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SELF-SUSTAINED STRONG MASS TRANSFER WITHOUT ROCHE LOBE OVERFLOW: CYGNUS X-3

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ABSTRACT

It is proposed that the binary evolution of Cyg X-3 is driven by a self-excited wind from a solar composition companion star sustained by radiation from a neutron star primary. The observed $\dot{P}_{\rm orb}/P_{\rm orb} \simeq +2 \times 10^{-6}$ yr^{-1} and luminosity would then imply that the companion is a white dwarf underfilling its Roche lobe, with mass $0.01 \lesssim m \lesssim 0.03\ M_\odot$. Cyg X-3 could then be in the late stage of very low mass X-ray binary evolution expected to result in a millisecond pulsar binary similar to the eclipsing system PSR 1957+20.

Subject headings: stars: binaries — stars: winds — stars: X-rays — X-rays: binaries

I. INTRODUCTION

Cyg X-3 is an intense X-ray source with luminosity near the Eddington limit if its distance is near the claimed lower limit of 10 kpc (Dickey 1983). It appears to be a low-mass X-ray binary (LMXB) with an orbital period $P_{\rm orb} = 4.79$ hr and an orbital period derivative $\dot{P}_{\rm orb} \simeq +10^{-9}$ yr^{-1} (Kitamoto *et al.* 1987; Molnar 1988). The unusually large and positive $\dot{P}_{\rm orb}/P_{\rm orb} \simeq +2. \times 10^{-6}$ yr^{-1} of Cyg X-3 is quite different from that of other observed LMXBs. The difficulty in understanding this large value under the canonical assumption of a Roche lobe–filling companion was recently discussed by Molnar (1988). Angular momentum loss from gravitational radiation or magnetic braking falls short by at least an order of magnitude in accounting simultaneously for the observed values of $P_{\rm orb}$, $\dot{P}_{\rm orb}$, and the relatively large value of mass transfer needed to power the intense X-ray emission. Models assuming the presence of a third star could account for them, but are otherwise unmotivated.

We propose that Cyg X-3 evolves by a self-sustained (bootstrap) mechanism for mass transfer driven by an evaporative wind (Ruderman *et al.* 1989, hereafter RSTE) from an X-ray– and possibly ~1 MeV γ-ray–illuminated companion underfilling its Roche lobe. (A wind-driven evolution of Cyg X-3 has been proposed, in different contexts, by Pringle [1974], Davidsen and Ostriker [1974], and Willingale, King, and Pounds [1985].) The main result of this *Letter* is that if the companion is a degenerate star underfilling its Roche lobe with mass a few hundredths of a solar mass, the bootstrap mechanism can stably sustain the needed large value of mass transfer and account for the observed value of $\dot{P}_{\rm orb}/P_{\rm orb}$. In this model the present evolutionary phase of Cyg X-3 resembles that of a binary which could evolve into a system similar to the eclipsing millisecond binary PSR 1957+20.

II. WIND-DRIVEN EVOLUTION OF CYGNUS X-3

A bootstrap regime of mass transfer is established if the accretion-powered illumination of the companion causes mass to be transferred to the neutron star (assumed to be the compact star in Cyg X-3), at a rate sufficient to sustain that level of accretion. We assume that the companion of Cyg X-3 is illuminated by the large flux of observed accretion-powered soft X-rays (van der Klis and Bonnet-Bidaud 1981; Willingale, King, and Pounds 1985), and possibly also by the ~1 MeV γ-rays of Kluźniak *et al.* (1988*b*) (Meegan, Fishman, and Haymes 1979; Lamb *et al.* 1977). A secondary's mass-loss rate driven by X-rays and ~1 MeV γ-rays[4] can be estimated (Basko *et al.* 1976; London, McCray, and Auer 1981; RSTE) as

$$-\dot{m} = (1 + \mathscr{A})2\pi R^2 P_{\rm min} \frac{1}{v_w}, \qquad (2.1)$$

where R is the radius of the companion star, v_w the evaporative wind velocity at the sonic point, $\mathscr{A}$ the fractional albedo, and $P_{\rm min}$ the value of the pressure in the companion's atmosphere below which heating by the external illumination is no longer suppressed by bremsstrahlung, radiative recombination and/or line cooling. $\mathscr{A} \simeq 0.4$ is the albedo for a typical incident LMXB X-ray spectrum (Basko *et al.* 1977); $\mathscr{A} \simeq 0.1$ for a monochromatic beam of ~1 MeV photons (Tavani 1989). For the intensity and spectrum of incident radiation appropriate for Cyg X-3 (White and Holt 1982; Willingale, King, and Pounds 1985), $P_{\rm min} = 8.1 \times 10^4 L_{38}\,\chi S(T_R,\ A)\Upsilon$ dyn cm^{-2}, where L_{38} is the accretion-powered neutron star luminosity in units of 10^{38} ergs s^{-1}, and χ ($\lesssim 1$) is the fraction of accretion-powered radiation reaching the secondary relative to the fractional solid angle subtended by it. The factor S (≤ 1), the fraction of the total cooling coefficient which is due to bremsstrahlung is a function only of the photospheric radiation temperature T_R and of the abundance of heavy elements (A) in the outer atmosphere of the companion. In the following we assume a solar composition companion star. $T_R \simeq 4.2 \times 10^4$ K in Cyg X-3, if the photospheric temperature is established only by absorption of incoming external radiation. The factor Υ is the ratio of 2.5 g cm^{-2} to the effective absorbing column density, for the illuminating radiation. It depends on the heating mechanism (whether the deposition of energy occurs from hard X-ray and γ-ray Compton scattering or from soft X-ray photoionization of heavy elements), as well as on the spectrum of incident radiation. Equation (2.1) assumes that the

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[4] Very high energy radiation, with energy $\gtrsim 1$ TeV from Cyg X-3 (Danaher *et al.* 1981; Samorksy and Stamm 1983) would not be effective in driving a wind because its energy is deposited too deeply in the companion's atmosphere.

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evaporative wind in the outer region of the atmosphere of the companion is heated to a temperature sufficiently high for the outflowing wind to escape the gravitational potential of the companion.[5] This condition is always satisfied for illumination by 1 MeV γ-rays (as long as a weak magnetic field $B \gtrsim 10^{-4}$ G exists in the companion's atmosphere; cf. RSTE), but X-rays may fail to satisfy this requirement for a typical LMXB spectrum.

An evaporative wind is formed in the outer atmosphere of the companion only if the heated gas is able to escape the gravitational potential of the companion star. This occurs if the temperature of the heated corona is larger than

$$T_* = \frac{3}{20}\left(\frac{R}{R_s}\right)\frac{\mu}{k_B}v_e^2 \simeq 10^6\ \mathrm{K}\left(\frac{v_e}{3 \times 10^7\ \mathrm{cm\ s^{-1}}}\right)^2 , \quad (2.2)$$

where R_s is the sonic radius, R the companion's radius, μ the mean molecular weight in the atmosphere, k_B the Boltzmann constant, and v_e the escape velocity from an isolated companion star. A large wind is formed only when $R_s \simeq R$; if $R \ll R_s$, the mass outflow of eq. (2.1) is suppressed by $\sim \exp(-R_s/R)$ (Basko *et al.* 1977). Even when X-rays alone cannot produce a strong evaporative wind because, in some cases, $R_s \gg R$ (a condition which depends on the spectrum of the illuminating flux and on the composition of the star), strong co-illumination by accretion-powered ~ 1 MeV γ-rays may sustain a large mass-transfer rate with $R_s \simeq R$ (RSTE). Under the simplifying assumption of illumination by X-rays with a typical LMXB spectrum and $\chi \simeq 0.1$ or by a monochromatic beam of ~ 1 MeV γ-rays with $\chi \simeq 1$, one obtains $\chi S \Upsilon \simeq 1$ (RSTE). If X-rays are not partially absorbed on their way to the companion star, then the $\dot{m}$ driven by X-ray illumination estimated below is a lower limit. The conclusions of this paper concerning Cyg X-3 are not changed as long as $\chi \gtrsim 0.05$. The velocity of the outflowing wind at the sonic point in equation (2.2) depends on the nature of the incident radiation. For X-rays, $v_w \simeq v_e$; for ~ 1 MeV γ-rays, $v_w = v_e \eta^{1/3}/2$, where $\eta = 8R\Lambda/3v_e^3$, and Λ is the net heating rate per unit mass (RSTE).

For the Cyg X-3 orbital parameters (Eggleton 1983),

$$\frac{1}{\Psi}\frac{R}{R_\odot} \simeq \frac{2}{3^{4/3}}\left(\frac{m}{M+m}\right)^{1/3}\frac{a}{R_\odot} \simeq 0.65\left(\frac{m}{M_\odot}\right)^{1/3} , \quad (2.3)$$

with $R_\odot$ the solar radius, a the orbit radius, M the mass of the primary, and $\Psi \equiv R/R_L$ the ratio of the radius of the companion star to its Roche lobe radius R_L. Equation (2.3) can be used to constrain masses of possible companion stars.

a) Main-Sequence Companion

We consider first a possible main-sequence companion. With the empirical mass-radius relation for lower main-sequence stars $R/R_\odot \simeq (m/M_\odot)^{0.88 \pm 0.02}$ (with $0.1 < m/M_\odot \lesssim 0.8$; Patterson 1984) equation (2.3) sets an upper limit for the companion's mass (obtained for a Roche lobe–filling companion) at $m \simeq 0.47\ M_\odot$ (Molnar 1988). X-rays alone are probably not able to drive enough substantial mass loss from a lower main-sequence companion with solar composition to sustain bootstrapped evolution because, in this case, the outer layer of the atmosphere is heated by X-rays to a temperature smaller than $T_* \simeq 3.8 \times 10^6$ K and $R_s \simeq 3R$. Consequently, the mass transfer obtained from equation (2.1) would be strongly reduced. On the other hand, illumination by ~ 1 MeV γ-rays may produce enough mass transfer to sustain a bootstrap phase even if the companion underfills its Roche lobe. In this case a lower limit for the companion mass is obtained below which wind-driven mass transfer can no longer be self-sustained. For ~ 1 MeV γ-ray illumination with $\chi S \Upsilon \simeq 1$, and from the observed accretion mass-transfer rate close to 10^{18} g s^{-1} this lower limit is at $m \sim 0.15\ M_\odot$, with $\Psi \simeq 0.6$. The solid lines (1), (2), and (3) of Figure 1 give the mass transfer driven by ~ 1 MeV γ-rays, X-rays with the sonic point temperature $T_s \gg T_*$, and X-rays with $T_s < T_*$, respectively, as a function of the mass of the lower main-sequence companion.

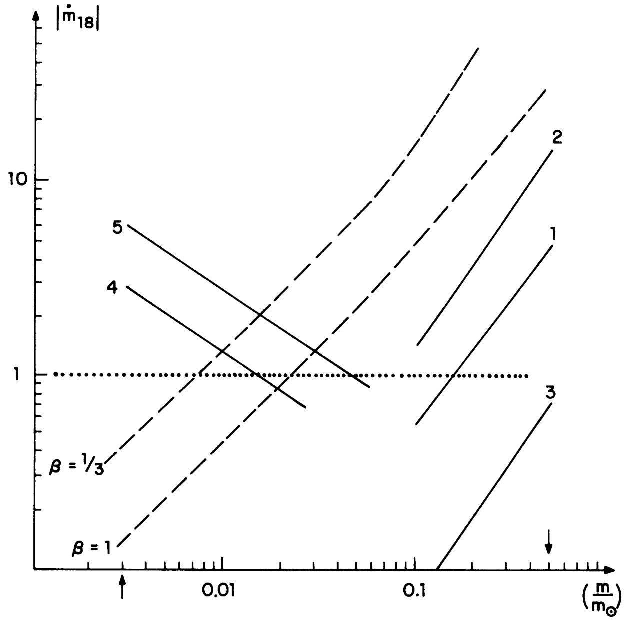

FIG. 1.—Wind-driven mass transfer rate as a function of mass for lower main-sequence and for solar composition degenerate companions in Cyg X-3. The arrows on the abscissa mark the masses of the Roche lobe–filling companions. Solid lines (1)–(4) give the mass transfer driven by incident LMXB radiation of luminosity 10^{38} ergs s^{-1} with $\chi S \Upsilon = 1$: (1) 1 MeV γ-ray illumination of a lower main-sequence secondary; (2) X-ray illumination of a lower main-sequence secondary, with temperature of the heated outer atmosphere of the companion much larger than T_* (eq. [2.2]); (3) X-ray illumination of a lower main-sequence star with the temperature of the heated outer atmosphere of the companion $T_s = 10^6\ \mathrm{K} < T_*$; (4) X-ray illumination of a degenerate companion. Solid line (5) is for X-ray illumination of a degenerate companion with $\chi S \Upsilon = 2$. The dotted curves follow from eq. (3.1) and the observed $\dot{P}_{\mathrm{orb}}/P_{\mathrm{orb}}$ of Cyg X-3, with different values of β. These intersect only the lines (4) and (5), indicating that only a degenerate companion is consistent with a self-sustained wind-driven evolution of Cyg X-3. The dotted line marks the value of $\dot{m} = 10^{18}$ g s^{-1} below which a self-sustained mechanism of mass transfer is expected to fail.

b) Degenerate Companion

With the Zapolsky-Salpeter (1969) mass-radius relation for a degenerate cold white dwarf, equation (2.3) sets a lower limit for a degenerate companion's mass at $m \simeq 0.003\ M_\odot$ (for a solar composition star which fills its Roche lobe). For planet-like He companion, the lower limit is $m \simeq 3 \times 10^{-4}\ M_\odot$. In contrast to the main-sequence case, soft X-rays are more effective than MeV γ-rays in sustaining a self-excited wind for a

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[5] The work of Eichler and Levinson (1988) is not relevant to the mechanism of wind formation under the conditions considered in RSTE and in the present *Letter* because of their incorrect treatment of gas cooling at the base of the high temperature corona. Furthermore, the presence of even a 10^{-3} G magnetic field in the companion's atmosphere would be sufficient to change the thermal conductivity such that their "limiting temperature" T_m would rise above the Spitzer limit.

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solar composition white dwarf when, as in the case of Cyg X-3, the critical temperature T_* is sufficiently low to allow the escape of the X-ray–heated gas from the surface of the very light companion.

Most significantly, we also consider cold degenerate companions which do not fill their Roche lobes. For $\chi S \Upsilon = 1$ and with an accretion mass transfer rate near to 10^{18} g s^{-1}, $m \simeq 0.015\ M_\odot$ ($\Psi \simeq 0.54$) is the upper limit for the value of the mass above which the X-ray–driven evaporative wind is no longer able to produce the mass transfer rate needed to sustain a 10^{38} ergs s^{-1} accretion luminosity. Lines (4) and (5) of Figure 1 show the behavior of the wind-driven mass transfer rate as a function of mass for a solar composition white dwarf secondary.

III. SIGNIFICANCE OF THE OBSERVED $\dot P_{\rm orb}/P_{\rm orb}$

In the limit of negligible binary angular momentum loss from gravitational radiation or magnetic braking, the canonical relation between changes in secondary mass and orbital radii (Rappaport, Joss, and Webbink 1982) can be combined with the observed $\dot P_{\rm orb}/P_{\rm orb}$ of Cyg X-3 to give (Tavani 1989)

$$\left(\frac{m}{0.01\ M_\odot}\right) \simeq 2.2\left[1 + (\beta - 1)\alpha(1 + q) - \beta q - \frac{1}{3}(1 - \beta)\frac{q}{1 + q}\right]|\dot m_{18}| \quad (3.1)$$

with $\dot m_{18} = \dot m/10^{18}$ g s^{-1}, $q = m/M$, β the fraction of $|\dot m|$ which remains in the system, α defined by $\delta J = \alpha\,\delta m(1 - \beta)a^2(2\pi/P_{\rm orb})$ with J as the orbital angular momentum. The dotted curves in Figure 1 follow from equation (3.1) for different values of β and $\alpha = 1$. From Figure 1 only a degenerate companion is consistent with the observed $\dot P_{\rm orb}/P_{\rm orb}$ in Cyg X-3 for any $\beta \leq 1$. For X-ray illumination of a Roche lobe–filling white dwarf, a wind velocity near v_e seems too small to give such a large fractional mass loss from the binary. A $\beta \simeq 1/20$ would be required for a Roche lobe–filling white dwarf with $m = 0.003\ M_\odot$. However, such a small value of β would give too small an accreted mass transfer rate to sustain bootstrapped mass transfer near 10^{18} g s^{-1}. For self-sustained binary evolution, stable Roche lobe overflow requires[6] $\beta = \frac{1}{3}$ (RSTE); when $\beta > \frac{1}{3}$, the companion contracts inside its Roche lobe (RSTE; Kluźniak *et al.* 1988*a*). There then exists a range of masses for companions underfilling their Roche lobes which satisfy equation (3.1) and, at the same time, are able to sustain a bootstrapped mass transfer rate close to 10^{38} ergs s^{-1} in the cases $\frac{1}{3} \leq \beta \leq \frac{1}{2}$ for $\chi S \Upsilon = 1$, and $\frac{1}{3} \leq \beta \leq 1$ for $\chi S \Upsilon = 2$. For example, a solar composition white dwarf with mass $m = 0.023\ M_\odot$ underfills its Roche lobe and satisfies equation (3.1) for $\beta \simeq 1$, if $\chi S \Upsilon \simeq 1.3$. We note that an upper limit of the companion mass may be obtained from knowing the combination $\chi S \Upsilon$; for example, if $\chi S \Upsilon = 2$ and $\beta|\dot m_{18}| \simeq 1$ then the upper limit is $m \simeq 0.03\ M_\odot$.

Thus the proposed bootstrap mechanism for mass transfer in Cyg X-3 could account for the observed $\dot P_{\rm orb}/P_{\rm orb}$, as well as the needed mass transfer rate close to 10^{18} g s^{-1} with a degenerate solar composition companion in mass range $0.01 \lesssim m \lesssim 0.03\ M_\odot$ which underfills its Roche lobe. X-ray illumination alone may be effective in producing the evaporative wind from such a low-mass degenerate companion. The present evolutionary phase of Cyg X-3 could then be a late stage of self-sustained evolution for the class of LMXBs which produces millisecond pulsars. Main features of this bootstrapped phase include a rapid accretion turnoff and consequent pulsar turnon when the mass of the companion becomes smaller than a critical value $m_c \simeq 10^{-2}\ M_\odot$ (Ruderman, Shaham, and Tavani 1987, hereafter RST; RSTE).

The RSTE evolutionary scenario for very low mass X-ray binaries considered the case where most of the evaporated $|\dot m|$ escapes the binary: bootstrapped mass transfer then occurred with a Roche lobe–filling companion ($\beta = \frac{1}{3}$). In this case, continued interaction of soft γ-rays with the evaporative wind may be the agent causing a large fraction of the outflowing gas to escape the binary. On the other hand, if most of the wind does not escape the system, so that $\beta \simeq 1$, the companion shrinks inside its Roche lobe. A transition from the first to the second case would be expected if the wind velocity drops with decreasing companion mass and illumination. If m^* is the companion's mass at the transition when the degenerate companion first begins to contract inside its Roche lobe ($\beta > \frac{1}{3}$), then $\Psi = (m/m^*)^{2(\beta - 1/3)}$. If v_w equals the escape velocity from the star and if escape from the binary requires a velocity $\gtrsim 0.2\ (GM_{\rm ns}/a^*)^{1/2}$, with $M_{\rm ns}$ the neutron star mass and a^* the orbit radius for a Roche lobe–filling degenerate star of mass m^* (RSTE), then $m^* \simeq 0.04\ M_\odot$. For Cyg X-3 we must have $m^* > m_c$ so that the bootstrap mechanism is sustained for a significant period of time during which the companion star contracts inside its Roche lobe. Self-sustained accretion turns off when m_c is reached; at that point an accretion–spun-up millisecond pulsar might be revealed with a rotational period $\lesssim 3$ ms (RST). Figure 2 shows the proposed evolution of the Roche lobe–filling factor Ψ as a function of degenerate companion mass. With the parameters of Cyg X-3 and angular momentum conservative evolution ($\beta = 1$), accretion turnoff should occur when $\Psi \lesssim \frac{1}{2}$. The time needed to reach such a transition $\sim P_{\rm orb}/\dot P_{\rm orb} \sim 0.5 \times 10^6$ yr. Self-sustained mass transfer from a

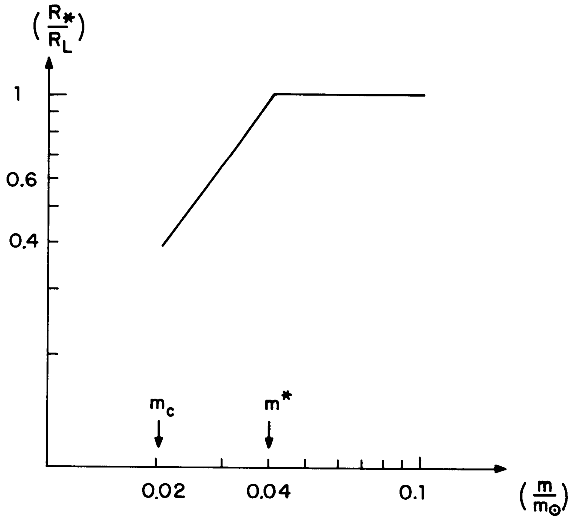

FIG. 2.—Possible evolution of the ratio $\Psi = R/R_L$ as a function of mass for a solar composition degenerate dwarf. The mass corresponding to the transition from a nonconservative ($\beta = \frac{1}{3}$) to a totally conservative regime of mass transfer ($\beta = 1$) under bootstrap conditions is $m^* \simeq 0.04\ M_\odot$. Accretion turnoff is expected in this case when the mass of the companion reaches $m_c \simeq 0.02\ M_\odot$ (Kluźniak *et al.* 1988*a*; Tavani 1989).

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[6] The value $\beta = \frac{1}{3}$ is not consistent with binary evolution driven by gravitational radiation (Rappaport *et al.* 1987). Mass transfer becomes unstable for $\beta \lesssim \frac{1}{3}$ if gravitational radiation is the only cause of angular momentum loss (cf., e.g., eq. [4] of Molnar 1988).

very low mass companion contracted inside its Roche lobe is similar to the proposed late evolution scenario for an LMXB which evolves into the eclipsing millisecond binary PSR 1957+20 (Fruchter, Stinebring, and Taylor 1988). As in the case of Cyg X-3, the secondary mass ($m \simeq 0.02\ M_\odot$) is quite small.

For completely conservative mass transfer driving the late evolution of a degenerate companion which underfills its Roche lobe, it can be shown that the ratio $m_c/m^* \sim \frac{1}{2}$ and is only weakly dependent on the exact value of m^* (Tavani 1989). From the inferred mass of the Cyg X-3 companion, and from the value of the companion mass of PSR 1957+20, one may conclude quite generally that self-sustained binary evolution will continue down to a secondary mass $m_c \sim$ a few hundredths of a solar mass.

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