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Circinus X-1: survivor of a highly asymmetric supernova

T. M. Tauris,[1] R. P. Fender,[1] E. P. J. van den Heuvel,[1] H. M. Johnston[2] and K. Wu[3]
[1]*Center for High-Energy Astrophysics and Sterrenkundig Instituut 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, 1098-SJ Amsterdam, the Netherlands*
[2]*Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia*
[3]*Research Centre for Theoretical Astrophysics, School of Physics, University of Sydney, NSW 2006, Australia*

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ABSTRACT

We have analysed the kinematical parameters of Cir X-1 to constrain the nature of its companion star, the eccentricity of the binary and the pre-supernova parameter space. We argue that the companion is most likely to be a low-mass ($\lesssim 2.0\,\mathrm{M}_\odot$) unevolved star and that the eccentricity of the orbit is 0.94 ± 0.04. We have evaluated the dynamical effects of the supernova explosion and we find it must have been asymmetric. On *average*, we find that a kick of $\sim 740\,\mathrm{km\,s^{-1}}$ is needed to account for the recently measured radial velocity of $+430\,\mathrm{km\,s^{-1}}$ (Johnston, Fender & Wu) for this extreme system. The corresponding *minimum* kick velocity is $\sim 500\,\mathrm{km\,s^{-1}}$. This is the largest kick needed to explain the motion of any observed binary system. If Cir X-1 is associated with the supernova remnant G321.9-0.3 then we find a limiting minimum age of this remnant of $\sim 60\,000$ yr. Furthermore, we predict that the companion star has lost ~ 10 per cent of its mass as a result of stripping and ablation from the impact of the supernova shell shortly after the explosion.

Key words: stars: individual: Cir X-1 – stars: neutron – supernovae: general.

1 INTRODUCTION

Cir X-1 is a unique binary in many aspects. Despite intensive X ray observations since its discovery in the early 1970s very little is known about its stellar components besides an orbital period of 16.6 d (Kaluzienski et al. 1976). It is still uncertain whether the binary is a high-mass (HMXB) or low-mass X-ray binary (LMXB). The discovery of Type I X-ray bursts (Tennant, Fabian & Shafer 1986) demonstrates that the accreting compact object must be a neutron star. In a recent paper Johnston, Fender & Wu (1999) presented new optical and infrared observations of Cir X-1 which show asymmetric emission lines. Combined with 20 years of archival Hα line emission data, they interpreted that the narrow components of the lines imply a radial velocity of $+430\,\mathrm{km\,s^{-1}}$ for the system (including a small correction for the Galactic rotation). This is the highest velocity known for any X ray binary.

Cir X-1 is located $25'$ from the centre of the supernova remnant G321.9-0.3 and is apparently connected by a radio nebula (Haynes et al. 1986). Furthermore, there is some evidence for an association from observations of arcmin-scale collimated structures within the nebula (Stewart et al. 1993) that are likely to originate from an arcsec-scale jet which has been observed (Fender et al. 1998) to be aligned with these larger structures. If the suggested association is correct then Cir X-1 is a young ($<10^5$ yr) runaway system and, in combination with the recent estimated distance to the remnant of 5.5 kpc (Case & Bhattacharya 1998), the inferred minimum transverse velocity ($390\,\mathrm{km\,s^{-1}}$) yields a resulting 3D space velocity of $>580\,\mathrm{km\,s^{-1}}$. In this paper we investigate what can be learned about Cir X-1 and the effects of the supernova explosion which gave rise to this high runaway velocity and orbital period of 16.6 d.

2 DYNAMICAL EFFECTS OF AN ASYMMETRIC SUPERNOVA EXPLOSION

We use the analytical formulae by Tauris & Takens (1998) to calculate the dynamical effects of an asymmetric supernova (SN) in Cir X-1. These formulae also include the effect of shell impact on the companion star. We assume that the exploding He-star with mass M_{He} (the progenitor of the neutron star with mass M_{NS}) is at the origin of the cartesian coordinate system which we shall use in our description. The positive z-axis points in the direction of the pre-SN orbital angular momentum. The positive y-axis points towards the companion star (with mass M_2) and the positive x-axis points in the direction of $\boldsymbol{v}$, which is the pre-SN relative velocity vector of the He-star with respect to the companion star. We assume the pre-SN orbit is circular and r_0 is the pre-SN separation between the two stellar components. The systemic velocity of a binary which survives the SN is

$$|\boldsymbol{v}_{\mathrm{sys}}| = \sqrt{\Delta p_x^2 + \Delta p_y^2 + \Delta p_z^2}/(M_{\mathrm{NS}} + M_{2\mathrm{f}}) \qquad (1)$$

where the change in momentum resulting from the SN is

$$\Delta p_x = \frac{M_{\rm NS}M_2 - M_{\rm He}M_{\rm 2f}}{M_{\rm He}+M_2} v + M_{\rm NS}\, w \cos\vartheta$$
$$\Delta p_y = M_{\rm NS}\, w \sin\vartheta\cos\varphi + M_{\rm 2f} v_{\rm im} \qquad (2)$$
$$\Delta p_z = M_{\rm NS}\, w \sin\theta sin\,\varphi$$

A kick with magnitude w is imparted to the neutron star (NS) by an asymmetric explosion. The pre-SN relative orbital speed is $v = \sqrt{G(M_{\rm He}+M_2)/r_0}$ and the angle between $\boldsymbol{v}$ and $\boldsymbol{w}$ is ϑ. The second position angle φ of $\boldsymbol{w}$, is taken such that $w_y = w\sin\vartheta\cos\varphi$. Finally, $v_{\rm im}$ is an effective speed taking into account the combined effects of incident shell momentum and the subsequent momentum resulting from mass loss owing to stripping and ablation of stellar material from the surface layers heated by the passing shock wave. It is given by (Wheeler, Lecar & McKee 1975; see also Fryxell & Arnett 1981)

$$v_{\rm im} = \eta v_{\rm eject}\left(\frac{R_2 x_{\rm crit}}{2r_0}\right)^2 \left(\frac{M_{\rm shell}}{M_2}\right)\frac{1+\ln(2v_{\rm eject}/v_{\rm esc})}{1-(F_{\rm strip}+F_{\rm ablate})} \qquad (3)$$

where R_2 is the initial radius of the companion star, $v_{\rm eject}$ is the speed of the material ejected in the SN, $v_{\rm esc} = \sqrt{2GM_2(x_{\rm crit})/R_2 x_{\rm crit}}$ is the escape velocity from the stripped companion star and the parameter $x_{\rm crit}$ is a critical fraction of the radius outside of which the total mass fraction, $F_{\rm strip}$ is stripped and inside of which a certain fraction, $F_{\rm ablate}$ is ablated. Thus after the shell impact the new mass of the companion is given by: $M_{\rm 2f} = M_2[1-(F_{\rm strip}+F_{\rm ablate})]$. A correction to the assumption of plane parallel layers is expressed by η. We assume $\eta = 0.5$.

Wheeler et al. (1975) have defined a parameter, Ψ in order to evaluate $x_{\rm crit}$ and $F = F_{\rm strip}+F_{\rm ablate}$ (their tabulation is given in Table 1)

$$\Psi \equiv \left(\frac{R_2}{2r_0}\right)^2\left(\frac{M_{\rm shell}}{M_2}\right)\left(\frac{v_{\rm eject}}{v_{\rm esc}}-1\right) \qquad (4)$$

In order to calculate the possible values of Ψ for the case of Cir X 1 we assume that a main-sequence companion star can be approximated by a polytropic model with index $n=3$. In this case one has $M_2(x_{\rm crit})/R_2 x_{\rm crit} \simeq 5/3\,{\rm M}_\odot {\rm R}_\odot^{-1}$ for $0.2 < x_{\rm crit} < 0.7$ (to an accuracy within 15 per cent). Furthermore we assume $E_{\rm eject} = 1/2 M_{\rm shell} v_{\rm eject}^2 = 1.0\times10^{51}$ erg.

The absolute minimum ZAMS mass for producing a NS is $\sim 8\,{\rm M}_\odot$. Such an early-type star evolves on a short time-scale, and hence at the time of the SN the maximum age of the companion is ~ 40 Myr. The companion star was less massive, and is therefore most likely to be unevolved. We fitted a mass–radius relation for ZAMS stars using the stellar evolution models of Pols et al. (1998)

$$R_2/{\rm R}_\odot = \begin{cases} 0.86(M_2/{\rm M}_\odot)^{1.21} & M_2 < 1.5\,{\rm M}_\odot \\ 1.15(M_2/{\rm M}_\odot)^{0.50} & M_2 > 1.5\,{\rm M}_\odot \end{cases} \qquad (5)$$

assuming $X = 0.70$, $Z = 0.02$ and a convective mixing-length parameter $\alpha = 2.0$.

The post-SN separation and eccentricity are given by

$$a = \frac{r_0}{2-\xi} \qquad e = \sqrt{1+(\xi-2)\,(Q+1)} \qquad (6)$$

where (see Tauris & Takens 1998)

$$\xi \equiv \frac{v^2 + w^2 + v_{\rm im}^2 + 2w(v\cos\vartheta - v_{\rm im}\sin\vartheta\cos\varphi)}{\tilde{m}v^2} \qquad (7)$$

$$Q \equiv \xi - 1 - \frac{(w\sin\vartheta\cos\varphi - v_{\rm im})^2}{\tilde{m}v^2} \qquad (8)$$

and $\tilde{m} \equiv (M_{\rm NS}+M_{\rm 2f})/(M_{\rm He}+M_2)$.

Prior to the SN we require that the companion star is able to fit *inside* its Roche-lobe, and after the SN it is required that the companion star *must* fill its Roche-lobe near the post-SN periastron, $a\,(1-e)$ in order to explain the observed X-ray emission (which is caused by mass accreted onto the neutron star from a disc which has to be fed by stellar material). Combining our mass-radius relation with Eggleton's (1983) expression for the Roche-lobe radius, $R_{\rm L}$ yields the following criterion for the radius of the companion star

$$R_{\rm L}(q_0)\big|_{r=r_0} \geq R_2 \geq R_{\rm 2f} > R_{\rm L}(q_{\rm f})\big|_{r=a(1-e)} \qquad (9)$$

where $R_{\rm L}(q) = r\,0.49\,q^{2/3}[0.6\,q^{2/3} + \ln(1+q^{1/3})]^{-1}$ and the mass ratios before and after the SN are given by $q_0 \equiv M_2/M_{\rm He}$ and $q_{\rm f} \equiv M_{\rm 2f}/M_{\rm NS}$, respectively.

Table 1. Parameters as a function of Ψ (see text) for a companion with the structure of a polytrope with index $n=3$. These numbers were calculated by Wheeler et al. (1975).

Ψ	$x_{\rm crit}$	$F_{\rm strip}$	$F_{\rm ablate}$	F
10	0.17	0.73	0.29	~1
5	0.26	0.43	0.34	0.77
4	0.29	0.35	0.34	0.69
2	0.37	0.19	0.28	0.47
1	0.44	0.10	0.19	0.29
0.4	0.52	0.04	0.11	0.15
0.2	0.58	0.02	0.07	0.09
0.1	0.64	0.01	0.04	0.05
0.01	0.78	0.001	0.006	0.01
0.001	0.87	~0	~0	~0

3 SIMULATION RESULTS AND DISCUSSION

We have performed Monte Carlo simulations of the SN effects on a large number of binaries to determine the mass of the companion star, the eccentricity of the present orbit and the pre-SN orbital parameter space. The constraints which must be fulfilled by any post-SN binary in order to be consistent with present observations of Cir X-1, are (i) the companion star must fill its Roche-lobe at periastron, (ii) the system must have a high velocity of at least 430 km s^{-1} (Johnston et al. 1999) and (iii) the system must have an orbital period between 14 and 18 d. For Cir X-1 $P_{\rm orb} = 16.6$ d, but tidal effects (increasing $P_{\rm orb}$) and accretion onto the NS (decreasing $P_{\rm orb}$ if $M_{\rm 2f} > M_{\rm NS}$) could have affected the orbital evolution since the SN.[1] However, we are not able to trace back the detailed evolution since the SN.

The results of our simulations are shown in Fig. 1. We now summarize what can be learned from these calculations.

The top panel shows $v_{\rm sys}$ as a function of $M_{\rm 2f}$, and $P_{\rm orb}$ as a function of eccentricity. There is 76 per cent probability that

[1] We tried to determine $\dot{P}_{\rm orb}$ from the All Sky Monitor XTE data of Cir X-1 over the last 3 years without any success. This is attributed to the poor timing resolution of the data near periastron. (However Fender 1997, found some evidence that the quadratic ephemeris is better than the linear, implying $\dot{P}_{\rm orb} \neq 0$).

$430 < v_{sys} < 500\,km\,s^{-1}$ and only 4.5 per cent probability that $v_{sys} > 580\,km\,s^{-1}$ if nothing is assumed to be known about the transverse velocity. The most probable present mass of the companion star, M_{2f} strongly decreases with increasing values of M_{2f}. If $M_2 > 1.0\,M_\odot$ we find there is only 30 and 5.6 per cent probability that $M_{2f} > 2.0$ and $3.0\,M_\odot$, respectively. We therefore conclude that Cir X-1 is most likely to be an LMXB. An absolute upper limit for M_{2f} is $4.6\,M_\odot$.

In the right-hand panel we see that we can constrain $e = 0.94 \pm 0.04$. The reason of this high expected eccentricity is

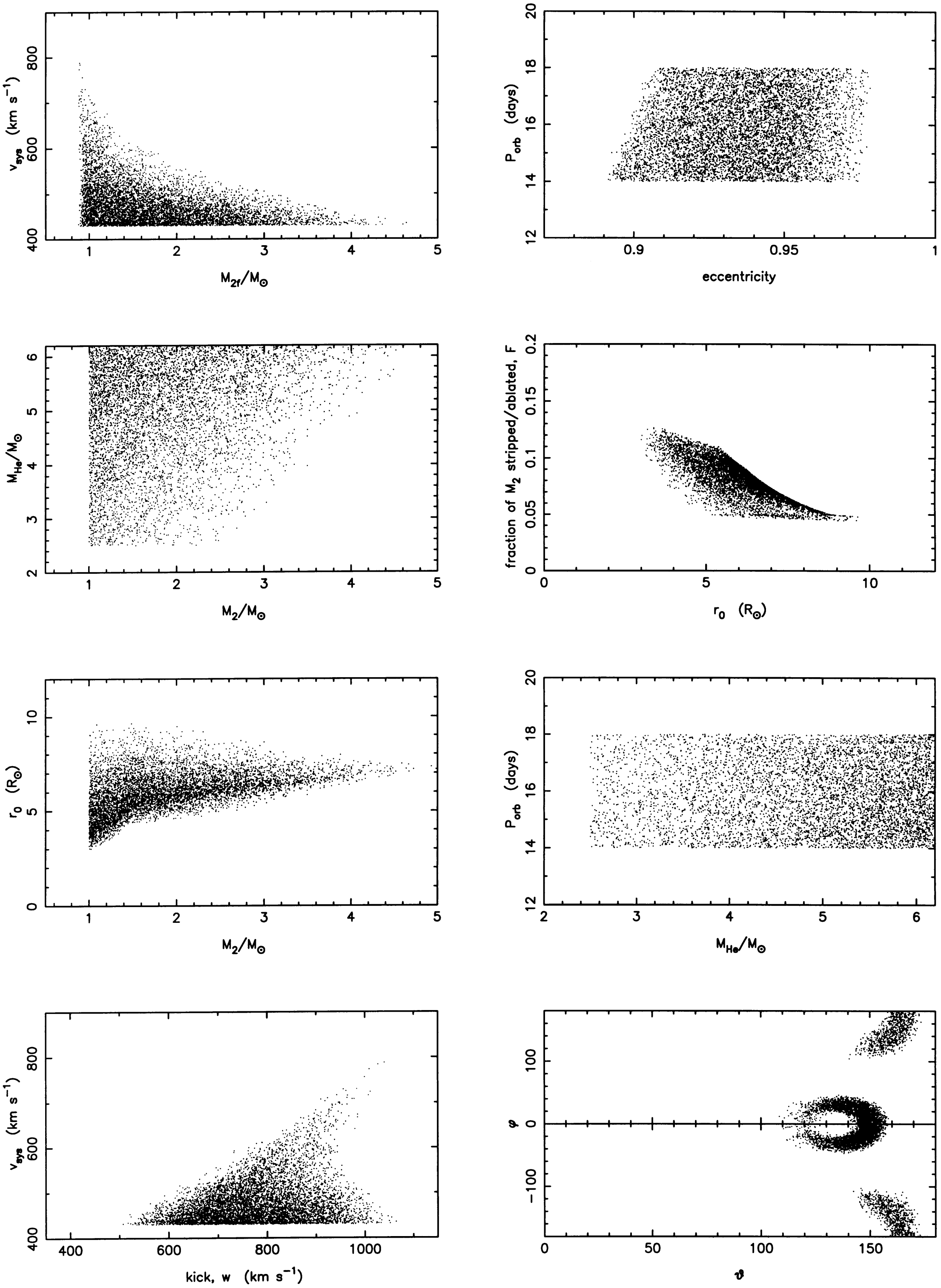

Figure 1. The distribution of various pre- and post-SN binary parameters obtained by Monte Carlo simulations in order to construct systems similar to Cir X-1. We assumed $M_{NS} = 1.3\,M_\odot$, $M_2 > 1.0\,M_\odot$ and $2.5 < M_{He}/M_\odot < 6.5$. We chose flat trial distributions of M_{He}, M_2, r_0 and w, and assumed an isotropic distribution of kick directions. The figure shows the characteristics of 10^4 binaries (out of $\sim 3.4 \times 10^8$ trial systems) which passed our selection criteria for resembling Cir X-1 – see text for discussions.

that (as we have argued) the companion must be unevolved and therefore has to pass by very close to the NS in order to transfer mass at each passage. (Also the extreme velocity of Cir X-1 infers that the SN nearly disrupted the system and thus e is expected to be large.)

In the second panel we plotted in the left-hand side the distribution of the allowed masses of the two stellar components prior to the SN. This, somewhat surprising plot, shows that we can not constrain the combination of these two pre-SN masses very well. All the combinations of masses shown can result in a post-SN binary which resembles Cir X-1. This result reflects the enormous amount of freedom owing to the unknown direction and magnitude of the kick imparted to the newborn neutron star. It should be noted that while the probability distribution of M_2 is decreasing with M_2, the most likely mass of the exploding He-star increases monotonically with $M_{\rm He}$. It is seen that the distribution of $M_{2\rm f}$ is slightly shifted towards lower masses compared to the distribution of M_2. This reflects the mass loss from the companion star owing to the shell impact. This effect is shown in the right-hand side of the second panel, where we have plotted the fraction of material lost from the companion star immediately after the SN as a function of the pre-SN separation, r_0. We see that we expect 5–12 per cent of the mass of the companion star to have been lost as a result of the shell impact. This is significant and future observations of the supernova remnant might be able to give evidence for this scenario. It is seen that the effect of the shell impact decreases with r_0 as expected, see e.g. equation (4).

In the third panel we plotted r_0 as a function of M_2, and $P_{\rm orb}$ as a function of $M_{\rm He}$. The lower limit to r_0 as a function of M_2 is given by the requirement that the companion star must be able to fit inside its pre-SN Roche-lobe, cf. equation (9). It can be seen that it is difficult to produce a system like Cir X-1 if r_0 is larger than $9\,{\rm R}_\odot$ (if r_0 is larger it becomes very difficult to keep the system bound after the SN and still require a large space velocity). Such a tight pre-SN binary is most likely to originate from a common envelope evolution. This fact also yields some preference for a low value of M_2, since common envelopes are most likely to form for extreme mass ratios between its stellar constituents (e.g. Iben & Livio 1993).

In the bottom panel we plotted $v_{\rm sys}$ as a function of the kick velocity (actually *speed*) and the distribution of allowed kick angles, in the left- and right-hand side, respectively. Cumulative probability curves for the kick velocity, w are presented in Fig. 2. An important result is that under *no* circumstances, for any pre-SN parameters, could Cir X-1 be formed in a symmetric SN. In recent papers Iben & Tutukov (1996, 1998) claimed that there is no proof for asymmetric SN in nature. Here our simulations show that the remarkably high radial velocity observed in Cir X-1 can only be explained by a substantial asymmetry in the SN explosion. For an average set of pre-SN parameters presented in Fig. 1 the probability for a binary to survive such a large kick is less than 10 per cent. The allowed parameter space of the kick angles show that the kick must have been directed backwards ($\vartheta > 110°$) with respect to the pre-SN orbital motion of the exploding He-star. This makes sense since a backward kick strongly increases the probability of a binary to stay bound (Flannery & van den Heuvel 1975; Hills 1983). Similarly, we also expect the NS to be kicked in a direction close to the orbital plane ($\varphi \simeq 0°$ or $\varphi \simeq 180°$) in order for the system to minimize its orbital energy and avoid disruption. However, if the resulting velocity vector of the NS relative to the companion star, just after the shell decouples gravitationally from the system ($\boldsymbol{u}_0 = \boldsymbol{v} + \boldsymbol{w} - \boldsymbol{v}_{\rm im}$; Tauris & Takens 1998) is directed exactly towards the companion, then the NS is shot directly into the envelope of the companion star and the binary is assumed to merge since $a(1-e) < R_{2\rm f}$. This explains the nice 'shadow image' of the companion star seen in the plot. Hence, in the case of Cir X-1 the NS must have been kicked in a direction close to the companion star, but without hitting it, in order for the binary to survive. It is interesting to notice that the radio image of Cir X-1 (Stewart et al. 1993) seems to indicate that the jet is perpendicular to the motion of the system. Since this jet is likely to be perpendicular to the inner accretion disc and the orbital plane, the motion of the binary seems to be in a direction along its orbital plane. This supports the requirement that the kick was directed near the pre-SN orbital plane.

In Table 2 we list the mean and minimum values of the kick velocity needed to produce Cir X-1 as a function of $v_{\rm sys}$. It is interesting to notice that the minimum kick velocity needed to explain the motion of Cir X-1 is smaller when the effects of the shell impact are included. This is explained by the fact that the

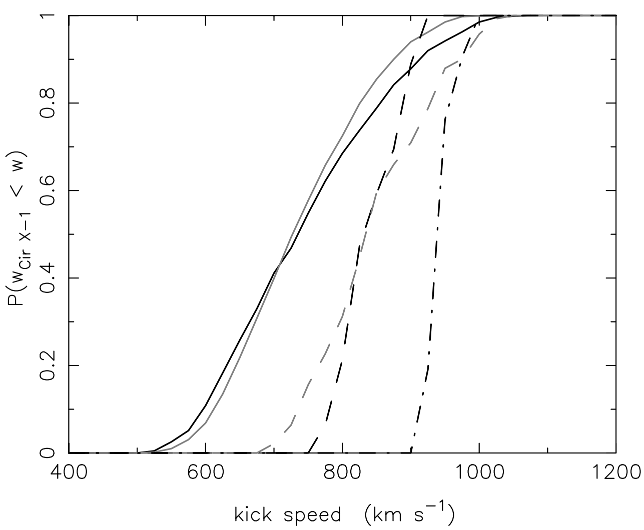

Figure 2. Curves representing the probability that the kick imparted to the NS in Cir X-1 was less than the value given on the x-axis. The full, dashed and dashed–dotted line correspond to $v_{\rm sys} = 430$, 580 and $700\,{\rm km\,s^{-1}}$, respectively. The full grey line assumes no shell impact on the companion star and $v_{\rm sys} = 430\,{\rm km\,s^{-1}}$; the dashed grey line includes shell impact with $E_{\rm eject} = 5.0 \times 10^{51}$ erg and assumes $v_{\rm sys} = 580\,{\rm km\,s^{-1}}$.

Table 2. The mean and minimum kick velocity imparted to the neutron star as a function of the assumed systemic velocity of Cir X-1. We assume $d = 5.5$ kpc and $\delta\theta = 25'$ for G321.9-0.3. $v_{\rm sys}^2 = v_{\rm rad}^2 + v_\perp^2$ and $v_\perp = d\delta\theta/t_{\rm SNR}$. All velocities are in ${\rm km\,s^{-1}}$ – see also Fig. 2.

$v_{\rm sys}$	$\langle w \rangle$	$w_{\rm min}$	
430	740	500	no association with G321.9-0.3 and $v_\perp = 0$ is assumed (devils advocate's solution for lowest possible kick)
430	740	520	no association with G321.9-0.3, no shell impact effects included and $v_\perp = 0$
580	840	760	association with G321.9-0.3 and $t_{\rm SNR} = 10^5$ yr
580	850	680	association with G321.9-0.3, $t_{\rm SNR} = 10^5$ yr and $E_{\rm eject} = 5.0 \times 10^{51}$ erg
700	940	920	association with G321.9-0.3 and $t_{\rm SNR} = 70\,000$ yr

momentum from the incident shell ejecta blows the companion star in the same direction as the NS is kicked, since the majority of NS are kicked in the direction of the companion in order to survive (as mentioned above). Hence a smaller kick is needed to produce a high runaway velocity, and the probability of surviving the SN is also increased.

3.1 Observations of the periastron passage

We have shown for the condition of Roche-lobe overflow at periastron, that Cir X-1 is expected to have a highly eccentric orbit ($e = 0.94 \pm 0.04$). Therefore the companion star passes by the NS at periastron in a very short interval of time. We find the fraction of the orbital period the companion spends between orbital phases θ_1 and θ_2 is given by:

$$\frac{\delta P_{\rm orb}}{P_{\rm orb}} = 1 - \frac{1}{2\pi}\left[\frac{\sqrt{1-e^2}e\sin\theta}{1-e\cos\theta} + \tan^{-1}\sqrt{\frac{1+e}{1-e}}\tan\frac{\theta}{2}\right]_{\theta_1}^{\theta_2} \quad (10)$$

Cir X-1 has an orbital period of 16.6 d. Assuming $e = 0.94$ we find it only takes ~ 3.5 h for the companion to move from $\theta_1 = 270°$ to $\theta_2 = 90°$ – see Fig. 3. The companion spends more than 99 per cent of its time between $90° < \theta < 270°$. Hence observations must be planned very carefully in order to catch the periastron passage where, for example, the effects of companion heating owing to X-ray irradiation are most severe.

3.2 Possible detection of ablated material from the shell impact and dependence on $E_{\rm eject}$

Our calculations show that we expect $\sim$ 10 per cent of the mass of the companion star to have been evaporated. Since $1.0 < M_2/{\rm M}_\odot < 5.0$ we estimate that $\sim 0.1 - 0.5\,{\rm M}_\odot$ of material in the SN nebula originates from the H-rich envelope of the companion star. This quantity is equivalent to $\sim$ 10–25 per cent of the amount of He-rich material which was ejected from the collapsing He-star progenitor of the NS. We therefore encourage detailed observations of the supernova remnant G321.9-0.3 to search for evidence of the shell impact. If $E_{\rm eject}$ is assumed to be 5.0×10^{51} erg then the mean fraction of evaporated material increases to 15 per cent. The constraints on the other parameters derived here are only slightly affected by a similar increase in $E_{\rm eject}$ – e.g. the minimum required kick velocity is then 470 instead of 500 km s^{-1}.

3.3 On the age of the SN remnant G321.9-0.3

Our simulations show that the maximum runaway velocity of Cir X-1 is: $v_{\rm sys}^{\rm max} = 800\,{\rm km\,s^{-1}}$. Hence the maximum transverse velocity is constrained to be: $v_\perp^{\rm max} = 675\,{\rm km\,s^{-1}}$ (given $v_{\rm rad} = 430\,{\rm km\,s^{-1}}$). Since the transverse velocity is inversely proportional to the age, $t_{\rm SNR}$ of G321.9-0.3 we therefore derive a minimum age of this remnant of $t_{\rm SNR}^{\rm min} \simeq 60\,000$ yr, if Cir X-1 is associated with it.

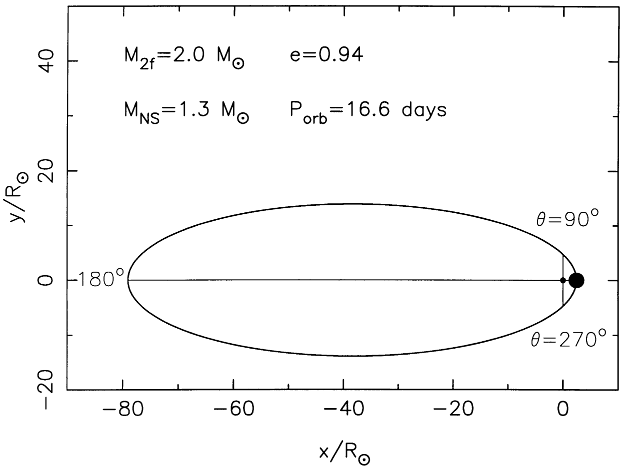

Figure 3. Orbital geometry of Cir X-1 in a reference frame fixed on the neutron star. We assumed $M_{2f} = 2.0\,{\rm M}_\odot$ and $e = 0.94$. The periastron passage $270° < \theta < 90°$ only lasts ~ 3.5 h.

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