determined by the requirement of accommodation of the WR star in the post-common-envelope orbit. Application of other prescriptions for mass and momentum loss in the evolution of close binaries cannot change this result either, because the only difference which can be expected is a different distribution over orbital periods with the same minimum period (see Portegies Zwart & Verbunt 1995 for a discussion of the influence of different population synthesis "recipes").

A neutron star in the "propeller" stage would experience spin deceleration. The characteristic time of a neutron star spin-down is (Illarionov & Sunyaev 1975)

$$t_{\rm A} \approx 4 \times 10^8 B_{11}^{-\frac{3}{7}} \dot{M}_{11}^{-\frac{11}{14}} M_{\rm NS}^{-\frac{1}{7}} v_{1000}^{\frac{1}{2}} \;\; {\rm yr} \quad (10)$$

or

$$t_{\rm A} \approx 3.8 \times 10^6 B_{11}^{-\frac{3}{7}} M_{\rm NS}^{-\frac{12}{7}} M_{\rm WR}^{-\frac{55}{28}} M_{\rm tot}^{-\frac{11}{49}} P_{\rm orb}^{\frac{22}{21}} v_{1000}^{\frac{45}{14}} \;\; {\rm yr}. \quad (11)$$

This deceleration time can be compared with the helium burning time in the core of a WR star, for which the fit to the Paczyński (1971) and Iben & Tutukov (1985) data gives:

$$\log t_{\rm He} \approx 7.15 - 3.7y + 2.23y^{1.37} \;\; {\rm yr}, \quad (12)$$

where $y = \log(M_{\rm WR}/M_\odot)$. The spin of the neutron star decelerates enough to allow accretion if the orbital period of the system is

$$P_{orb} \lesssim 0.5 t_{\rm He}^{\frac{21}{22}} B_{11}^{\frac{9}{22}} M_{\rm WR}^{\frac{15}{8}} M_{\rm tot}^{\frac{3}{14}} v_{1000}^{-\frac{135}{44}} \;\; {\rm hr}, \quad (13)$$

where t_{He} is in units of 10^6 yr. This critical period is plotted in Fig. 2 [panels (c) and (d)] for WR wind velocity 1500 km s^{-1} and three values of the strength of the magnetic field which fit the range expected for neutron stars with an age of several Myr, typical of NS + WR systems. Fig. 2 shows that even if deceleration is taken into account, the propeller effect excludes accretion for the overwhelming majority of NS +WR binaries.

If a WR star forms due to wind mass loss, one can expect a much lower accretion rate onto the NS than in the common envelope, hence, a longer equilibrium period. For the same wind velocities, conditions for disk formation may become more favourable. However, as Fig. 2 clearly shows, descendants of very massive stars probably comprise a small fraction of all WR stars in NS + WR binaries: *e.g.* $\log M_{WR/M_\odot} = 1.2$ under our formalism corresponds to a main-sequence mass of $\sim 35 M_\odot$.

2.4. Future evolution of the Cyg X-3 system

Accepting that Cyg X-3 contains a 10 $M_\odot$ WR star and a 10 $M_\odot$ black hole it is possible to speculate about possible endpoints of its evolution. A substantial amount of mass may be lost in the WR evolutionary stage. This matter leaves the system in an isotropic, high-velocity wind, carrying away specific angular momentum of the primary. Then

$$\frac{\dot{a}}{a} = -\frac{\dot{M}_{\rm WR}}{M_{\rm BH} + M_{\rm WR}}. \quad (14)$$

For a 10 $M_\odot$ helium star, the evolutionary timescale is $\sim 5.5 \times 10^5$ yr (Langer 1989). At the end of the evolution of the present WR star, the system will have $P_{\rm f} \approx 8$ hr, $M_{\rm WR,f} \approx 5 M_\odot$. If the outcome of evolution is a collapse into a black hole, then the system's further evolution will proceed due to gravitational wave radiation and in $\sim 4 \times 10^8$ yrs time the system will merge. If a Wolf-Rayet star forms a neutron star and expels its envelope, then, depending on the magnitude and direction of the natal kick, its semi-major axis may become so large that the neutron star will not merge with its black hole companion in a Hubble time.

3. Discussion and conclusion

Our study, as one could expect from previous studies of a similar kind, suggests that there may exist a significant (~ 100 objects) Galactic population of massive ($\sim 10 M_\odot$) black holes and neutron stars accompanied by Wolf-Rayet stars. Yet, the only example of such systems observed to-date is Cyg X-3 which is suspected to harbour a black hole. Rather rough estimates made in Sec. 2 suggest a combination of reasons for the low proportion of such observed systems. First, both BH+WR and NS+WR systems predominantly form with orbital periods exceeding several days. Second, for disk accretion from the WR star wind to occur, the angular momentum of the wind matter has to be high. Hence, the formation of accretion disks is possible only in BH+WR systems with relatively short orbital periods. However, the number of such systems is vanishingly small (Fig. 1). Cyg X-3 may be a unique example of such a system.

The formation of accretion disks in NS+WR systems is excluded by their specific evolutionary history. Namely, the spin-up of neutron stars due to Eddington rate accretion in common envelopes which accompany the birth of the overwhelming majority of WR stars suffices to prevent accretion via the action of the "propeller" mechanism if, in the subsequent stage, the wind velocity of the WR star exceeds ~ 1000 km s^{-1} (Fig. 2), the actual lower limit for WR star winds. The lower limit of the model orbital periods of BH/NS+WR systems depends solely on the radii accepted for helium stars and does not depend on other parameters of the population synthesis models, such as the common envelope parameter.

Recently, the possibility that Cyg X-3 may harbour a black hole as the compact object has been discussed by Brown (1995). Having considered the masses of the components in this system, Brown (1995) suggests that the progenitor of the present compact object had $M_{\rm ZAMS} \gtrsim 35\ M_\odot$. The immediate progenitor of Cyg X-3 in Brown's model contains two massive WR stars. However, the requirement of accomodation of two WR stars in the post-common-envelope orbit combined with severe mass loss by helium stars prevents, in this model, the formation of BH+WR systems with orbital periods less than several days.

It is also suggested that low-mass black holes in close binaries may originate as a result of hypercritical accretion onto neutron stars in common envelopes (Zel'dovich et al. 1972; Chevalier 1993; Brown 1995; Fryer et al. 1996). However, it is unclear whether these black holes may survive in the common envelopes and avoid swallowing of the whole envelope of the companion.

All low-mass X-ray binaries with suspected black hole components (with the possible exception of GX 339-4, Makishima et al. 1986) are soft X-ray transients (SXT), while SXT are absent among massive X-ray binaries. Since Cyg X-3 has a short orbital period, similar to the periods of SXT's, one may wonder why Cyg X-3 is a persistent source. Recently, van Paradijs (1996) and King et al. (1996, 1997), have discussed the conditions necessary for disk instability in low-mass X-ray binaries in the presence of X-ray irradiation. King et al. (1997) have realized that irradiation is much weaker if the accreting object is a black hole rather than a neutron star, since black holes do not have hard surfaces and cannot act as point-like central sources. According to King et al. , a system is persistent in X-rays if

$$\dot{M} \gtrsim \dot{M}_{\rm crit}^{\rm irr} \approx 2.86 \times 10^{-11} M_{\rm BH}{}^{\frac{5}{6}} M_2^{-\frac{1}{6}} P_{\rm hr}^{\frac{4}{3}} \quad {\rm M}_\odot\ {\rm yr}^{-1}, \quad (15)$$

where M_2 is the mass of the companion to the BH. For $M_{\rm BH} = M_2 = 10 M_\odot$, $P_{\rm hr} = 4.8$, $\dot{M}_{\rm crit}^{\rm irr} \approx 10^{-9}\ {\rm M}_\odot\ {\rm yr}^{-1}$, well below the estimated accretion rate in Cyg X-3 of $\dot{M}_{\rm acc} \approx 5.7 \times 10^{-7}\ {\rm M}_\odot\ {\rm yr}^{-1}$.

Acknowledgements. The authors acknowledge support to E.E. through the "Fund to advance the participation of women in higher academic positions" and to L.R.Y. through NWO Spinoza Grant to E. P. J. van den Heuvel. The present work was completed thanks to the Estonian Science Foundation grant 2446 and to the Russian Foundation for Basic Research grant 96-02-16351.

Both authors acknowledge the warm hospitality extended to them at the Astronomical Institute "Anton Pannekoek" where this study was accomplished. We are indebted to Prof. E. P. J. van den Heuvel and Dr. S. F. Portegies Zwart for their stimulating discussions on the subject of the evolution of binaries, and to the referee, Dr. A. Moffat, for his comments on the earlier version of the paper.

References

Abbott, D.C., Garmany C.D., Hansen C.J., Henrichs H.F., Pesnell W.D. 1986, PASP, 98, 29
Becklin, E.E. Neugebauer G., Hawkins F.J. et al. 1973, Nat, 245, 302
Brown, G.E. 1995, ApJ, 440, 270
Brown, G.E., Weingartner, J.C., Wijers, R.A.M.J. 1996, ApJ, 463, 297
Burrows, A. in SN 1987A, ESO Workshop No. 26, ed. I. J. Danziger (Garching: ESO), p. 315
Cappellaro, E., Turrato M., Tsvetkov D.Yu., et al. 1997, A&A, 322, 431
Cherepashchuk, A.M. 1991, in Wolf-Rayet stars and Interrelations with Other Massive Stars in Galaxies, ed. K.A. van der Hucht, B. Hidayat (Dordrecht: Kluwer), p. 187
Cherepashchuk, A.M., Moffat, A.F.J. 1994, ApJ., 424, L53
Chevalier, R. 1993, ApJ, 411, L33
Conti, P.S. 1988, in O stars and Wolf-Rayet stars, NASA SP-497, p. 81
Davidson, K., Ostriker, J.P. 1973, ApJ, 179, 585
Ergma, E., van den Heuvel, E.P.J. 1998, A&A, accepted
Giacconi, R. Gorenstein P., Gursky H., Waters J.R. 1967, ApJ, 148, L119
Geldzahler, B.J. Johnston, K.J., Spencer J.H., et al. 1983, ApJ, 273, L65
Gregory, P.C., Kronberg P.P., Seaquist E.R., et al. 1972, Nat Phys Sci, 239, 114
Fryer, C.L., Benz, W., Herant, M. 1996, ApJ, 460, 826
Iben, I.Jr., Livio M. 1993, PASP, 105, 1373
Iben, I.Jr., Tutukov, A.V. 1985, ApJSS, 58, 661
Iben, I.Jr., Tutukov, A.V. 1996, ApJ, 456, 738
Iben, I.Jr., Tutukov, A.V., Yungelson, L.R. 1995, ApJSS, 100, 217
Illarionov, A.F., Sunyaev, R.A. 1975, A&A, 39, 185
King, A.R., Kolb, U., Burderi, L. 1996, ApJ, 464, L127
King, A.R., Kolb, U., Szuszkiewicz, E. 1997, ApJ, in press
Kitamoto S., Hirano A., Kawashima K., et al. 1995, PASJ, 47, 233
Langer N., 1989, A&A, 220, 135
Lipunov, V. M. 1982, SvALett, 8, 358
Lloyd-Evans, J., Coy R.N., Lambert A., et al. 1983, Nat, 245, 302
Livio, M. 1996, in Evolutionary Processes in Binary Stars, ed. R.A.M.J. Wijers, M.B. Davies, C.A. Tout (Dordrecht: Kluwer), p. 141
Marchenko, S.V., Moffat A.F.J., Lamontagne R., Tovmassian G., 1996, ApJ, 461, 386
Massevich A., Popova E.I., Tutukov A.V., Yungelson L.R., 1979, ApSpSci, 62, 451.
Makishima, K. Maejima Y., Mitsuda K., et al. 1986, ApJ, 308, 635
Mason K.O. Becklin E.E., Blankenship L., et al. 1976, ApJ, 207, 78
Mason, K.O., Cordova, F.A., White, N.E. 1986, ApJ, 309, 700
Moffat, A.F.J. 1995, in Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, ed. K.A. van der Hucht, P.M. Williams (Dordrecht: Kluwer), p. 213.
Paczyński, B. 1971, Acta Astron., 21, 1
Portegies Zwart, S.F., Verbunt, F. 1995, A&A, 309, 179
Portegies Zwart, S.F., Yungelson, L.R. 1998, A&A, in press (astro-ph/9710347)
Pringle, J.E., Rees, M.J. 1972, A&A, 21, 1
Schmutz, W., Geballe, T.R., Schild, H. 1996, A&A, 311, L25
Sybesma, C.H.B. 1986, A&A, 168, 147
Tanaka Y., Lewin W.H.G. 1995 in X-Ray Binaries, ed. W.H.G. Lewin, J. van Paradijs, E.P.J. van den Heuvel (Cambridge: CUP), p. 126
Tanaka, Y., Shibazaki N., 1996, ARA&A, 34, 607
Tutukov, A.V., Yungelson, L.R. 1973a, Nauchn. Informatsii, 27, 93
Tutukov, A.V., Yungelson, L.R. 1973b, Nauchn. Informatsii, 27, 3
Tutukov, A.V., Yungelson, L.R. 1979, in Mass Loss and Evolution of O Stars, ed. C. De Loore, P. S. Conti (Dordrecht: Kluwer), p. 401
Tutukov, A.V., Yungelson, L.R. 1993a, MNRAS, 260, 675
Tutukov, A.V., Yungelson, L.R. 1993b, SvA, 37, 411
Vanbeveren, D. 1991, A&A, 252, 159
van den Heuvel E.P.J., De Loore C. 1973, A&A, 25, 387
van den Heuvel, E.P.J., Habets, G. 1984, Nat, 309, 598
van den Heuvel, E.P.J., van Paradijs, J. 1997, ApJ, 483, 399
van Kerkwijk M.M. Charles P.A., Geballe T.R., et al. 1992, Nat, 355, 703
van Kerkwijk M.M. 1993, A&A, 276, L9

van Kerkwijk M.M., Geballe T.R., King D.L, van der Klis M.& van Paradijs J. 1996, A&A, 314, 521
Vrancken, M., de Greve J.P., Yungelson L., Tutukov A. 1991, A&A, 249, 411
van Paradijs, J. 1996, ApJ, 464, L139
Webbink R.F. 1984, ApJ, 277, 355
White, N.E., van Paradijs, J. 1996, ApJ, 473, L25
Woosley, S.E., Weaver, T. 1995, ApJS, 101, 181
Woosley, S.E., Langer, N., Weaver, Th.A. 1995, ApJ, 448, 315
Yungelson L., Tutukov, A. 1991, in Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, ed. K. A. van der Hucht, B. Hidayat (Dordrecht: Kluwer), p. 459
Zel'dovich, Ya.B., Ivanova, L.N., Nadezhin, D.K. 1972, SvA, 16, 209