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Circinus X–1: a runaway binary with curved radio jets

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ABSTRACT

We present high-resolution radio studies at 1.47 and 4.79 GHz, made with the Australia Telescope, which show clear evidence for jet-like structure within the nebula surrounding Cir X–1. The jets originate in a compact source at the position of the binary, then extend outwards about 30 arcsec before curving back several arcmin towards the nearby supernova remnant G 321.9 – 0.3. This behaviour can be explained if Cir X–1 is a runaway binary from the supernova explosion which gave rise to G 321.9 – 0.3. When critical accretion occurs, the binary ejects mass in two collimated jets which interact with the surrounding interstellar material, and accelerate relativistic electrons which emit radio continuum by the synchrotron process. The radiating electrons are left behind and form a curved wake extending back towards the SNR.

Key words: binaries: spectroscopic – stars: individual: Cir X–1 – ISM: jets and outflows – radio continuum: stars – X-rays: stars.

1 INTRODUCTION

Circinus X–1 is one of the more puzzling X-ray binaries because its X-ray and radio properties do not conform to those of known high- or low-mass systems (White 1989; Stewart et al. 1991). Clark, Parkinson & Caswell (1975) first proposed that Cir X–1 is a runaway binary ejected from the supernova remnant (SNR) G 321.9 – 0.3 during the supernova explosion, and that the compact object is now in an eccentric orbit around a more massive star. There is considerable evidence to support this hypothesis.

The observation that intense radio flares (Whelan et al. 1977) and abrupt changes in X-ray levels (Kaluzienski et al. 1976) occur with a 16.6-d periodicity indicates a binary with an eccentric orbit where critical accretion occurs when the two stars are at closest approach (Murdin et al. 1980).

Cir X–1 appears to be at a similar distance to that of G 321.9 – 0.3. On the basis of the diameter of G 321.9 – 0.3 and a Σ–D relationship, Clark, Caswell & Green (1975) estimated its age to be between 2×10^4 and 10^5 yr and its distance to be 5.5 kpc. From an H I absorption measurement during an intense radio flare, Goss & Mebold (1977) estimated the distance to Cir X–1 at 8 kpc. Considering the uncertainties of both estimates, the two are in reasonable agreement; the values are re-assessed at the end of the paper.

We also know from *EXOSAT* observations of quasi-periodic oscillations and Type I X-ray bursts that the compact object in Cir X–1 is a neutron star (Tennant, Fabian & Shafer 1986; Tennant 1987). Also, the X-ray brightness measured by *Ginga* during flaring and high states indicates a neutron star mass of 1.1 to 1.4 $M_\odot$ if the object is at 6.5 to 10 kpc (Stewart et al. 1991).

Neither the companion star nor the orbital parameters are known because of Cir X–1's location in a highly obscured region on the Galactic plane, where three faint stars (Moneti 1989) lie within one arcsec of the radio position (Argue et al. 1984). Stewart et al. (1991) have argued that the soft X-ray properties show more similarities to low-mass binaries than to high-mass systems, suggesting that the companion star has a mass of only a few $M_\odot$.

Also, Cir X–1 is surrounded by a diffuse radio nebula extending over an area of 5×10 arcmin^2 (Haynes et al. 1986), corresponding to a size of 15×30 pc^2 at 10 kpc. For an X-ray binary, this is another unusual property. Haynes et al. speculated that the southward extension of this nebula towards SNR G 321.9 – 0.3 indicates an earlier connection with the SNR and is further evidence for a runaway system. The reason for the existence of a nebula around Cir X–1 but not around other X-ray binaries is unclear.

All these questions prompted us to take a closer look at this object. Here we discuss the results of our studies at 1.47 and 4.79 GHz using the Australia Telescope compact array (ATCA). Further studies at 8.64 GHz are under way and will be discussed in a later publication. The high-resolution images described below give a much clearer picture of Cir X–1 than previous radio studies have done; they reveal jet-like structure within the nebula which can be explained by transverse motion of Cir X–1 away from the SNR.

2 RADIO OBSERVATIONS

2.1 Wide-field continuum image at 1.47 GHz

Two overlapping fields, centred on G 329.1 − 0.3 and Cir X-1 respectively, were observed at 1.47 GHz over a bandwidth of 88 MHz using five antennas of the ATCA. The field centred at G 329.1 − 0.3 was first observed for 12 h on 1990 November 20, and the Cir X-1 field on 1991 January 21; for each field, the processed images showed strong Galactic H II regions in the antenna sidelobes.

To test whether spurious features from these strong sources were removed by subsequent cleaning, we repeated observations of both fields on 1991 February 24, June 2 and July 16 by time-sharing the 12-h observing period, and compared overlapping regions in the final images. Each field was observed on four occasions using four complementary array configurations. The combined baselines ranged from 30 m to 2 km, in increments no smaller than 15 m. The resulting UV coverages, allowing for time lost due to calibration, time-sharing and equipment problems, were sufficient to produce synthesized beams with sidelobes less than 10 per cent of the main lobe.

Synthesis images of each field were obtained using the AIPS software package and then merged with (zero-spacing) data obtained with the Parkes 64-m telescope on 1991 August 21. The merging was done by re-gridding the Parkes image to match that of the ATCA, combining the two images and the two beams, and finally cleaning the combined dirty image

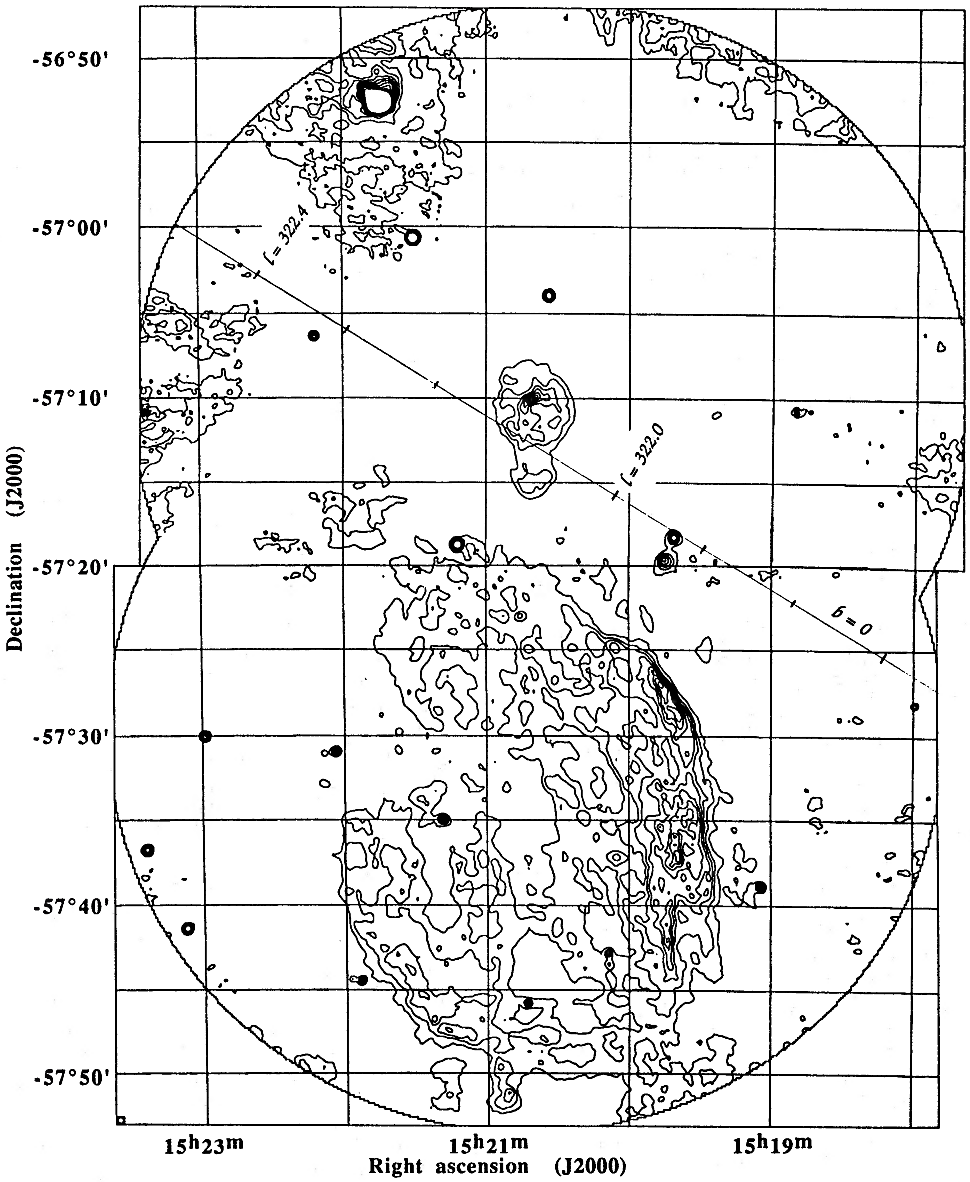

Figure 1. Plot of ATCA wide-field image towards Cir X-1 at 1.47 GHz (HPBW 21 arcsec). The contour interval is 1.5 mJy beam^{-1} (seven times rms noise). The two adjacent fields observed are shown out to the quarter-power points of the primary beam, diameter 48 arcmin. Cir X-1 is at RA (J2000) $15^h\,20^m\,41^s$, Dec. (J2000) −57° 10′ 00″; the corresponding position for B1950 is RA $15^h\,16^m\,48\overset{s}{.}5$, Dec. − 56° 59′ 11″. To the south of Cir X-1 and its surrounding nebula (size ~ 7 arcmin) can be seen the shell supernova remnant G 321.9 − 0.3 with diameter ~ 26 arcmin.

with the combined beam. The two fields produced identical images of the Cir X-1 nebula, showing that sidelobe responses to strong sources had been successfully removed. After correcting for the primary beam attenuation (out to the quarter-power level), the two synthesized fields were combined to produce the high-resolution image of Fig. 1.

The half-power beamwidth (after tapering) for this image is 21×21 arcsec^2. This is the highest resolution radio image made so far of the field around Cir X-1 and G 321.9 − 0.3. It represents an improvement by a factor of five in beam area over the 843-MHz Molonglo Observatory Synthesis Telescope (MOST) image (43×51 arcsec^2) of Haynes et al. (1986), and Haynes (1987). Comparison of the ATCA image of Fig. 1 with the 843-MHz image of Haynes (1987) shows similar features but more point sources and sharper outlines, as expected from the higher resolution and sensitivity. Note that the low-level contours near the boundary of Fig. 1 are mostly noise (enhanced by the primary beam correction).

The field sources at 1.47 GHz stronger than 5 mJy are listed in Table 1. For the weakest ones, positional errors may be as large as 5 arcsec. Apart from the core of an H II region, there are 17 sources; all of these are likely to be extragalactic since, in a region of the size shown, 21 extragalactic sources of this intensity are expected (Landecker & Caswell 1983).

The boundary of the supernova remnant G 321.9 − 0.3 is very sharply defined in some regions, and we have used this to revise the mean angular diameter estimate to 26 arcmin (compared to 24 arcmin given by Clark & Caswell 1976, based on the 408-MHz map from the MOST). The nebula surrounding Cir X-1 is also seen in much greater detail than before. The southward extension towards G 321.9 − 0.3 first noted by Haynes et al. (1986) is confirmed, but the most remarkable feature is the structure seen for the first time within the nebula, which appears to be two jets extending from the Cir X-1 point-source position.

2.2 Continuum images of the nebula at 4.79 GHz

To examine the structure of the nebula in more detail, we observed it with the ATCA at 4.79 GHz for 12 h on 1991 July 20 and December 10/11, and 1992 January 4/5, June 4, 12 and 16. Five array configurations were used with baselines ranging from 30 m to 1.5 km, giving sufficient UV coverage to resolve the jet structure in the nebula with adequate sensitivity. The 4.79-GHz image (HPBW of 12×12 arcsec^2) is shown as a contour plot in Fig. 2. This shows two curved, jet-like structures superimposed on more diffuse and extended features within the nebula. The jets extend linearly outwards about 34 arcsec from a compact source centred on Cir X-1, and then curve away towards the SNR in the south. There is a strong indication that one of the jet structures extends all the way to the southern extremity of the nebula. There is also a hint of unresolved substructure within the jets. This question will be explored further when higher resolution 8.6-GHz images are available.

2.3 Measurement of the compact source in Cir X-1

The compact source in Cir X-1 is known to be highly variable at radio and X-ray wavelengths; from 1978 to 1988

Table 1. Small-diameter sources near G321.9 − 0.3 and Cir X-1.

R.A. (J2000)	Dec.(J2000)	S (1.47GHz)	Remarks*
h m s	° ' "	(mJy)	
15 17 59.5	-57 28 07	5.0	
15 18 49.9	-57 10 51	5.0	
15 19 04.3	-57 38 51	9.4	
15 19 40.7	-57 18 14	5.9	M: 6 mJy
15 19 44.8	-57 19 36	6.8	M: 16.7 mJy
15 20 08.8	-57 42 50	5.0	
15 20 34.1	-57 03 54	28.2	M: 34.4 mJy; AT: 23 mJy at 4.79 GHz
15 20 43.0	-57 45 47	5.6	
15 21 12.1	-57 18 43	43.6	M: 58.6 mJy
15 21 18.6	-57 34 59	8.6	
15 21 30.7	-57 00 37	74.4	M: 87.9 mJy
15 21 43.3	-56 52 41	94.0	core of HII G322.39+0.21
15 21 53.7	-57 44 27	6.2	
15 22 03.6	-57 30 56	10.3	
15 22 12.1	-57 06 18	7.8	
15 22 59.0	-57 30 02	25.7	
15 23 07.4	-57 41 22	32.8	
15 23 23.9	-57 36 47	24.9	

*M refers to measurements by the MOST at 843 MHz (Haynes 1987); AT refers to the current AT compact array measurements (see text).

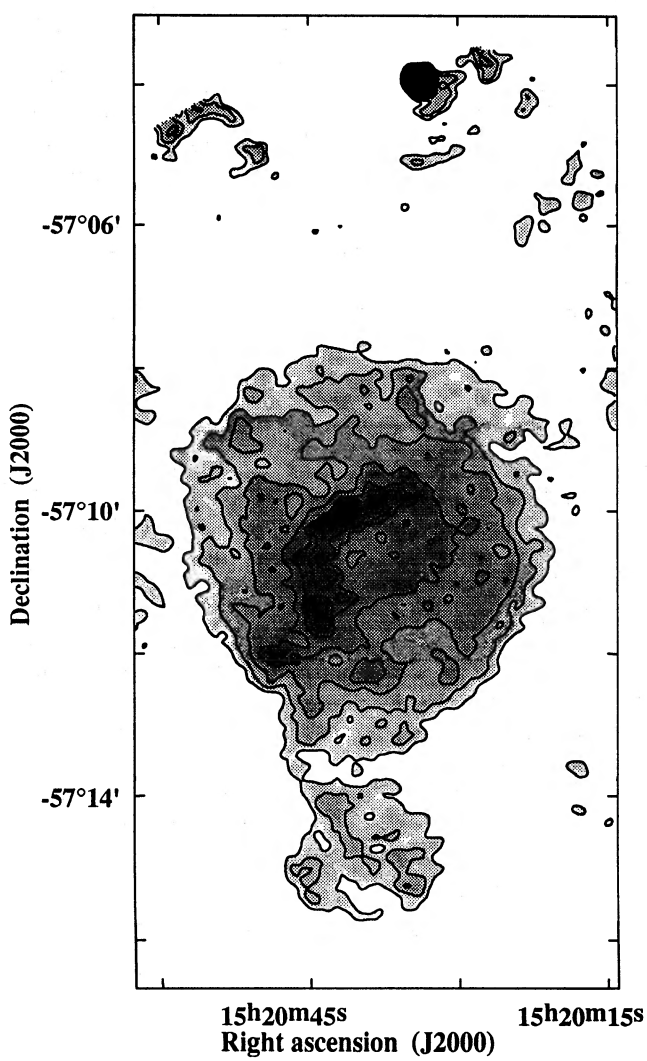

Figure 2. ATCA plots of the Cir X-1 nebula at 4.79 GHz (HPBW 12 arcsec) showing extended jet-like structure. The contour interval is 0.5 mJy beam^{-1} (five times rms noise) except for an extra step between 2.5 and 3.0 mJy (contour 6). The northern source has a peak flux density of 23 mJy beam^{-1}.

many intense radio flares were recorded, lasting several days and sometimes reaching flux densities of several Jy. The onset of radio flares during this period occurred within a day of the zero orbital phase derived by Nicolson (private communication), where zero phase for the *N*th flaring episode is given by

$$\mathrm{JD}_{0N} = 244\,3076.87 + (16.576\,8 - 0.000\,035\,3\,N)N. \qquad (1)$$

Regular monitoring of Cir X-1 near zero orbital phase by Nicolson at the HARTRAO indicated that the flare activity has been decreasing in intensity over each successive period of activity since 1978, and in 1988/89 only four flares with flux densities >100 mJy were recorded at 5 GHz. On the four occasions (at various orbital phases) during 1989/90 when Australia Telescope observations were made, no flares with 5-GHz flux densities >5 mJy (Stewart et al. 1991) were detected.

To place better limits on the point-source flux density from Cir X-1, we included the 6-km antenna of the ATCA in our observations from 1991 December 10 onwards, giving a beam size of ~ 2.5 arcsec at 4.79 GHz. These measurements set an upper limit on the 12-h integrated flux density from Cir X-1 at a value of $S \sim 3 \pm 1$ mJy, except on 1992 June 4 when the point-source flux density increased from 8 to 12 mJy during the observing interval. The estimated orbital phase for each observation is given in Table 2. Note that, on the day the flux density increased, the orbital phase was $\sim 61°$ according to Nicolson's ephemeris for the onset of radio flares, suggesting that the ephemeris is now in error by ~ 2 d. If we modify this ephemeris to fit the *maxima* of the three radio flares of 1980 April 23/24 (Preston et al. 1983), 1985 July 28 (Nicolson 1985) and the 1992 June 4 flare, we find a simpler relation:

$$\mathrm{JD}_{0N} = 244\,3074.5 + 16.580\,6\,N, \qquad (2)$$

which should give a more accurate prediction for future flares.

The compact source during four observations in 1992 June has a mean position RA (J2000) $15^{\mathrm{h}}\,20^{\mathrm{m}}\,40\overset{\mathrm{s}}{.}99$, Dec. (J2000) $-57°\,09'\,59\overset{''}{.}91$, relative to a nearby calibrator source 1516 − 56, whose position was assumed to be RA (J2000) $15^{\mathrm{h}}\,15^{\mathrm{m}}\,12\overset{\mathrm{s}}{.}8$, Dec. (J2000) $-55°\,59'\,32\overset{''}{.}6$. The current position of Cir X-1 agrees within 0.5 arcsec with a VLBI position measured during the intense flare of 1980 April 23/24 (Argue et al. 1984). The discrepancy reflects the inaccuracies in calibrator absolute positions rather than measurement errors (which have rms values ~ 0.05 arcsec). Note that, in the absence of a distinct flare, it is not certain whether emission at a level of several mJy is from a quiescent point source or from the most compact portion of the jets. In either case, the position measurement is likely to be essentially that of the binary itself but we refer to the flux densities as an upper limit to the point source.

Table 2. Flux density and ephemeris phase of Cir X-1.

Year	Day	Phase	S(5GHz) (mJy)
1991	Dec. 10/11	.51	3.5
1992	Jan. 4/5	.01	2.3
1992	June 04	.17	8-12*
1992	June 12	.65	2.3
1992	June 16	.89	1.8

*See text.

3 DISCUSSION

The radio images described above are remarkable because they indicate that Cir X-1 may be the only object known to possess both jet structure and a synchrotron nebula. Several Galactic X-ray binaries (most notably SS 433) and star formation regions, as well as active galaxies, have jets. Some neutron stars, such as the Crab pulsar and the possible runaway pulsars near the SNRs G 5.4 − 1.2 and CTB 80, are associated with synchrotron nebulae. None of these objects exhibits both features, except Cir X-1.

Clearly, SS 433 and Cir X-1 have similarities and, since SS 433 has been studied extensively, it is worth making some direct comparisons between these two objects. Both have twin-jet structure, comparable binary periods and likely association with supernova remnants. Studies at optical wavelengths have established that the jets in SS 433 precess with a period of 164 d about an axis inclined at an angle of 80° to the line of sight at position angle 100° (Margon 1984). The jets are highly collimated with a cone angle of 20°, and the jet material travels outwards at a maximum speed of 0.28 *c*. The jets have been detected in X-rays (Seward et al. 1980) as diffuse features extending at least 30 arcmin from SS 433 and aligned along the major axis of the supernova remnant W 50. There seems to be no doubt that both SS 433 and the extended jets lie within the SNR. There is also an indication that the jets align with bulges further out in the SNR shell, strongly suggesting an interaction between the jets and the shell material. High-resolution VLA observations (Hjellming & Johnston 1981) have traced the corkscrew motion of ejecta in the precessing jets, showing that the rotation is clockwise about the jet axis.

However, the appearance of SS 433 differs from that of Cir X-1 in several important ways.

(i) Cir X-1 lies well outside its associated SNR, whereas SS 433 lies almost at the centre of W 50.

(ii) Unlike Cir X-1, SS 433 shows no sign of a diffuse extended nebula surrounding it. If such a nebula exists, it must be intrinsically much weaker because Cir X-1 is further away.

(iii) The radio jets from Cir X-1 are linear out to a distance of 34 arcsec, then curve sharply and extend 5 to 10 arcmin towards the SNR G 321.9 − 0.3. In SS 433, the radio jets extend only about 1 arcmin but are associated with diffuse X-ray jets extending about 30 arcmin along the major axis of W 50 until they interact with the SNR shell.

These differences can best be explained if Cir X-1 is moving through the interstellar medium outside G 321.9 − 0.3 – in contrast to SS 433 which is situated within the cavity of W 50.

As Haynes et al. (1986) noted, if SNR G 321.9 − 0.3 has an age of 10^5 yr then the transverse velocity (assuming no deceleration) at a distance of 10 kpc would be 500 km s^{-1}, and the total kinetic energy of ejection 5×10^{48} erg for a 4-$M_\odot$ system. This is considerably less than the total kinetic energy, about 10^{50} erg, released in a supernova explosion, and could be supplied by the recoil of the ejected mass. According to Paczyński (1971) and Bekenstein & Bowers (1974), if a supernova occurs in a binary system, then in most cases one would expect the binary to remain bound even if expelled at a high velocity.

Further evidence supporting a runaway hypothesis comes from a spectroscopic study by Nicolson, Feast & Glass (1980) who found Hα emission lines during flares from Cir X-1 to have mean radial velocities between 200 and 300 km s^{-1}. Such velocities are considerably greater than the maximum possible due to differential Galactic rotation and solar motion, and are strong supporting evidence for a runaway system whose transverse velocity could be at least several hundred km s^{-1}.

The apparent absence (or non-detection) of a radio nebula surrounding SS 433 is not surprising if it lies in a cavity where interstellar material and a frozen-in magnetic field have been swept out by a supernova explosion. Evidence for the cavity comes from X-ray observations (Seward et al. 1980), which show that the jets move outwards virtually unimpeded for about 10^3 yr until they reach the compressed material in the SNR shell. There they interact to produce enhanced X-ray emission as well as shock-excited optical filaments (Zealey, Dopita & Malin 1980) and bulges in the radio SNR shell (Geldzahler, Pauls & Salter 1980).

The situation is very different for Cir X-1. This lies well outside the SNR shell in the ambient interstellar medium where a synchrotron nebula can be produced by shock-accelerated electrons diffusing from the neutron star. As the binary travels through the medium, it will leave a wake caused by the relativistic electrons in the neutron stellar wind. Such a wind will also penetrate ahead of the binary until stopped by ram pressure of the interstellar material (Cheng 1983).

Compared with SS 433, the higher interstellar density near Cir X-1 causes the jets to lose more energy by friction and slow down more quickly. We estimate from the curvature of the jets (Fig. 2) that the stopping time, defined as the time taken for the binary to travel a projected distance of 34 arcsec at a speed of 500 km s^{-1} at 10 kpc, is about 3×10^3 yr. Although the jets slow down in this time, the synchrotron loss time is much longer – of the order of 10^5 to 10^6 yr for a magnetic field $B=10$ μG (Ginzburg & Syrovatskii 1965) – allowing relativistic electrons trapped on the interstellar magnetic field lines to continue emitting synchrotron radiation. Thus a jet wake is produced behind the runaway binary trailing most of the way back towards SNR G 321.9 − 0.3 (see Fig. 2).

We now remark on some similarities between the radio appearance of the Cir X-1 nebula and those of G 5.27 − 0.90 (which trails behind the runaway pulsar PSR 1758 − 24) and CTB 80 (which surrounds a 39.5-ms pulsar). Both these pulsars, like Cir X-1, have escaped outside their SNR shells. The CT 80 pulsar's transverse velocity (Kulkarni et al. 1988; Strom 1987) is estimated to be several hundred km s^{-1}, that of PSR 1758 about 1600 km s^{-1} (Frail & Kulkarni 1991; Manchester et al. 1991). High-resolution VLA images (Frail & Kulkarni 1991) show the pulsar at the head of a wake trailing back to its synchrotron nebula. Presumably, PSR 1758 is moving so fast that it leaves its radially diffusing nebula behind. It would be interesting to know if higher resolution images (beam size < 1 arcsec) also show jet structure in the wake of PSR 1758, similar to that observed now in Cir X-1. Apparently there is more than enough rotational energy lost from pulsars (about 10^{36} erg s^{-1}) to power synchrotron nebulae (Kulkarni et al. 1988). Whether the same is true for Cir X-1, which requires $<10^{33}$ erg s^{-1} to account for the radio emission, is not certain. However, there is additional energy available in Cir X-1 associated with the momentum transfer from the stellar wind of the mass-loss companion.

As cited earlier (Haynes et al. 1986), previous considerations of Cir X-1 as a runaway binary have adopted the parameters of distance 10 kpc and age 100 000 yr. Such order-of-magnitude estimates will, inevitably, have considerable uncertainty. It is, none the less, worthwhile estimating the best values from the currently available data. For the SNR distance we adopt the slightly revised angular diameter estimate of 26 arcmin, together with the Σ–D relationship from Caswell & Lerche (1979). Furthermore, we adopt a Sun-to-Galactic Centre distance of 8.5 rather than 10 kpc. The net result is that the preferred SNR parameters are distance 6.5 kpc, diameter 50 pc and age 28 600 yr. The distance is unlikely to be significantly underestimated unless the object is extremely luminous. Cir X-1 is estimated from H I absorption measurements (Goss & Mebold 1977) to be at a distance at least equal to 0.79 times the Galactic Centre distance, i.e. greater than 6.7 kpc if the Galactic Centre is at a distance of 8.5 kpc. We propose that Cir X-1 was indeed ejected from the SNR and, adopting the 6.5-kpc distance for both objects, together with an age of 28 600 yr, we derive a mean velocity of 1600 km s^{-1} or 1 arcsec in 19 yr. This velocity is the same as that inferred by Frail & Kulkarni for PSR 1758 − 24. However, age is a notoriously uncertain estimate and a value as large as 100 000 yr (implying a somewhat lower velocity of 450 km s^{-1}) cannot be excluded. Proper-motion measurements of Cir X-1 are clearly of great importance, and a definitive measurement may be possible within a few years. Unfortunately, past absolute-position measurements have quite large formal rms errors (at least 0.3 arcsec) and, furthermore, it is difficult to reconcile the reference frame with those currently used. Future measurements of the type reported here could be made with *relative* accuracy better than 0.05 arcsec and could achieve a significant result in several years. The most promising route is to use the strong 23-mJy source, seen in the field of Fig. 2, as a reference source and to make the measurements during flare activity. Failure to detect proper motion would not discount the ejection hypothesis but would put a lower limit on the age of ejection; successful measurement of proper motion would both confirm the ejection hypothesis and yield an age that would be of great importance.

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