An asymmetric arcsecond radio jet from Circinus X-1

Robert Fender$^1$, Ralph Spencer$^2$, Tasso Tzioumis$^3$, Kinwah Wu$^4$, Michiel van der Klis$^1$, Jan van Paradijs$^{1,5}$, Helen Johnston$^6$

Received __________________; accepted __________________

Submitted to ApJ Letters

---

$^1$Astronomical Institute ‘Anton Pannekoek’, University of Amsterdam, and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

$^2$University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK 11 9DL, U.K.

$^3$Australia Telescope National Facility, CSIRO, Paul Wild Observatory, Narrabri NSW 2390, Australia

$^4$Research Centre for Theoretical Astrophysics, School of Physics, University of Sydney, NSW 2006, Australia

$^5$Physics Department, University of Alabama in Huntsville, Huntsville AL 35899, USA

$^6$Anglo-Australian Observatory, P.O. Box 296, Epping NSW 2121, Australia
ABSTRACT

In observations with the Australia Telescope Compact Array we have resolved the radio counterpart of the unusual X-ray binary Cir X-1 into an asymmetric extended structure on arcsecond scales. In order to quantify the asymmetry we have redetermined as accurately as possible both the optical and radio coordinates of the source. The extended emission can be understood as a compact, absorbed core at the location of the X-ray binary, and extended emission up to 2 arcsec to the southeast of the core. The arcsec-scale extended emission aligns with the larger, more symmetric arcmin-scale collimated structures in the surrounding synchrotron nebula. This suggests that the transport of mass and/or energy from the X-ray binary to the synchrotron nebula is occurring via the arcsec-scale structures. The ratio of extended flux from the southeast to that from the northwest of the core is at least 2:1. Interpreted as relativistic aberration of an intrinsically symmetric jet from the source, this implies a minimum outflow velocity of 0.1 c. Alternatively, the emission may be intrinsically asymmetric, perhaps as a result of the high space velocity of the system.

Subject headings: Astrometry, Radio continuum:stars, Stars:individual:Cir X-1, Stars:neutron
1. Introduction

Circinus X-1 is a highly variable, at times very luminous X-ray binary, with an orbital period of 16.6 days, as revealed by the periodic recurrence of sudden drops or enhancements in its X-ray flux and radio flaring (Kaluzenski et al. 1976; Haynes et al. 1978). The system is optically identified with the most reddened of three faint stars lying within 1.5 arcsec of each other in sky (Moneti 1992; Duncan, Stewart & Haynes 1993; see also HST image in Fig 1). Stewart et al. (1993) have reassessed published distance estimates to Cir X-1 and concluded that the most likely distance to the system is $\sim 6.5$ kpc.

For some time Cir X-1 was considered as a black-hole candidate because of its rapid erratic X-ray flux variations (see Dower et al. 1982 for a review of the older literature on Cir X-1), but the detection of type I X-ray bursts, caused by thermonuclear flashes on the surface of the neutron star (Tennant, Fabian & Shafer 1986a, Tennant, Fabian & Shafer 1986b) established that Cir X-1 is an accreting neutron star. In the 1970s the periodic radio flares of Cir X-1 peaked at $>1$ Jy; since then its radio flux has decreased dramatically, and in the past 10 yr it has rarely been detected at a level above 50 mJy (e.g. Stewart et al. 1991). The source is embedded within a synchrotron nebula and may be associated with the nearby supernova remnant G321.9–0.3. Within the synchrotron nebula observations at 6.3 cm with an angular resolution of 12 arcsec have revealed collimated structures which appear to be swept back towards G321.9–0.3 (Stewart et al. 1993).

2. Observations

We have imaged Cir X-1 at high angular resolution ($\sim 1$ arcsec at 3.5 cm) with the Australia Telescope Compact Array (ATCA), on 1995 Sept 2, 1996 June 1, 1998 Feb 5 and Feb 23. Fig 1 shows the image of Cir X-1 from the 1998 Feb 23 observations, which had
the best observing conditions, revealing a strong ($\geq 30\sigma$) extension to the southeast. The image was formed from 12 hr of observations at 3.5 cm with baselines between 214 and 5970 m. Observations were regularly (2.5 of every 21.5 min) interleaved with those of a nearby phase calibrator PMN J1524–5903 and of a compact source 6 arcmin to the north, which we designate J1520.6–571. Absolute flux calibration was achieved with reference to PKS B1934–638; the data were reduced using the MIRIAD software (Sault, Teuben & Wright 1995). The observations were carefully planned to occur around binary orbital phase $\sim 0.5$, and inspection of the X-ray light curve at the time (as monitored with the Rossi XTE All Sky Monitor; Levine et al. 1996) reveal that the observations occurred at least three days after the end of the previous periodic outburst. No radio flaring occurred during the 12 hr observation. Mapping of the nearby compact source J1520.6–571 (Fig 2), with the same phase calibration, produces an almost-perfect point source (residuals from model point subtraction $\leq 1\%$) ruling out phase errors as an origin for the extension of Cir X-1. The extension, though less pronounced, is also evident in simultaneous observations with the same array at 6.3 cm. An extension to the southeast is also present in our earlier observations. The arcminute-scale nebula and structures around the source (Stewart et al. 1993) are undetected due to resolution effects, implying that they contain no bright components on angular scales of arcseconds or less.

It is clear from Fig 1 that the extended emission is more intense to the southeast of the emission peak than in other directions, but in order to quantify this asymmetry it is necessary to determine as accurately as possible the location of the X-ray binary itself (and hence, presumably, the point of origin of any jets). We have proceeded to do this in two ways, by redetermining as accurately as possible the optical coordinates for Cir X-1 and by fitting simple models to the radio map.

We have determined a new position for the optical counterpart to Cir X-1 by performing
astrometry on the red Second Epoch Sky Survey plate (original glass negative) for field 177 from the UK Schmidt Telescope. Positions of stars near our object were measured from SuperCOSMOS scans of the plate; the astrometric solution was determined using stars from the Tycho-ACT catalogue. We then tied this astrometric solution to stars in a WFPC-1 archival image of the field taken by HST (see Fig 1), using a linear fit between the coordinates determined by SuperCOSMOS and the rectangular coordinates on the WFPC mosaic image. This fit was used to derive the position for the optical counterpart of Cir X-1. Our improved optical position is RA 15:20:40.87, Dec –57:10:00.18 (J2000.0) with an error of ±0.3 arcsec in each coordinate.

The simplest adequate model for the radio map of Cir X-1 presented in Fig 1 is a simultaneous fit of a 2D Gaussian and a point source (fitting of a point source only without a simultaneous Gaussian strongly over-subtracts at the emission peak). This fit is illustrated in Fig 3, which is a flux profile along the jet axis (as indicated by the lines in Fig 1). The same model fit was applied to the 6.3 cm data, and flux densities for the total structure, and the point and Gaussian components are listed in Table 1. The positive and negative spectral indices for the Point and Gaussian components, respectively, agree with expectations of an inverted spectrum, self-absorbed core and steep spectrum, optically thin jets as seen in other X-ray binaries. Confidently associating the point source with unresolved emission close to the binary, we derive improved radio coordinates for the X-ray binary of RA 15:20:40.84, Dec –57:10:00.48 (J2000.0) with an error of up to 0.25 arcsec in both RA and Dec, arising from uncertainties in the exact coordinates of the phase reference source PMN J1524–5903. This is compatible within combined uncertainties with the optical position derived above (radio to optical offset is ∼0.4 arcsec to the northwest, illustrated by the overlay of the radio contours on the HST image in Fig 1).

The emission is reasonably well fit by the Gaussian component described above.
and illustrated in Fig 3. This component is clearly offset to the southeast of the X-ray binary coordinates stated above. Given the limitations imposed by the modelling, we can conservatively place a lower limit of 2:1 on the ratio of fluxes in the southeast to northwest jets. The lower limit on the ratio is very similar if using instead the optical coordinates (as the location along the asymmetry axis is almost identical). We cannot at this time exclude significantly higher ratios.

3. Discussion

There are two distinct probable origins for the observed asymmetric structure, an intrinsically symmetric jet which appears one-sided because of relativistic aberration, or a structure which for some reason is intrinsically asymmetric. We briefly discuss both possibilities below.

3.1. A relativistic jet

The asymmetry in the extended radio emission is suggestive of relativistic aberration of an intrinsically symmetric twin jet inclined at some angle to the line of sight. This effect is well observed in the relativistic jets of the X-ray binary GRS 1915+105 (Mirabel & Rodriguez 1994), the core of SS 433 (Vermeulen et al. 1993); and possibly Cygnus X-3 (Mioduszewski et al. 1998). In this case the stronger emission to the southeast would be the approaching jet. We note that the jet aligns extremely well with the large scale structures reported by Stewart et al. (1993) shown by the lines drawn on Fig 1, indicating the position angle of those structures which we estimate to be $110 \pm 10$ degrees. This suggests that whether or not the jet is relativistic, it is the route by which mass and/or energy is flowing from the X-ray binary to the larger structures in the surrounding synchrotron nebula. The
ratio of approaching to receding jet flux, for an intrinsically symmetric jet, is given by

\[ \frac{S_a}{S_r} = \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right)^{k-\alpha} \]

where \( \alpha \) is the spectral index of the radio emission (\( S_\nu \propto \nu^\alpha \)), \( \beta \) is the intrinsic bulk velocity of the jet as a fraction of the speed of light, \( \theta \) is the angle of the jet to the line of sight, and \( k = 2 \) for a continuous jet and \( k = 3 \) for discrete ejections. From table 1 a spectral index of -1.2 is used for the extended component. As \( (S_a/S_r) \geq 2 \), we derive

\[ \beta \cos \theta \geq 0.13 \]

for a continuous jet, and

\[ \beta \cos \theta \geq 0.09 \]

for discrete components. Thus the minimum velocity for an intrinsically symmetric radio jet in Cir X-1 (for \( \theta = 0 \) and discrete components) is 0.1c. We note that our inferred velocities are in conflict with the limit of \( \leq 0.1c \) on expansion velocity from an early southern hemisphere VLBI observation, derived by Preston et al. (1983), apparently confirmed by further VLBI observations by Preston et al. (1989). However, we believe that the failure to resolve the source following an outburst may have resulted from the compact structure on milliarcsecond scales being dominated by the Doppler boosted approaching component, in which case the limit applies to the expansion of the component itself and not the outflow velocity.

Deceleration of jets on arcsec scales could affect the conclusions we draw from arcsec images about the jets in Cir X-1. However, previous experience has shown that this is not a serious problem. Hjellming & Johnston (1981) determined the proper motions and structure
of the SS 433 radio jet on an angular scale of up to 5 arcsec. The physical properties derived by those VLA observations were later shown to be entirely compatible with much higher resolution VLBI mapping (e.g. Vermeulen et al. 1993). Furthermore the superluminal radio jets of GRS 1915+105, as observed by Mirabel & Rodriguez (1994) with the VLA displayed a flux asymmetry on angular scales $\geq 1$ arcsec which is in agreement within a factor of order unity with flux asymmetries observed later on much smaller scales with MERLIN (Fender et al., 1998), and which are a direct result of relativistic aberration. In fact there is no convincing evidence for the deceleration of ejected radio components from X-ray binaries on angular scales up to several arcseconds. The flux ratios of separate ejections of very different magnitudes from GRS 1915+105 are all comparable (Mirabel & Rodriguez 1994; Fender et al. 1998), implying the same jet formation and acceleration process is in action for ejections of very different sizes. However, as discussed below, larger radio structures associated with some X-ray binaries are more symmetric than their compact jets, suggesting that deceleration of ejecta does take place on angular scales between several arcsec and arcmin.

### 3.2. Intrinsically asymmetric emission

The apparent one-sidedness of the extended emission may be intrinsic. While an intrinsically one-sided jet is possible, this is not favoured theoretically (e.g. Wiita 1991) and it seems instead likely that any asymmetry is determined by the environment beyond the point of origin. However, this is not seen in other X-ray binaries, where large radio structures which may not be moving at relativistic velocities are observed to be roughly symmetric. For example, symmetric radio lobes of extent $\sim 6$ arcsec were reported around the X-ray binary Cyg X-3 by Strom, van Paradijs & van der Klis (1989) and have been recently confirmed by Peracaula, Paredes & Martí (1998).
Perhaps the proposed high space velocity of Cir X-1 (a ‘runaway’ X-ray binary – e.g. Stewart et al. 1993) is responsible for the observed asymmetry. If the system has a high space velocity, a jet may be continually having to propagate into a dense, inhomogenous medium. If the binary really is moving north away from G321.9–0.3, then clearly the southeast jet would feel less resistance from the ISM than its northwest counterpart. However, we would not expect this effect to be significant unless the space velocity of the binary and the outflow velocity were of the same order of magnitude, which would rule out a relativistic jet, and explanation of the larger collimated structure to the NW then becomes problematic.

4. Conclusions

We have presented radio observations of Cir X-1 with an angular resolution of \( \sim 1 \) arcsec which clearly resolve the radio counterpart of the system into a core and extended emission to the southeast at a position angle of \( \sim 100 \) degrees and an angular extent of \( \sim 2 \) arcsec. In order to quantify the asymmetry we have redetermined as accurately as possible the radio and optical coordinates for the source. We find these to be in agreement within uncertainties and to imply an asymmetry in the fluxes of extended emission to the southeast and northwest of at least 2:1.

We have interpreted this asymmetric emission in two ways. Firstly we discuss the apparent flux asymmetry which would be produced by a relativistic jet inclined at some angle to the line of sight. Following these arguments, and assuming an intrinsically symmetric jet and ballistic motions of ejecta we derive a minimum outflow velocity of 0.1 c. In this case the much more symmetric collimated radio structures on arcmin scales implies the deceleration of the ejecta on angular scales of tens of arcseconds. As the compact object in Cir X-1 is a neutron star this may be the first observational evidence that the formation
of relativistic jets does not require the presence of an event horizon or some other unique property of black holes. We have also discussed the possibility that the extended radio emission is intrinsically asymmetric, possibly due to the large space velocity of the system. In either case we think it is likely that the extended emission on arcsec scales from Cir X-1 originates in compact jets from the X-ray binary.

RPF thanks Jim Caswell and George Nicolson for several useful discussions. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. We are grateful to the SuperCOSMOS Unit at the ROE for providing the scanned data from the UKST Southern sky red survey, and to Nigel Hambly for providing assistance with the data. The optical image is based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. RPF was funded during the period of this research by ASTRON grant 781-76-017 and EC Marie Curie Fellowship ERBFMBICT 972436.
REFERENCES


Levine A.M., Bradt H., Cui W., Jernigan J.G., Morgan E.H., Remillard R.A., Shirey R.,


This manuscript was prepared with the AAS LATEX macros v4.0.
Fig. 1.— The asymmetric radio jet in Cir X-1. (a) Top panel. Enhanced section of Fig 2 of Stewart et al. (1993) showing extended structures on arcminute-scales extending SE and NW from Cir X-1. (b) Lower panel. Overlay of our new high-resolution radio image at 3.5 cm from 1998 Feb 23 (contours) over a high-resolution optical image from the HST WFPC-1 (greyscale). This entire panel is contained within the single central resolution element of the upper panel. The peaks of radio and optical emission correspond to the new, more accurate coordinates we have derived (see text). Contours are at -5, 5, 7.5, 10, 15, 20, 30, 50, 75 and 100 times the r.m.s. noise of 40 µJy per beam. The solid ellipse in the top left-hand corner represents the synthesised beam, 1.31 × 1.17 arcsec at a p.a. of -4.0 degrees. Section from Stewart et al. (1993) reproduced by permission of Blackwell Scientific Publishers from MNRAS 1993, 261, pp 593-598.

Fig. 2.— Image at same frequency, from same observing run, using same phase calibration as for Cir X-1 image in Fig 1, of a nearby compact source which we designate J1520.6-571 (see text). Contours are at the same multiples of the r.m.s. noise, in this case 70 µJy per beam. The beam is 1.34 × 1.17 arcsec at a p.a. of -14.6 degrees. Subtraction of a point source from this image leaves residuals of ≤ 1% of the total flux. The lack of any significant emission beyond a point source profile completely rules out an origin for the extension of Cir X-1 in phase errors.

Fig. 3.— A profile of the flux density of the image of Cir X-1 presented in Fig 1 along the jet axis (as indicated by lines in Fig 1), integrated over a strip of width two arcsec. Negative offset indicates a southeasterly direction. Also indicated are the results of a simultaneous fit of a point source and Gaussian, and residuals from this fit (see text). No residuals are greater than 8% at any point. Assuming the point source is associated with the core of the X-ray binary, the asymmetry in the structure of ≥ 2:1 from the SE to the NW must reflect Doppler boosting of the approaching (SE) side of the jet or an intrinsic asymmetry.
Table 1. Measured flux densities at 6.3 & 3.5 cm for Cir X-1 from 1998 Feb 23 data. Total flux (i.e. inclusive of point and extended structure, measured directly from maps within 5σ contours) as well as fluxes of simultaneous Point plus Gaussian fits are tabulated. Overall spectral index corresponds to optically thin emission, but resolution into extended and point-like components reveals core to have an inverted (self-absorbed) spectrum, supporting its association with the compact core of the binary.

<table>
<thead>
<tr>
<th>Component</th>
<th>$S_{6.3\text{cm}}$ (mJy)</th>
<th>$S_{3.5\text{cm}}$ (mJy)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (5σ contours)</td>
<td>9.9</td>
<td>7.7</td>
<td>-0.7</td>
</tr>
<tr>
<td>Gaussian (model fit)</td>
<td>8.5</td>
<td>4.3</td>
<td>-1.2</td>
</tr>
<tr>
<td>Point (model fit)</td>
<td>1.7</td>
<td>2.8</td>
<td>+0.8</td>
</tr>
</tbody>
</table>